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Modeling and Simulation Performance of a Small Electric Vehicle on Different Floor Slopes

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ABSTRACT

This paper presents the development of a mathematical model of a small electric vehicle which is propelled by permanent magnet direct current (PMDC) motor. The tractive force required to drive the vehicle is obtained from (PMDC) motor. The torque-speed characteristics of the motor are used to obtain tractive force at given vehicle load and floor conditions. The simulation model of the vehicle for acceleration is developed, considering various forces that are acting in favour and opposite to the vehicle acceleration and also floors having different slopes. The vehicle parameters used in simulation are determined beforehand. The vehicle acceleration model is simulated in MATLAB for various floor slopes and simulation performance results are presented for the vehicle that is moving on floors like flat, upslope, downslope and more.

Key Words: *Modeling, Simulation, Acceleration, Vehicle, Slope.*

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1. INTRODUCTION

Recently, electric vehicles including fuel-cell and hybrid vehicles have been developed very rapidly as a solution to energy and environmental problems. The selection of traction motors for the electric vehicle (EV) propulsion systems is a very important step that requires special attention. In fact, the automotive industry is still seeking for the most appropriate electric propulsion system. In this case, key features are efficiency, reliability and cost. The process of selecting the appropriate electric propulsion systems is however difficult and should be carried out at the system level. In fact, the choice of electric propulsion systems for EVs mainly depends on three factors: driver expectation, vehicle constraint, and energy source. The eclectic vehicle modeling generally consists of modeling of electric and vehicle systems.

The mathematical model formulated in this paper consist of various forces like tractive force in favour of a vehicle acceleration and forces acting opposite is rolling resistance, aerodynamic drag and inertia. The grade resistance force favoursthe acceleration when a vehicle is moving on downslope and in opposes acceleration when a vehicle is moving on upslope. A problem with vehicle kinematics models is that by empirically developing mathematical expressions that describe the acceleration patterns of the vehicle, the actual components that affect the motion of the vehicle; the tractive force provided by the prime mover (PMDC motor) and the resistance forces opposing the vehicle’s motion are not modeled explicitly. Therefore, these models are difficult to calibrate and do not generally provide a good fit to field data for each of the acceleration, speed, distance, and time domains. They also do not account for different vehicle types, roadway grades, and other factors that affect the vehicle acceleration patterns.The system takes voltage as an input to the electric motor, and output is the rotational speed of electric motor or the linear motion of the electric vehicle. The electric motors are capable of generating high torque at low speed, can operate efficiently over a greater range of speeds and can be smoothly controlled [1].

2. RELATED WORK

Torsten Butz et al., proposed a two-level optimization scheme, which allows estimating unknown chassis model parameters of the commercial vehicle simulation package DYNA4.. The basic parameter estimation task yields a nonlinear least-squares problem, which was numerically solved by a Levenberg–Marquardt algorithm. To increase the sensitivity of the unknown parameters with respect to the least-squares objective, the parameter estimation scheme has been enhanced by a method for optimal experimental design. Numerical results have been reported for a sample application [2]. Jose C. Pascoa et al., proposed an alternative approach to the standard on-road coast down test used in automotive industry and in ground vehicle research. A detailed description of both methods was provided in order to highlight the advantages and drawbacks of each one. The new approach has been implemented in order to compute the rolling and aerodynamic coefficients for an Eco-marathon vehicle designed and built at University of Beira Interior [3]. Kichun Jo et al., proposed a road-slope estimation algorithm of intelligent vehicle. The algorithm integrates three types of road-slope measurements from a GPS receiver, automotive onboard sensors, and a longitudinal vehicle model. The measurement integration was achieved through a probabilistic data association filter (PDAF) [4]. Yazid Sebsadji et al., presented a method for the estimation of vehicle state by an EKF, and to reconstitute the road slope using a Luenberger observer [5]. Eduard Ribar et al., presented analysis how ascending and descending road slopes influence energy management in hybrid electric vehicle power-train [6]. Gorantla Srinivasa Rao et al, developed battery charge indication and propulsion system of electric/HEV. The proposed system was analyzed using MATLAB software and the results have been used in designing a physical model of a vehicle [7]. Hongyu Shu, Xingpeng Diao et al., proposed a novel in-wheel tri-motor power train (IWTMP) [8].

Fengjun Yan, Junmin et al., presented power management system for plug-in hybrid electric vehicle has been developed using model predictive control and torque split strategy [9]. Amir Taghavipour et al., presented similar study can found in [9][10]. Nicolas Sockeel et al, evaluated numerically the impacts of the vehicle battery model on the MPC optimal control solution when the plug hybrid electric vehicle (PHEV) is in the battery charge sustaining mode [11]. Krishna Veer Singh e .al., presented architectures and components of hybrid eclectic vehicles [12].

3. MODELING VEHICLE FORCES

The electric vehicle used in modeling is considerably very small and consists of two subsystems, the electric motor and the vehicle system; both these subsystems are modeled all acting forces and vehicle parameters and are coupled with the wheel rotational velocity via characteristics of the electric motor. In order to model the dynamic behavior of the vehicle; all forces acting on the vehicle must be modeled. Figure 1; shows all the forces that are acting on the vehicle when it is moving on floor at a upslope an angle (ϕ) [13], [14]. It is to be noted that the effect of these forces in longitudinal direction only is considered. The forces acting on the vehicle are divided into two groups, the forces in the direction of movement, and the forces in the opposite direction of the movement. The first step in a vehicle modeling is to obtain an equation for the tractive effort (Nm) produced by the prime mover which is selected to propel the vehicle. This tractive effort produced by the prime mover is converted into the tractive force through selected gear train and is applied on the wheels for propelling the vehicle forward, transmitted to the ground through the drive wheels. The various vehicle parameters are estimated by conducting tests on the vehicle and some are standard. The formulation of acceleration model for the vehicle is explained in following sections.

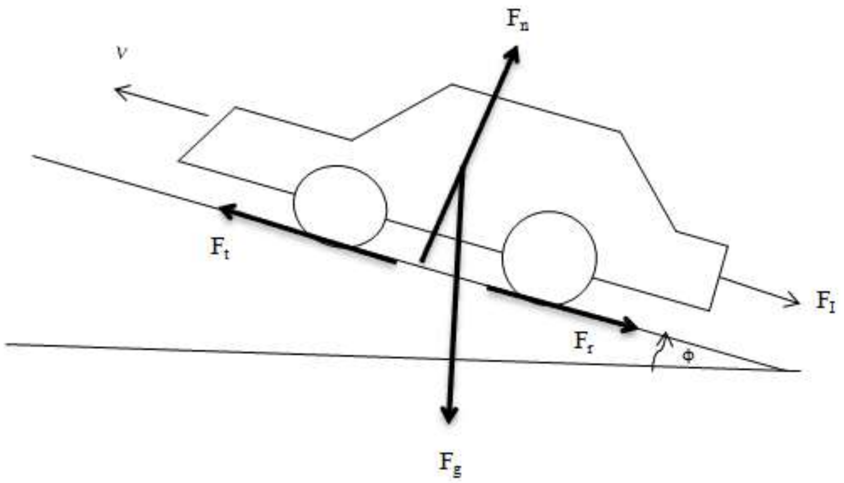

Figure 1. Free body diagram of forces acting on the vehicle on inclined surface at an angle (ϕ)

3.1 Tractive Force

The tractive force is used to move the vehicle forward by overcoming the resistances that occurs during the motion. The maximum torque developed by the electric motor is a fairly simple function of angular speed. In most cases, at low speeds, the maximum torque is a constant, until the motor speed reaches a critical value ω_c after which the torque falls. In the case of a brushed shunt or PMDC motor the torque falls linearly with increasing speed. The test vehicle used in experimentation was a

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variable speed vehicle fitted with a PMDC electric motor as a prime mover. The angular velocity of the motor depends on the gear ratio 'G' and the radius of the drive wheel 'r' and gear transmission efficiency η. The torque developed by the motor (T_{motor}=T_{shaft})and torque (T_{wheel}) available at the end of gear train is given by equation(1).

$$T_{wheel} = G\eta T_{shaft} \tag{1}$$

Equation for T_{shaft} is given as;

$$T_{shaft} = \frac{F_t}{G} r \tag{2}$$

Rearranging equation (2), we get ;

$$F_t = \frac{G}{r}\eta T_{shaft} \tag{3}$$

For PMDC motor the relation between motor torque ($T_{motor} = T_{shaft}$) angular speed ω, maximum torque (T_{max}) and torque constant K can be written as given by equation (4). This is basic important equation which gives the input for formulation of a simulation model for the vehicle.

$$T_m = T_{max} - K\omega \tag{4}$$

Equation (4) can be modified as;

$$T_w = T_{max} - \frac{KG}{r} v \tag{5}$$

Further equation (5) can be modified as;

$$T_w = T_{max} - K_m v \tag{6}$$

Now the equation (6) gives the tractive effort (Nm) developed by the motor which is applied on the wheels to accelerate the vehicle.

3.2 Rolling Resistance Force

Rolling resistance force F_r acting on a tyre or vehicle is mainly due to the hysteresis of the deformation of the tyre in the contact zone with the road surface, which gives rise to energy losses. If related to the vertical normal force (F_n) it can be expressed as a rolling resistance coefficient $\mu_r = F_r / F_n$. This coefficient depends on several tyre and road surface parameters as well as the vehicle speed. The test vehicle used in the modeling has low weight and it operates at low speed. Therefore, the rolling resistance force is approximately constant for low speed vehicle, and is proportional to vehicle weight. It is calculated using equation (7).

$$F_r = \mu_r mg\cos(\phi) \tag{7}$$

3.3Aerodynamic Drag Force

This part of the force is due to the friction of the vehicle body moving through the air. It is a function of the frontal area and shape of the vehicle. The drag from air resistance depends on the dynamic pressure and is thus proportional to the square of the speed. At low speed it is negligible. The aerodynamic drag force can be calculated using equation (8).

$$F_{ad} = \frac{1}{2}\rho A_f C_d v^2 \tag{8}$$

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The vehicle used in the experimentation has very low speed, thus the effect of aerodynamic drag force is negligible, and it is taken as $F_{ad} \cong 0$.

3.4 Grade Resistance Force

Grade resistance force is required to be calculated when the vehicle is moving on the road or floor which is inclined at an angle (ϕ). If the vehicle is moving on the floor having upslope, the weight of the vehicle will create a grade resistance force directed downward; this force will oppose to the motion. But, when a vehicle is moving on the floor having down slope, the weight of the vehicle will create a grade resistance force directed downward; this force will help to the motion. Therefore, the effect of grade resistance depends upon the direction of movement of the vehicle on the slope. The grade resistance force can be calculated using equation (9).

$$F_g = mg\sin(\phi) \tag{9}$$

3.5 Acceleration Force

If the velocity of the vehicle is changing, then clearly a force will need to be applied in addition to the forces shown in figure 1. This force will provide the linear acceleration to the vehicle, and is given by the equation derived from Newton's second law of motion, as in equation (10).

$$F_a = ma \tag{10}$$

3.6Total Force

The total tractive force required to overcome the various resistance forces acting on the vehicle and to accelerate the vehicle in forward direction at required speed is given by equation (11).

$$F_t = F_r + F_{ad} + F_g + F_a \tag{11}$$

The dynamical model and analysis of DC shunt, series and permanent-magnet (PM) motors fed by photovoltaic (PV) energy systems at different illuminations are found in [15]. The characterization of small DC brushed and brushless motors can found in [16]. The design, analysis, experimental verification and field weakening performance study of a brushless direct current (BLDC) motor for a light electric vehicle is presented in [17].

4. MODELING VEHICLE ACCELERATION

The general equation for acceleration of the vehicle is given by Newton's second law of motion, which can be written as;

$$F = ma_v \tag{12}$$

In case of variable speed vehicle, the equation for acceleration can be written as;

$$a_v = \frac{F_t - \Sigma F_{lr}}{m} \tag{13}$$

F_t is the tractive force applied by the PMDC motor in direction of vehicle motion and ΣF_{lr} is the sum of all resistance forces acting against the vehicle motion. The equation (13) can be written as;

$$a_v = \frac{F_t - (F_r + F_{ad} + F_g)}{m} \tag{14}$$

As the speed of the vehicle used in real time application is low, hence, F_{ad} can be neglected. Equation (14), can be modified for the acceleration, when the vehicle moving on floor at certain upslope by angle (ϕ), can be written as ;

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$$a_v = \frac{F_t - (F_r + F_g)}{m} \tag{15}$$

Putting values of F_t, F_r and F_g in equation (15), we can obtain the general for vehicle acceleration as in equation(16) ;

$$a_v = \frac{T_{max}}{mr} - \frac{K_m}{mr} v - \mu_r g\cos(\phi) - g\sin(\phi) \tag{16}$$

Putting

$$K_1 = \frac{T_{max}}{mr}, K_2 = \frac{k_m}{mr}, K_3 = \mu_r g\cos(\phi), K_4 = g\sin(\phi) \tag{17}$$

The acceleration equation (17), can modified as for given road of slope angle (ϕ);

$$a_v = (K_{up} - K_v v) \tag{18}$$

The velocity of the vehicle can be calculated using equation (19)

$$V_{(n+1)} = V_{(n)} + (K_{up} - K_v V_n)dt \tag{19}$$

The distance covered by the vehicle can be calculated using equation (20),

$$S_{(n+1)} = S_{(n)} + V_{(n)}dt \tag{20}$$

The inertia force can be calculated using equation (21).

$$F_a = (K_{up} - K_v V) \times m \tag{21}$$

The other forces like rolling resistance, grade resistance and total resistance can be calculated using equation (7), (9) and (11) respectively. When the vehicle is moving on floor having zero slope then ϕ =0, equation (16), can be written as

$$a_v = \frac{T_{max}}{mr} - \frac{K_m}{mr} v - \mu_r g \tag{22}$$

When the vehicle is moving on floor at downslope then, equation (16), can be written as

$$a_v = \frac{T_{max}}{mr} - \frac{K_m}{mr} v - \mu_r g\cos(\phi) + g\sin(\phi) \tag{23}$$

5. SIMULATION RESULTS

This section presents simulation results of the vehicle acceleration performance model. In simulation two basic vehicle ranges are considered i.e. acceleration and cruising. The third deceleration vehicle range is not considered. The acceleration model developed for different floor slopes i.e. flat, upslope and downslope is simulated in MATLAB. The simulation time was 10 seconds for all floor slopes. For each floor slope the values of K_1, K_2, K_3, K_4,etc are calculated and put in equation (18), (19), and

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(20) to calculate acceleration, velocity and distance covered by the vehicle during simulation. The vehicle parameters are given in table 1; arealso used as the inputs for the simulation.

The vehicle parameters mentioned in table 1 are obtained by conducting different tests on the test vehicle. The tractive force is obtained by conducting torque- speed characteristics of the PMDC motor. The small set up was developed to find the torque – speed characteristics of the motor. The rolling resistance is determined by steady state pulling of the vehicle on flat floor. The coefficient of rolling friction is calculated by knowing the weight of the vehicle and rolling resistance force. The gear ration is calculated from the no of teeth's on the gears. The up slope angle considered is 3 degrees and down slope is also 3 degrees.

Table 1.Estimated vehicle parameters

Tractive force (F_t)	*2.8 N*
Rolling resistance (F_r)	*1.6 N*
Vehicle mass (m)	*1.2 Kg*
Coefficient of rolling friction (μ_r)	*0.136*
Gear ratio	*9.21*
Slope of F_t-V diagram K_m	*0.0284*
Wheel radius	*0.024 m*
Acceleration due to gravity (g)	*9.81 m/s^2*
Slope up and down angle (ϕ)	*3^0*

The simulation results for different floor slopes are presented in following sections**.**

5.1 Vehicle on Flat Floor

When the vehicle is moving on flat floor, the acceleration equation used for simulation is equation (22). To test developed mathematical model of the vehicle on flat floor, it is firstly, simulated in MATLAB for 10 sec with a time interval of 200 ms. The vehicle range considered in simulation is acceleration and cruising. The third vehicle range i.e. deceleration is not presented graphically but the time take by third range to stop the vehicle and distance coved during this range is calculated and presented in table 2. The deceleration of the vehicle i.e. after power cut-off of PMDC motor depends on three vehicle parameters i.e. maximum velocity attained by the vehicle, mass of vehicle and the coefficient of rolling friction. In case of flat floor, the deceleration time was found to be 0.76 sec. The total time for all three ranges i.e. acceleration; cruising and deceleration is sum of these three. The acceleration, velocity and distance covered by the vehicle during simulation are presented in figure 2. The maximum velocity recorded by the vehicle is 1 m/s.

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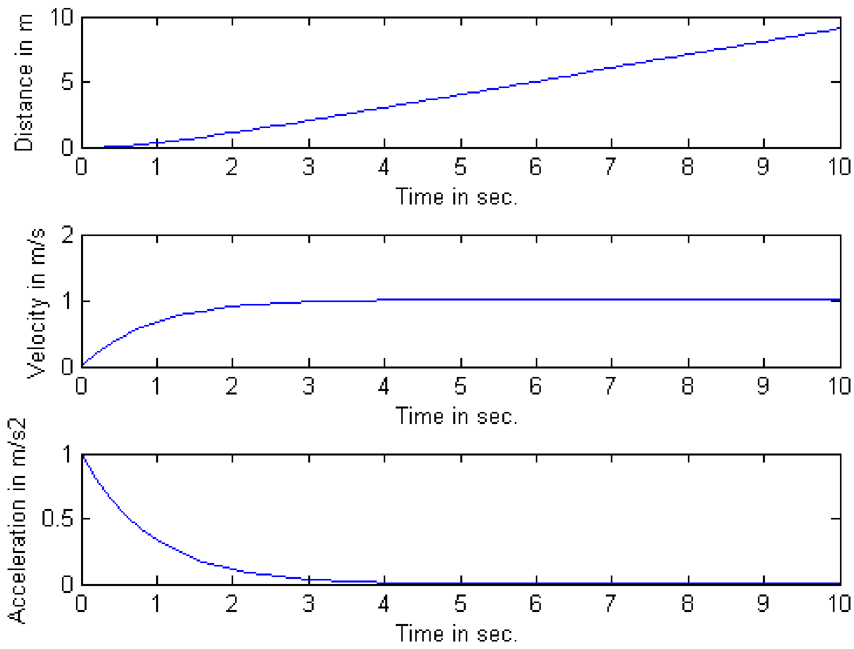

Figure 2. Simulation results with distance, velocity and acceleration of the vehicle moving on a flat floor

The forces that are taking part in vehicle acceleration are tractive, rolling resistance and vehicle inertia, when the vehicle is moving on flat floor. These forces are calculated during vehicle ranges acceleration and cruising is presented in figure 3. It shows that inertia force becomes zero when a vehicle velocity reaches to its maximum value and at that velocity tractive force is equal and opposite of rolling resistance force.

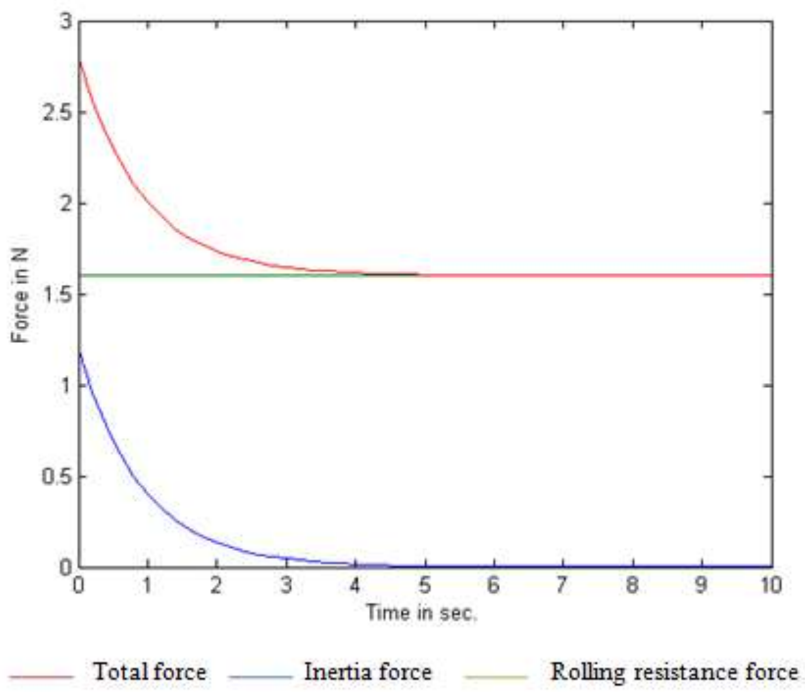

Figure 3. Display of various forces during simulation for the vehicle moving on a flat floor

5.2 Vehicle on Floor of Up Slope

To test the performance a vehicle simulation model on an inclined floor, the angle of inclination was taken 3degrees with flat floor. The model was simulated for 10 sec with a time interval of 200 ms for acceleration and cruising range. When vehicle is moving on floor which is inclined at certain angle with flat floor; naturally, the maximum velocity attained by the vehicle will be

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less as compared to the flat floor. Therefore, the maximum velocity recorded in this case was 0.5 m/s. The deceleration time was found to be 0.42973 sec. The vehicle acceleration, velocity and distance covered for acceleration and cruising ranges are presented in figure 4.

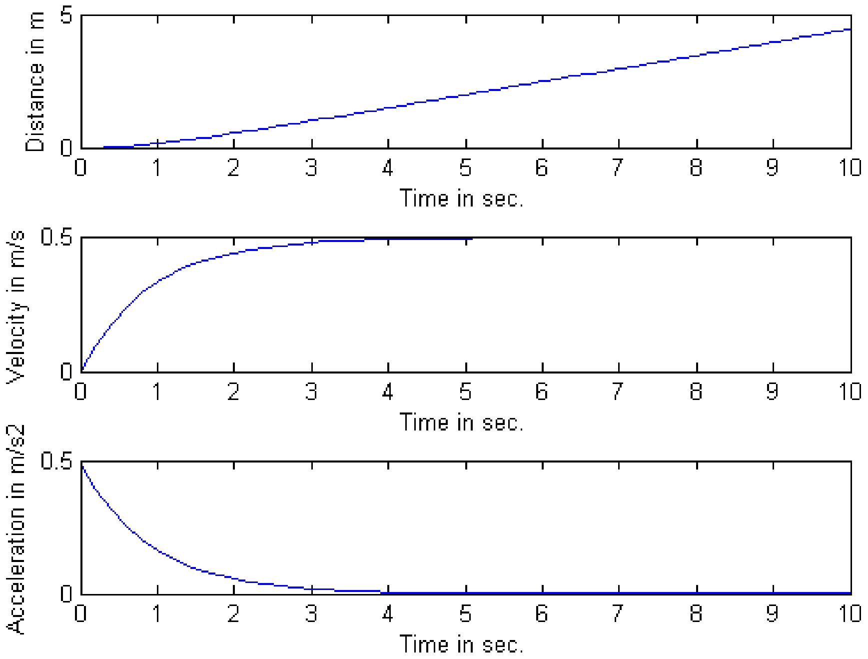

Figure 4. Simulation results with distance, velocity and acceleration of the vehicle moving on floor of upslope

The forces that are taking part in simulation are tractive, rolling, inertia and grade. The figure5 shows the variation of various forces with a time for floor having upslope. The tractive force at maximum velocity is found to be 2.2 N which is balanced by rolling resistance force 1.6 N and grade resistance force 0.6 N. The inertia force becomes zero after 3 seconds of simulation where the vehicle velocity reached to its peak value.

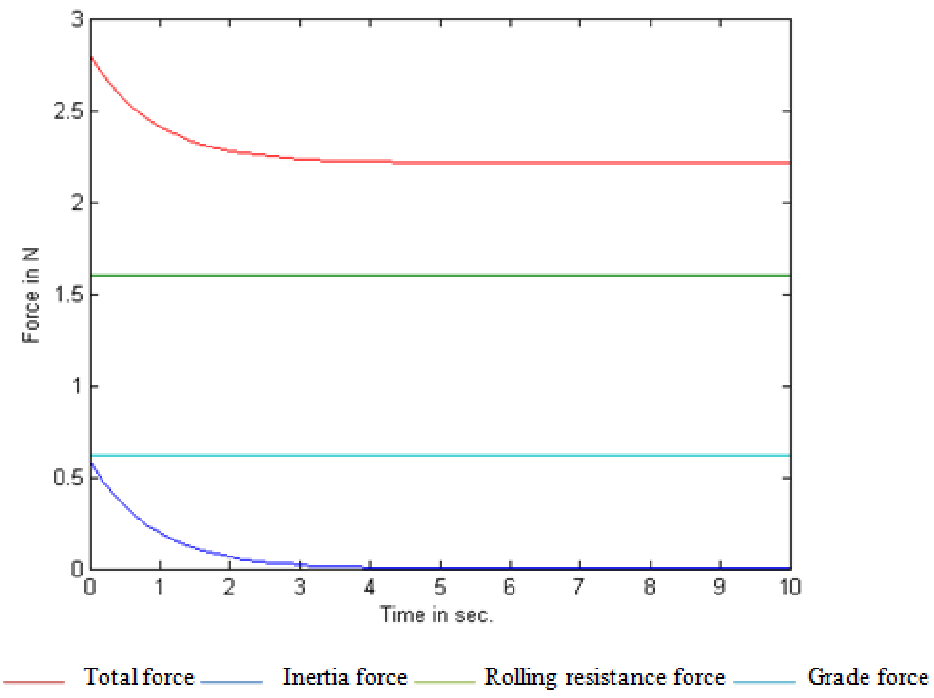

Figure 5. Display of various forces in simulation of the vehicle moving on floor of upslope

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5.3 Vehicle on Floor of Down Slope

To test the simulation performance a given vehicle acceleration model on a floor of downslope, the angle of a down slope taken was 3degrees with flat floor. The model was simulated for 10 sec with a time interval of 200 ms for acceleration and cruising range. As the vehicle is moving on floor which has downslope, vehicle grade resistance force helps to acceleration to increase the speed of the vehicle. Therefore, in this case maximum speed attained by the vehicle was recorded 1.5 m/s, which is greater than 1 m/s for flat floor. The vehicle deceleration time was found 1.1524 sec. The vehicle acceleration, velocity and distance are presented in figure 6.

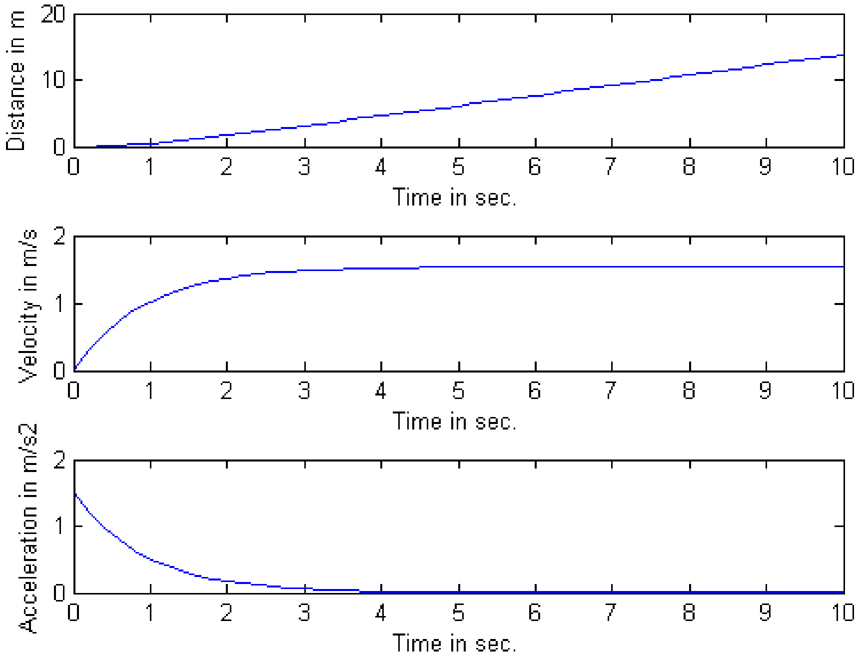

Figure 6. Simulation results with distance, velocity and acceleration of the vehicle moving on floor of downslope

The forces that are taking part in simulation are tractive, rolling, inertia and grade. The forces acting on the vehicle when it is moving on the floor of downslope are calculated and presented in figure 7. The tractive force at maximum velocity is found to be 1 N which is balanced by rolling resistance force 1.6 N and grade resistance force 0.6 N in favour of acceleration.

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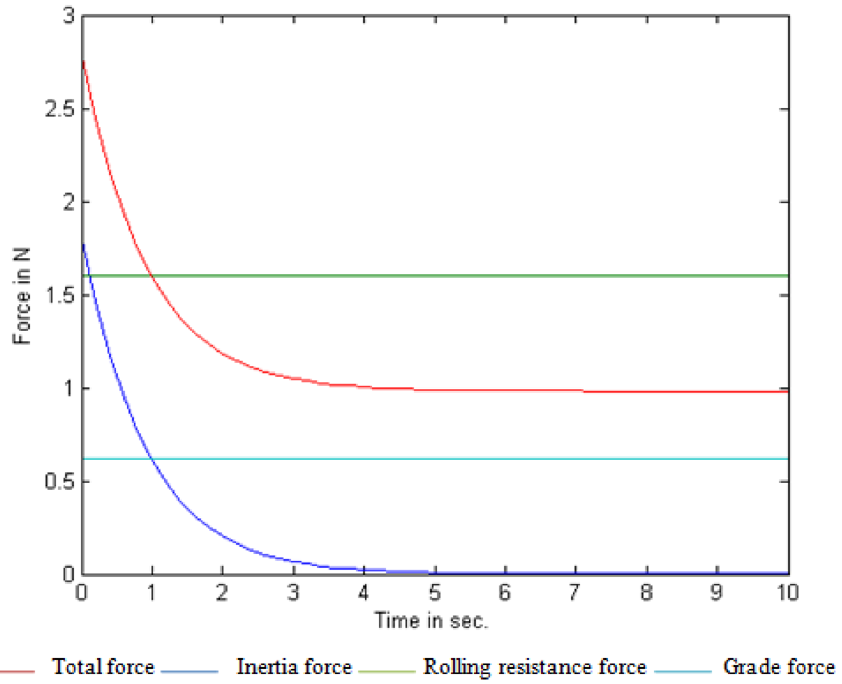

Figure 7. Display of various forces in simulation of the vehicle moving on floor of downslope

5.4 Tractive Force Vs Vehicle Velocity

The maximum tractive force used in simulation is obtained from torque-speed characteristics of the PMDC motor. When the electric motor is used to propel the vehicle then tractive force available at the wheel is calculated using torque at motor shaft, gear ratio, vehicle wheel diameter, transmission efficiency, vehicle speed, etc. The maximum tractive force obtained by the PMDC motor connected to the test vehicle was found to be 2.8 N. This tractive force is used as input to the vehicle for acceleration by overcoming resistance forces. The velocity of the vehicle is depends upon the floor slopes and tractive force available. The tractive force Vs vehicle velocity for floors like flat, upslope and down slope is displayed in figure 8.

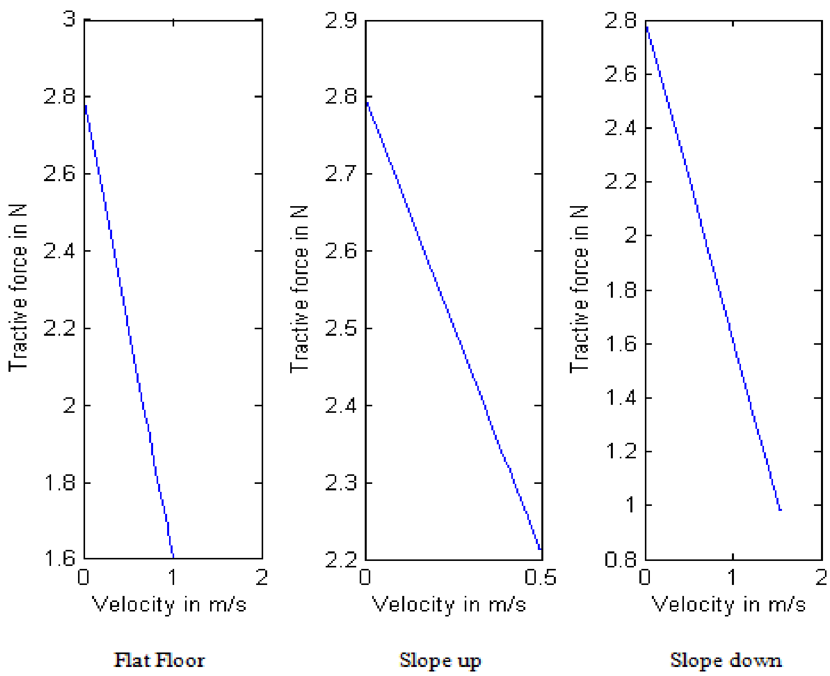

Figure 8. Display of tractive force Vs vehicle velocity for different floor slopes

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Figure 8 shows that for flat floor the vehicle reached at maximum velocity of 1m/s at tractive force 1.6 N, at this velocity vehicle inertia force becomes zero and tractive force is balanced by rolling resistance force. For floor having upslope the maximum velocity found to be 0.5m/s at tractive force of 2.2.N; at this velocity grade resistance is added to the rolling resistance force. For floor having downslope the maximum velocity obtained is 1.5 m/s at tractive force of 1 N, at this velocity grade resistance is subtracted from rolling resistance force.

The distances covered by the vehicle during a simulation for vehicle ranges i.e. acceleration, cruising and deceleration are given in table 2. From the simulation results, it is observed that when the vehicle is moving on floor having a upslope, the distance covered is less as compared to flat floor. While, when it moving on floor having a downslope by the same angle the distance covered is more as compared to flat floor. In a simulation, the vehicle velocity was low; the coefficient of rolling resistance is assumed to be constant. Therefore, for different road conditions, vehicle grade resistance force plays important role for changing vehicle velocity.

Table 2. Distance covered by the vehicle on different floor slopes

Floor slope	***Distance during acceleration in m***	***Distance during cruising in m***	***Distance during deceleration in m***	***Total in m***
Flat	*4.25*	*4.87*	*0.45*	*9.57*
Upslope (3^0)	*2.87*	*1.58*	*0.3*	*4.75*
Down slope (3^0)	*5.52*	*8.29*	*1.0*	*14.81*

6. CONCLUSION AND DISCUSSIONS

The basic objective of the paper was to develop a mathematical model for acceleration of small electric vehicle which is propelled by PMDC motor. The developed vehicle acceleration model is simulated on floors of different slopes like flat, upslope downslope, etc. The test vehicle selected for simulation has low weight and low speed, therefore, the aerodynamic drag is not considered in a mathematical modelling. The coefficient of rolling resistance is determined by conducting test on the vehicle and it is assumed to be constant for low speed vehicle. The tractive force applied on the vehicle for given floor slope was obtained from torque-speed characteristics of the PMDC motor. The simulation performance of a vehicle acceleration model for different floor conditions is presented and their results are compared.

It is observed from the simulation results that the peak velocity found to be increasing from upslope, flat and downslope floors. This could be the effect of rolling resistance and grade resistance force. The upslope floor grade resistance force opposes to the acceleration and downslope it acts in favour of the vehicle acceleration and it is zero when vehicle is moving on flat floor. The distributions of forces are presented in figure 4, 6 and 8 for flat, upslope and downslope floors respectively. The distances covered by the vehicle during simulation with various ranges are given in table 2.

The selected test vehicle has to be used to control with the help of a camera sensor with coloured markers. Therefore, the vehicle velocity was kept as low as possible to recognize coloured markers for the camera sensor. The simulation results are validated using a camera sensor for flat floor only. The results could not get validated for floor having up slope and down slope because of small field of view (FOV) camera i. e .less working space.

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