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Modelling of Electric Vehicles Using Matlab/Simulink

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Abstract

In this paper, we present a Matlab/Simulink model for electric vehicles (EVs). We model the vehicle dynamics, transmission performance, and battery of the EVs to acquire the power requcirements of the battery and to later deduce the best types of battery to use for such applications. The simulations are performed through an integration of the Matlab code and Simulink blocks. The velocity of the vehicle and its distance travelled correspond to actual driving cycles and torque variations of an EV. The added value of this model is that it simulates the aerodynamic drag, linear acceleration, and rolling resistance forces where the modelled motor efficiency hit 73%. Other results corresponding to its tractive effect, motor efficiency, and battery requirements are obtained. The simulations are verified and all fit the theory behind EVs.

Keywords

Electric vehicles, Simulink, Matlab, Vehicle dynamics, Transmission performance, Battery, Torque, Mechanical power, Electrical power, Motor efficiency

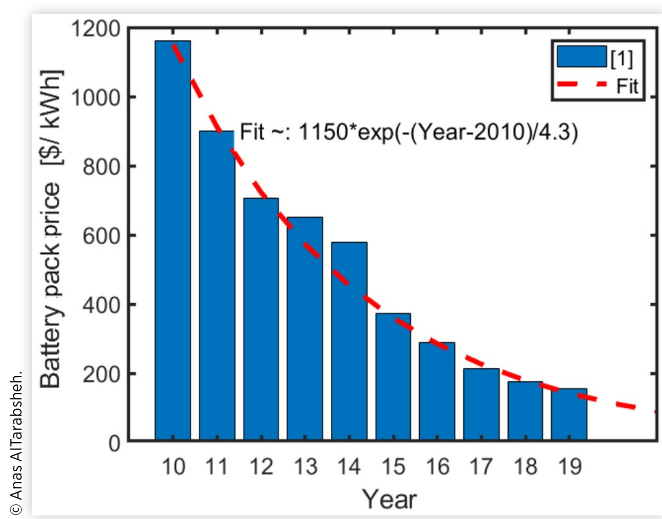
1. Introduction

The Electric Vehicles (EVs) market is growing rapidly because the people are more worried about carbon dioxide (CO_2) emissions and the impact of fossil fuels on the environment. The key point for the EV market to succeed is to focus on research and development to model and develop the battery technology, motor efficiency, vehicle dynamics, and transmission performance. The EVs' battery prices have declined, as depicted in Figure 1, where the expected price (according to the fit) in 2020 will be $112 per kWh.

The industry of EV has grown rapidly in the last five years and is expected to continue as the electric range is improved. This is noticed by the market decline of conventional vehicles. With the increase in the automation market demand, however, comes the increase in fuel consumption. This adversely affects the environment, especially with the CO_2 emissions. Regular vehicles can only run on petroleum as opposed to EVs or hybrid EVs. This alternative method of transportation has a huge impact on the environment as it reduces the toxic emissions by making use of electricity and/or batteries.

The authors of [2] have simulated Proton IRIZ Battery Electric Vehicle (BEV), a Malaysian car, using Simulink. They identified and modelled the six electric components of such system with their corresponding mathematical equations. They investigated the flow of energy and the performance and efficiency of the BEV. Their model is subjected to further modifications and can provide a solid foundation for BEV modelling.

FIGURE 1 Battery pack prices and the fitted data (dashed lines). Data taken from Ref. [1].



The analysis of a novel Switched Reluctance Motor (SRM) hub motor is presented in [3] to improve the performance of EVs. The authors followed a passive load scheme to model such vehicles and analyze their performance. The modelled SRM consists of eight stator and six rotor poles. Its simple construction and low-inertia rotor make the SRM a good candidate for EVs in both generation and motoring modes. Due to the generated torque's phase current polarity independenc of such motor, we only require few static semiconductor switching devices for driver applications. Moreover, the main advantage of using SRMs is the torque-to-inertia ratio, where the initial torque is very high to accommodate the high starting inertia and hence its suitability for high-speed applications.

Another method for improving the performance of EVs is presented in [4]. The authors propose a composite power supply for such that consists of a supercapacitor, large power, and a conventional battery. To enhance the topology of the composite power supply, the Direct Current (DC)-to-DC converter in its structure uses the parallel staggered technology. The whole structure is modelled in Matlab/Simulink, and the energy storage system is managed through fuzzy logic control. The results conclude that this system improves the output power of the EVs, energy efficiency, and the process of discharging the battery. Also it is more applicable economically.

Plug-in EVs utilize rechargeable batteries to drive the motor unlike the Internal Combustion Engine vehicles. As such, there are charging stations for these vehicles that allow them to be plugged into the power grid [5]. A fast DC off-board charging station that can accommodate multiple EV charges is presented in [6] through the use of Matlab/Simulink. Two types of controls are deployed: Voltage Regulation Control (V-Control) for the front-end and Power Control (P-Control) for the back-end. There is an Alternating Current (AC)-to-DC converter in the front-end to exchange the power between the grid and the DC bus. The voltage on the DC link is maintained constant, while the grid voltage is regulated using the V-Control. On the back-end side, there is a DC-to-DC converter, where the P-Control is responsible for providing a constant current or reduced constant current. Also, the authors propose a battery management system for controlling the battery's charging current, voltage, and temperature. Their simulated results conclude that varying the charging current reduces the charging time of the battery. The dynamic model of an EV is investigated by Matlab in [7], and the effect of different vehicle's resistance forces on the vehicle performance is tested too.

The work of [8] presented a comprehensive EV system simulation to directly resemble the physical system using Matlab/Simulink graphical software environment. The article [9] developed a GUI in Matlab to monitor the most important variables from the EV where the measured variables depend on the sensors' signal to be later adapted to the appropriate voltage range. A testing method focusing on the EVs' driveability is proposed in [10] where the Matlab/Simulink models were developed to mimic the real-time testing cases. On the other hand, the authors in [11] used the Matlab/Simulink to study and model the system of EVs, and they obtained simulation results that proved the accuracy and efficiency of the proposed dynamic model.

In our work, we deduce the best types of battery via modelling the EV dynamics and transmission performance, and the used battery to acquire the power requirements. The added value of this model is that it simulates the aerodynamic drag, linear acceleration, and rolling resistance forces to maximize the motor efficiency. On the other hand, the velocity of the EV and its distance travelled correspond to the actual driving cycles and the torque variations.

The rest of the paper is summarized as follows: Section 2 presents the proposed Matlab/Simulink model, Section 3 discusses and analyzes the results, and Section 4 concludes the paper.

2. Proposed System

The proposed Simulink model is based on the simulated model in [12], which is based on the EV modelling presented in [13]. Our model is presented in Figure 2. To model any EV, three major parts should be taken into consideration: vehicle dynamics, transmission performance, and battery. These three will be explained in detail while referring to the Matlab/Simulink model.

All parameters used in modelling EVs are presented in Table 1. The velocity and hence the acceleration of the vehicle is simulated and inputted into the Simulink model to model a driving cycle of an EV.

2.1. Vehicle Dynamics

The first step towards modelling an EV is studying its vehicle dynamics. This represents the net forces acting on a vehicle during its driving cycle and the effect of multiple parameters on its velocity and performance. Figure 3 illustrates the different types of forces acting on a vehicle. These include the aerodynamic drag F_{ad}, acceleration, rolling resistance F_{rr}, and hill-climbing F_{hc} forces. The combined effect results in a tractive effect force F_{te}. These four forces are represented in the upper half of the Simulink model in Figure 2.

2.1.1. Aerodynamic Drag Force The first force acting on the EV is the aerodynamic drag force. This is caused by the friction of the air when the vehicle is moving. It can be defined as Equation 1:

$$F_{ad} = \frac{1}{2}\rho A C_d v^2 \qquad \text{Eq. (1)}$$

where ρ is the air density, A is the frontal area of the vehicle, C_d is the air drag coefficient, and v is the vehicle speed in relation to the air. The subsystem that models this force is demonstrated in Figure 4.

2.1.2. Acceleration Force There are two types of accelerations to be considered while modelling an EV: linear and angular accelerations. The angular acceleration can be denoted as

$$F_{wa} = \frac{IG^2}{n_g r^2} a \qquad \text{Eq. (2)}$$

where I is the moment of inertia, G is the gear ratio, n_g is the gear system efficiency, r is the tire radius, and a is the

FIGURE 2 Proposed Simulink model for EVs.

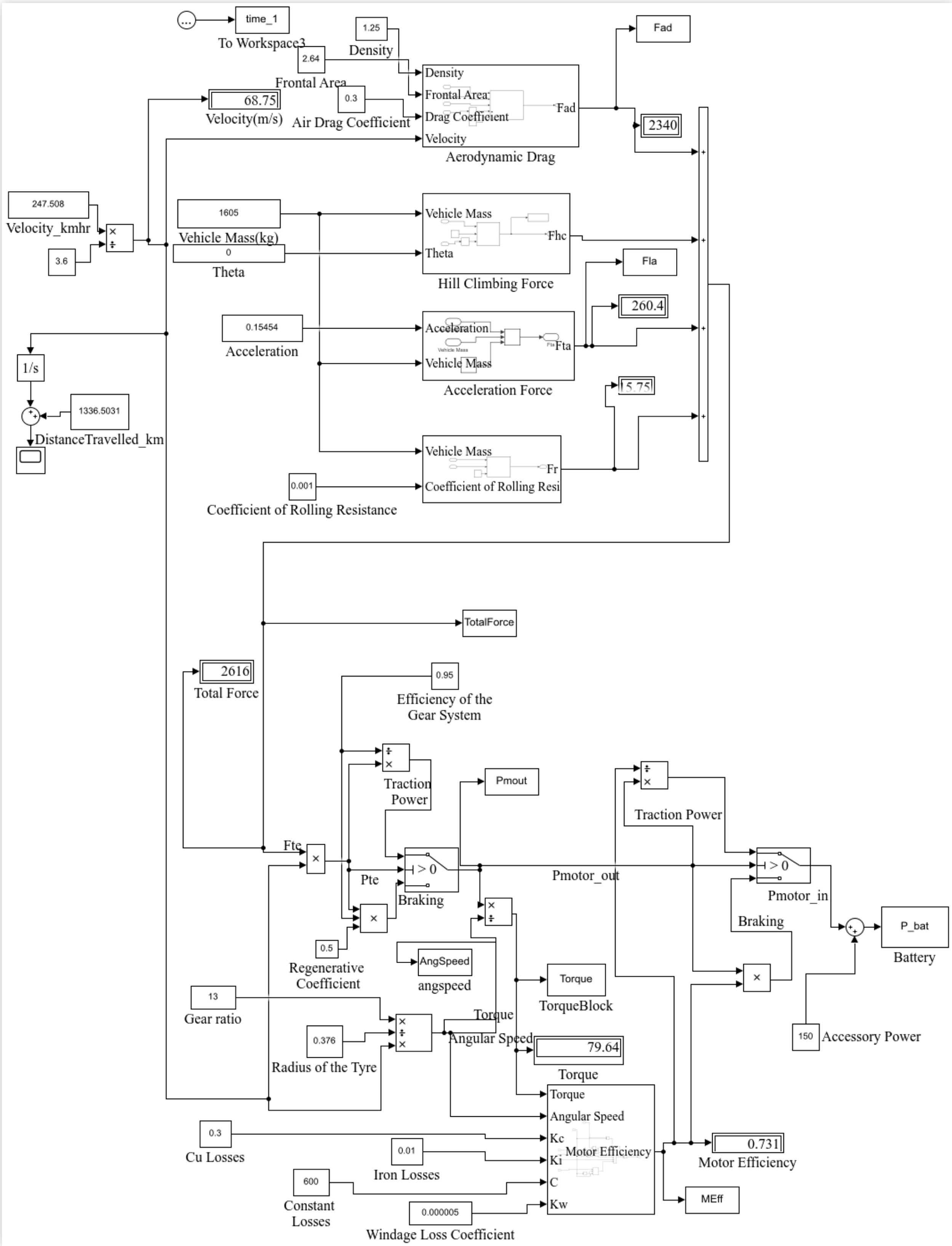


TABLE 1 Simulation parameters.

Parameters	
Air density	1.25 kg/m^3
Frontal area	2.64 m
Air drag coefficient	0.3
Vehicle total mass	1605 kg
Coefficient of rolling resistance	0.001
Gravitational force	9.81 m/s^2
Efficiency of gear system	0.95
Regenerative coefficient	0.5
Gear ratio	13
Radius of the Tire	0.376 m
Copper losses coefficient	0.3
Iron losses coefficient	0.01
Windage losses coefficient	0.000005
Constant losses	600
Average power of accessories	150 W

FIGURE 3 Total tractive effect on a vehicle.

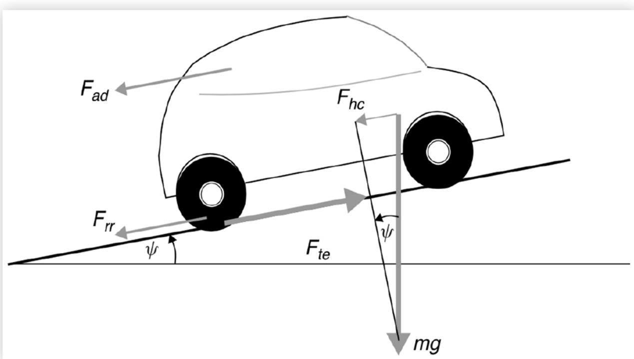
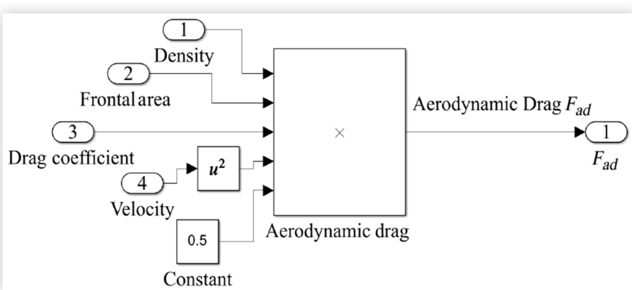
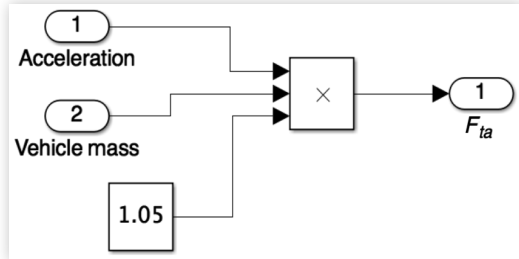


FIGURE 4 Aerodynamic drag force Simulink subsystem.



acceleration. Often the moment of inertia will be unknown, so to account for angular acceleration, we deduce a ratio from Equation 2. Assuming a 30 kW motor with G/r values typically given at 40 and n_g of 0.025 kg m^2 with a weight of approximately 800 kg, this will return a considerably small value as compared to the linear acceleration with a ratio of 40/800 = 0.05; hence the 5% ratio. Due to this reason, we increase the mass in the linear acceleration formula by 5% to model a typical scenario. This is explained in [13], where the authors

FIGURE 5 Linear acceleration force Simulink subsystem.



modelled their vehicle as such. The formula for the linear acceleration force model, which is shown in Figure 5, is therefore given by Equation 3:

$$F_{La} = 1.05ma \qquad \text{Eq. (3)}$$

2.1.3. Rolling Resistance Force

This force depends on the friction between the tires of the vehicle and the road. As such, it is modelled by Equation 4, where the coefficient of rolling resistance, μ_{rr}, depends on the type of the tire utilized and its pressure.

$$F_{rr} = \mu_{rr} mg \qquad \text{Eq. (4)}$$

The Simulink subsystem model that is represented is shown in Figure 6.

2.1.4. Hill-Climbing Force

The last force accounted for in the vehicle dynamics of an EV is the hill-climbing force. This force depends on the angle of inclination of the road and is given by Equation 5.

$$F_{hc} = mgsin(\psi) \qquad \text{Eq. (5)}$$

Our proposed model assumes level ground; thus, the angle of inclination is zero, which in turn means that there is no effect to the hill-climbing force on our model. However, the blocks for modelling this force are shown in Figure 7.

2.1.5. Tractive Effect

The total tractive force is modelled by Equation 6, which is simply the addition of all four aforementioned forces affecting an EV. Since F_{hc} is 0 N, it is not mentioned in Equation 6.

$$F_{te} = F_{ad} + F_{la} + F_{rr} \qquad \text{Eq. (6)}$$

FIGURE 6 Rolling resistance force Simulink subsystem.

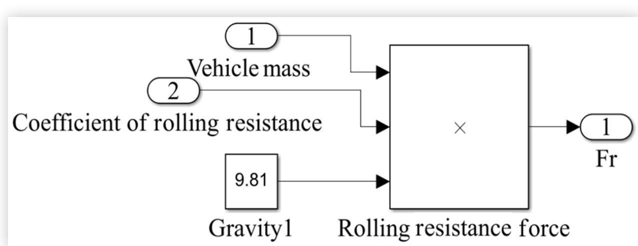
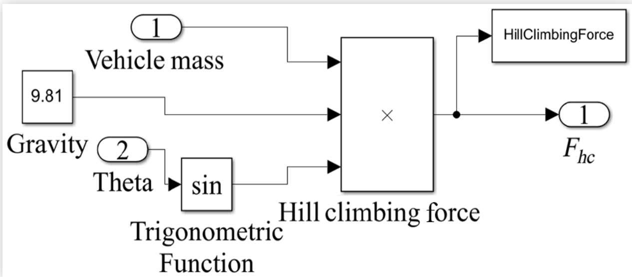


FIGURE 7 Hill-climbing force Simulink subsystem.



The required output from the vehicle dynamics part of our proposed model is the energy required to drive the vehicle for each second time slot. This is equivalent to the tractive power, which is defined in Equation 7.

$$P_{te} = F_{te} v \qquad \text{Eq. (7)}$$

This represents the end of the vehicle dynamics modelling section. The transmission performance primarily depends on the power calculated in this step in addition to other parameters, which will be discussed in Section 2.2.

2.2. Transmission Performance

The next stage in the proposed model accounts for mechanical losses. It deals with the motor of the EV, and it considers the input and output powers of the motor, its efficiency, torque, and other parameters. This is represented by the lower section up until the battery model in Figure 2. It is essential for finding the energy requirements of the EV's battery.

2.2.1. Motor Power The motor converts the electrical power into mechanical power. Using the tractive power, we can find the output power of the motor and hence the torque and the electrical power needed into the motor. The EV undergoes two distinct scenarios while on the road. The first is when it is driving, and the other one when it is slowing down and braking. When the vehicle is moving and accelerating, the electric power into the motor is greater than the output mechanical power. On the other hand, the electric power into the motor is reduced when the motor is slowing down the vehicle when the brakes are hit. These two scenarios are summarized as follows with their respective equations:

- EV is being driven; the vehicle is accelerating:
  - Output Motor Power

$$P_{motor_{out}} = \frac{P_{te}}{n_g} \qquad \text{Eq. (8)}$$

  - Power into Motor

$$P_{motor_{in}} = \frac{P_{motor_{out}}}{n_m} \qquad \text{Eq. (9)}$$

- The vehicle is slowing down due to braking:
  - Output Motor Power

$$P_{motor_{out}} = P_{te} n_g \qquad \text{Eq. (10)}$$

  - Power into Motor

$$P_{motor_{in}} = P_{motor_{out}} n_m \qquad \text{Eq. (11)}$$

EVs can be in one of two states: normal forward driving or regenerative braking. Typically, there's a single gear in EVs, which means the gear efficiency denoted by n_g is constant. Motor efficiency, n_m considers both the efficiency of the motor and its controller and is calculated using Equation 13. In the case of the vehicle being driven, the electrical input power required by the motor, $P_{motor_{in}}$, is greater than the mechanical power. On the other hand, when there is a case of braking, the motor is being used to slow down the vehicle, so the electrical power is reduced and the mechanical output power, $P_{motor_{out}}$, increases.

Two switches are used to model the four aforementioned equations related to the output and input motor powers. n_g and n_m represent the efficiency of the gear system and the motor and controller efficiency, respectively. The efficiency of the gear system is a constant taken from Table 1, while the motor efficiency is calculated and modelled in Section 2.2.3.

2.2.2. Motor Torque Torque is represented by the mechanical output power of the motor divided by the angular speed as seen in Equation 12.

$$Torque = \frac{P_{motor_{out}}}{\omega} \qquad \text{Eq. (12)}$$

The angular speed is calculated using Equation 13.

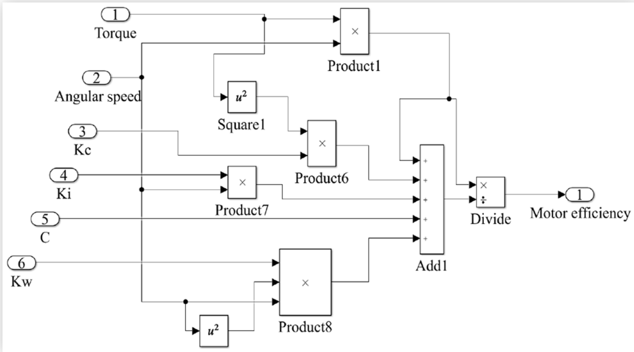
$$\omega = \frac{Gv}{r} \qquad \text{Eq. (13)}$$

The gear ratio and the tire radius are constants taken from Table 1, and the velocity is taken from the Matlab workspace. The angular velocity is measured in radian per second (rad/s). The torque and angular speed, in addition to multiple losses coefficients, are used to calculate and model the motor's efficiency.

2.2.3. Motor and Controller Efficiency Modelling The subsystem for modelling the motor efficiency is presented in Figure 8. All the constants are unitless and are taken from Table 1. The derivation of the motor efficiency is presented in Equation 14:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$
$$\eta = \frac{P_{out}}{P_{out} + Losses} \times 100\% \qquad \text{Eq. (14)}$$
$$\eta = \frac{T\omega}{T\omega + K_c T^2 + K_i \omega^3 + C} \times 100\%$$

FIGURE 8 Motor and controller efficiency Simulink subsystem.



T represents the torque and *w* represents the angular speed. Since the current is directly proportional to the torque provided by the motor, we use the torque instead of the current in our proposed model. The coefficients of losses in Table 1 are that of a 100 kW induction motor primarily used for modelling EVs.

2.3. Battery

Accurate battery models are a vital part of EV simulation. An efficient battery model in [14] studied the Li-ion battery in Matlab/Simulink to validate the reliability of the proposed model. The final stage of the in-hand proposed model is the battery requirements. It is modelled in the farthest lower right side of the Simulink model in Figure 2. It depends on the total electric power into the motor and the average accessory power. Their addition corresponds to the total power utilized by the battery. The accessory power, P_{ac}, can include the power required by the radio or the headlights, for instance. Equation 15 shows how to calculate such.

$$P_{Battery} = P_{Motor_{in}} + P_{ac} \qquad \text{Eq. (15)}$$

3. Results

The velocity modelled for the simulation of the EV ranges from 0 km/h to 350 km/h. The derivative of the velocity gives us the acceleration. Figure 9 shows the velocity and acceleration graphs versus time, which are inputted to our Simulink model. These are in meter per second (m/s) and meter per second squared (m/s^2), respectively.

The red highlighted area of the velocity graph represents the region where the torque is constant. After that, the torque changes so the velocity is modelled using another equation. Since the velocity doesn't change dramatically, the acceleration corresponding to it changes slightly. The distance travelled in meters by the EV corresponding to the simulated velocity can be seen in Figure 10.

FIGURE 9 Velocity (solid line) and acceleration (dashed line) of the EV vs. time.

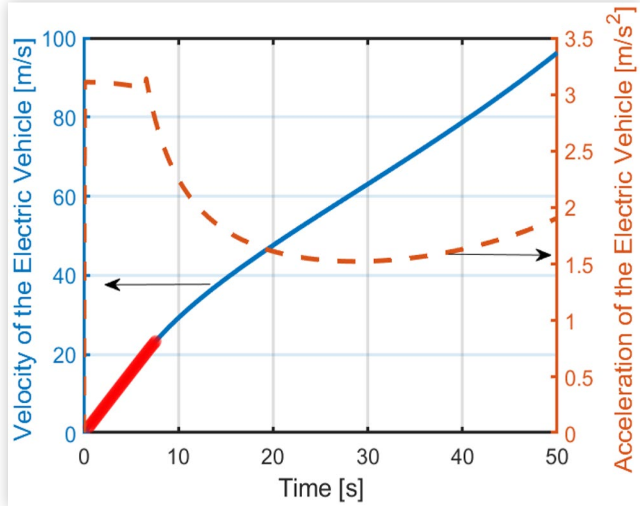
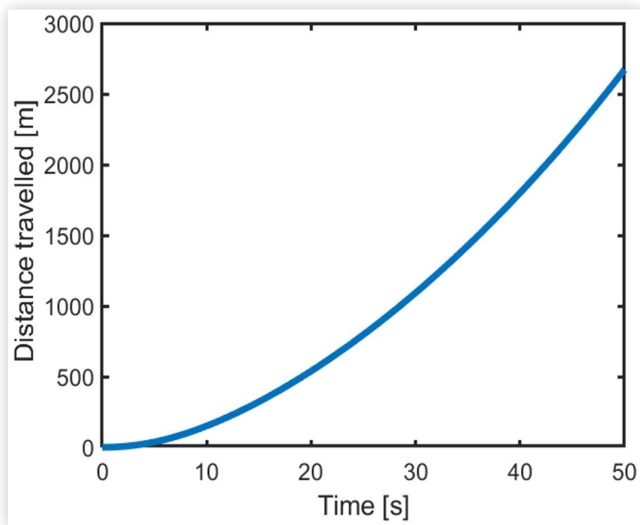


FIGURE 10 Distance travelled vs. time.



3.1. Vehicle Dynamics Results

The proposed model studies the vehicle dynamics and the effect of different forces on the EV's performance. With the increase in velocity, the aerodynamic drag force increases. There is a direct relationship between the force and the square of the velocity, which is clearly shown in Figure 11.

As for the linear acceleration, it is directly proportional to acceleration, as seen in Figure 12. As acceleration increases, the acceleration force increases. It is important to note that this acceleration takes into account the angular acceleration since it accounts for an increase in the mass by 5%. When it comes to the rolling resistance force, it only depends on the vehicle weight. As such, it will be constant throughout the whole simulation time. The addition of the forces results in

FIGURE 11 Aerodynamic drag force vs. velocity of the EV.

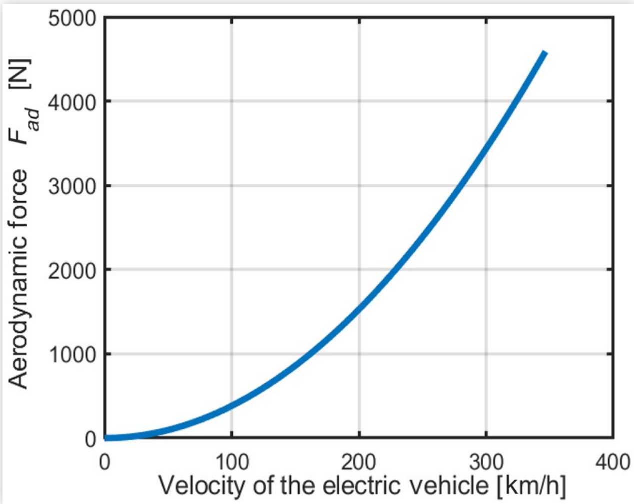


FIGURE 12 Linear acceleration force vs. acceleration of the EV.

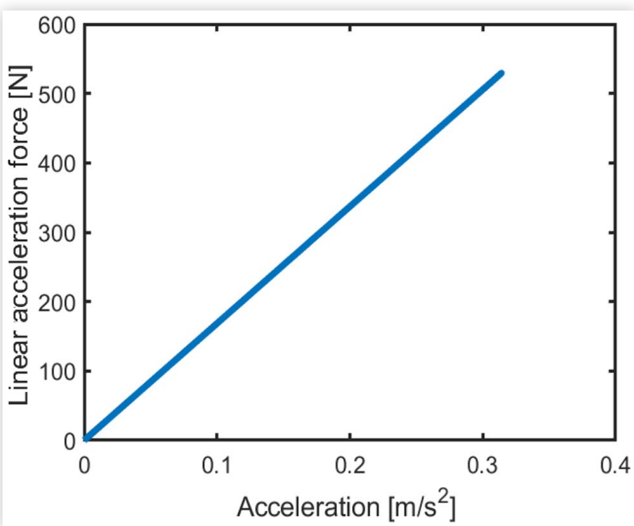


FIGURE 13 Total tractive force vs. velocity of the EV.

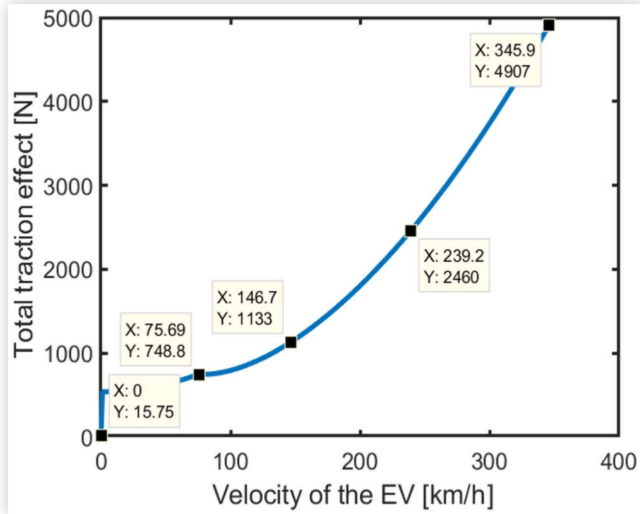
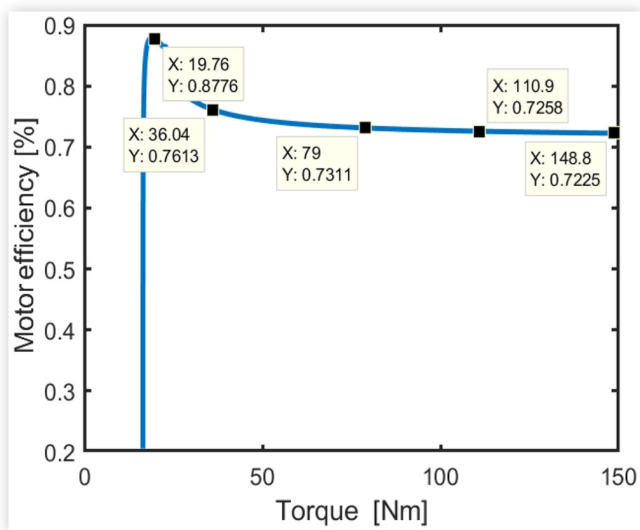


FIGURE 14 Motor efficiency vs. motor torque.



the total tractive force. Figure 13 shows how the change in velocity affects the total tractive force [15]. As mentioned previously, there is a small section where the torque is constant up until around 19.8 m/s, which is equivalent to 71.28 km/h. This justifies why most of the results showcase two distinct sections in the graphs. The increase in speed after the point where the torque is constant clearly shows that it is followed by an increase in the total tractive force.

3.2. Transmission Performance Results

The transmission performance results deal with the motor's torque, efficiency, and electrical and mechanical powers. Figure 14 represents the relationship between the motor efficiency and torque. In the beginning the induced torque is very high, where the motor efficiency reaches its peak at around 88%, and then it drops until it stabilizes at around 72%. This corresponds to the induction motor's behavior, which verifies the results we obtained. As for the torque-speed characteristics, it can be noticed that an increase in the angular speed, which is directly proportional to the velocity, increases the torque since the mechanical output power of the motor is not constant. In the beginning, the torque is almost constant or slowly varying, but after 695 rad/s it increases significantly until it reaches a maximum of 150 Nm.

As expected, the simulated graph of the torque versus the velocity, Figure 16, will show a similar curve in Figure 15, since there is a direct relationship between the two speeds.

In theory and practice, the higher the mechanical output power of the motor the higher its torque. Our simulated graph shown in Figure 17 validates such concept. The highest mechanical output power reached is 500 kW.

FIGURE 15 Motor torque vs. angular speed.

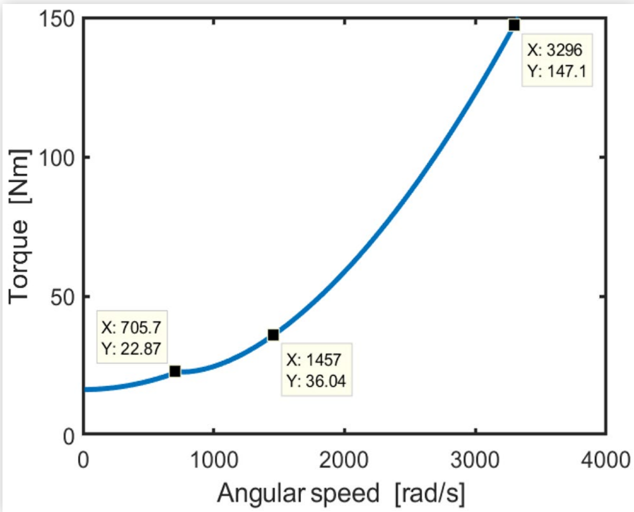


FIGURE 16 Motor torque vs. velocity.

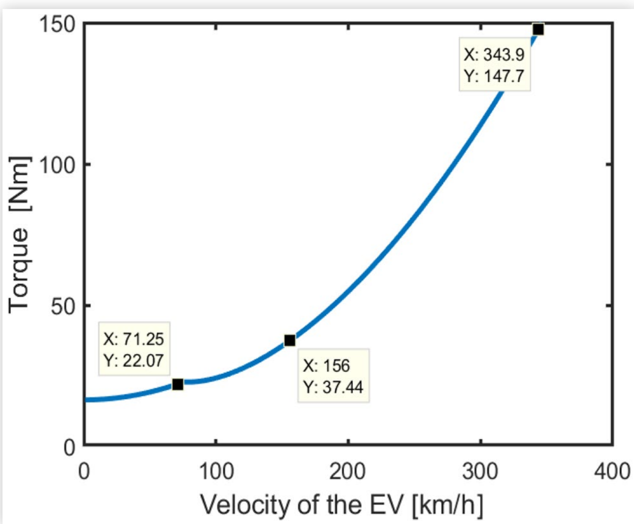


FIGURE 17 Motor torque vs. mechanical output power.

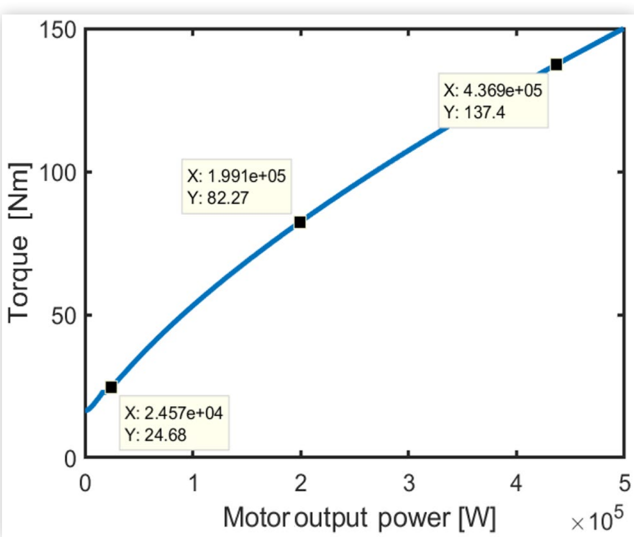
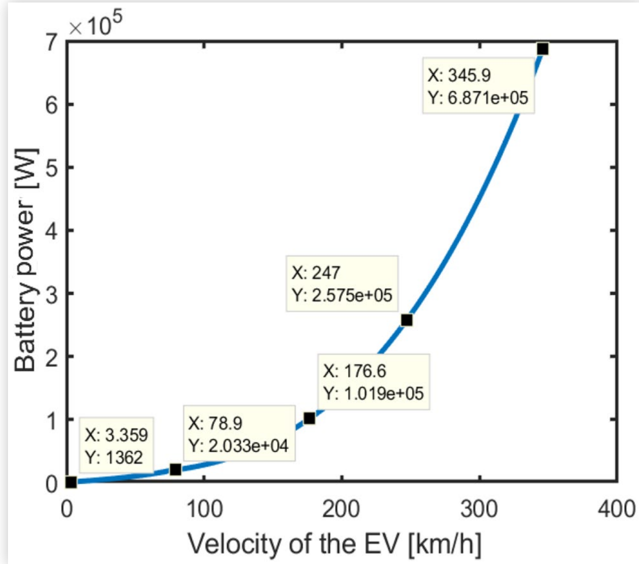


FIGURE 18 Battery power required vs. the velocity of the EV.



3.3. Battery Results

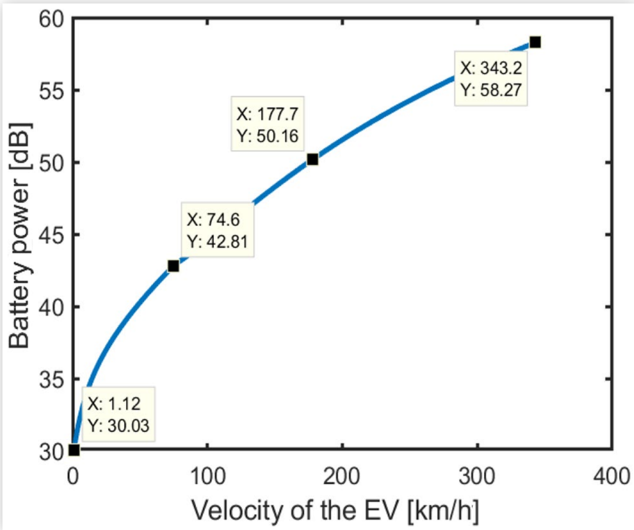
The battery needs require the electrical power into the motor as well as any additional power from powering on or activating the EV's accessories. For instance, turning on the headlights consumes power, and that has to be accounted for in the battery needs. Another example would be turning on the radio. These power requirements are negligible when compared to the electrical power, but they are still important while sizing the battery and selecting the best type. Figure 18 shows that the increase in the velocity of the EV increases the electric power into the motor, which in turn increases the required power of the battery.

In the very beginning, when the car is not moving, the power is at its minimum of about 1 kW. The highest required power of the battery required is 700 kW. For simplicity, the log scale is used for such and is presented in Figure 19.

4. Conclusion

In this paper, we model an EV while taking into consideration its vehicle dynamics, transmission performance, and battery. The model is done in Matlab/Simulink, and all the parameters used mimic real EVs. There are three forces acting on the modelled EV, which are the aerodynamic drag, linear acceleration, and rolling resistance forces, as we assume level ground for the hill-climbing force. The motor efficiency modelled reached an average of 73%, which meets the expectations of EV's motor efficiency. The power required from the battery may reach up to 700 kW for high speeds. As for the initial power required, it reaches 1 kW due to the accessory power and the initial start of the vehicle. Part of the future work includes modelling the depth of discharge for multiple battery types to ensure it doesn't exceed 90%.

FIGURE 19 Battery power required vs. the velocity of the EV.



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Nomenclature

μ_{rr} - Coefficient of rolling resistance
ω - Angular speed
Inclination of the road
ρ - Air density
A - Frontal area of the vehicle
a - Vehicle's acceleration
C_d - Air drag coefficient
F_{ad} - Aerodynamic drag force
F_{hc} - Hill-climbing force
F_{La} - Linear acceleration
F_{rr} - Rolling resistance force
F_{te} - Tractive effect force
F_{wa} - Angular acceleration
G - Gear ratio
g - Gravity acceleration
I - Moment of inertia
m - Vehicle's mass
n_g - Gear efficiency
n_g - Gear system efficiency
n_g - Motor efficiency
P_{ac} - Accessory power
$P_{motor_{out}}$ - Electrical input power required by the motor
$P_{motor_{out}}$ - Output motor power
P_{te} - Tractive power
r - Tire radius
T - Torque
v - Vehicle's speed in relation to the air

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