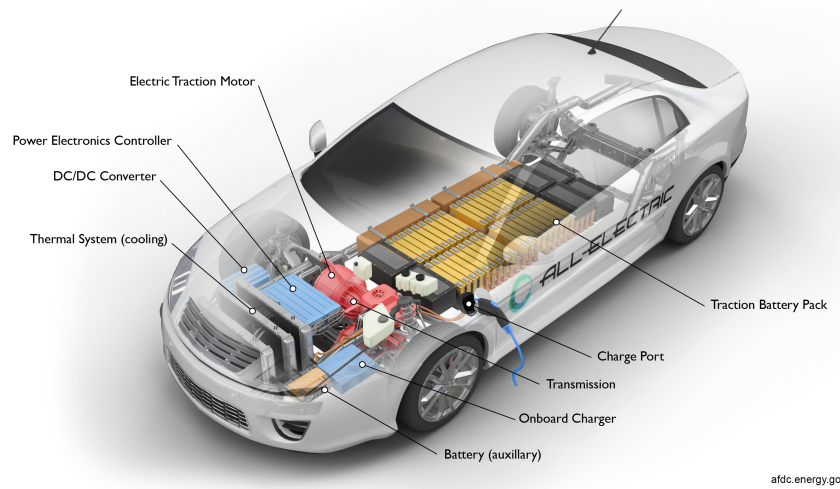


Graphical Abstract

Electric Vehicles Modeling and Simulation

Abd-Alfatah Alodainy

All-Electric Vehicle



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Abstract

Nowadays electrical vehicles are becoming more attractive as they are emission-free, and they can replace the need for a traditional car that uses oil as its fuel, knowing that oil is not renewable energy and cause pollution, while electricity can be produced with clean and renewable energy like solar energy. In this paper, we will build a simple electrical-vehicle model with the the help of python programming language. This paper aims to build a complete model for the EV including its different parts and finalize the model by making a simulation for each part, and comparing the results, In the first part of this paper, we will show the mathematical model for the different vehicle parts. The vehicle battery, the wheels, the brakes, the car controller, and the vehicle dynamic will be discussed in this paper, furthermore, we will choose a motor and using MATLAB Simulink to simulate it and get the motor characteristics. In addition, in this paper, we will make the simulation for the driver with a PID-based model. Therefore a simple mathematical model and a simple theoretical background will be introduced for every vehicle's part. In the last part of my paper, we will show how we simulated each part and the methods used to make the simulation. Finally, the results of the simulation and the further implementation of the program will be specified.

Keywords: Electrical vehicles, Emission-free, Vehicle modeling, PID driver, Car controller (PID/PI), Simulink

1. Introduction

Due to the facts introduced at the beginning of this paper, in the abstract, we can see the benefits behind having an electrical vehicle, so being able to design electrical vehicles in a fast and reliable way is very helpful, not only this but also being able to simulate the results and show different parameters relationships is an amazing advantage, which will lead to further parameter

optimization and fault detection also to predict and optimize the total cost of the car, for this purpose(modelling and simulation), we used python as a programming language for making this simulation. In this project, we used data that was before established with MATLAB, that those data are collected based on previous simulations and they have been calculated with the help of MATLAB[1] look here. In this part a small introduction for each part of the electric vehicle will be given.

1.1. Vehicle dynamics

It's crucial to comprehend how much energy is needed to propel a vehicle when looking into new power sources much energy is needed to propel a vehicle. When discussing the vehicle dynamic, we will concentrate on this particular type of vehicle since it uses a large percentage of energy for transportation (84 % in the U. S.) those types are vehicles with wheels like cars, trucks, and trains, as opposed to ships and planes. You can see the vehicle dynamic model here.2.2

1.2. Motors

An electric car needs a mechanism to convert the power from the battery into the rotary motion needed to move the vehicle ahead for it to operate. Thankfully, as we will see in this article, there are numerous sophisticated ways to accomplish this by utilizing a range of various sorts of electrical machines. a wide range of different motor types, such as brushless DC and AC motors (also known as synchronous motors), induction motors, reluctance motors, and brushed DC motors. Faraday's Law must be understood in order to fully comprehend induction motors. This law also has an impact on our comprehension of other types of motors allowing for regenerative braking and enabling motors to run backwards and generate energy. There are many laws that motors rely on for their basic operation like, The Lorentz Force Law, Coulomb's Law, Biot-Savart's Law, and Faraday's Law

1.2.1. Motor efficiency

Any sort of motor's efficiency, η_m , which is determined by dividing the output power by the input power, is a crucial factor to take into account. Sadly, this number never reaches 100% . In general the efficiency can be given by

$$\eta_m = \frac{\text{output power}}{\text{input power} + \text{losses}} \quad (1)$$

The losses can be approximated by [2]

$$losses = k_c \cdot T^2 + k_i \cdot \omega + k_w^3 + C \quad (2)$$

The first loss, $k_c T^2$, is known as the "copper loss" since it simulates losses brought on by electrical resistance in the motor's wire stator winding. These losses are inversely proportional to $I^2 \cdot R$, where I denotes the current flowing through the winding and R denotes their resistance. We may describe conduction loss as proportional to torque squared because torque is parallel to the current.

The second loss, $k_i \cdot \omega$, is referred to as the "iron loss" since it simulates losses brought on by the iron parts of the motor. Iron losses are primarily brought on by two factors: (1) the energy required to continuously magnetize and demagnetize the iron components of the motor as the magnetic field changes, and (2) the current that is induced in the iron as a result of the changing magnetic flux, which warms the iron. This iron loss is related to ω and both effects grow as the frequency of magnetic field changes rises.

The third loss, $k_w \omega^2$, is known as windage loss and represents the rotor's aerodynamic resistance. The windage loss is related to ω^3 because the amount of power needed to overcome aerodynamic resistance is proportional to the speed cubed.

The controller's power consumption and the power needed to maintain the magnetic field when the motor is stationary are included in the fourth loss, C, which is a constant loss that does not change with speed or torque.

1.2.2. Maximum acceleration

The ability of an electric vehicle to respond swiftly and smoothly to the torque of its electric motor is one of its most appealing characteristics. In actuality, the engine power of an electric automobile greatly influences how quickly it can accelerate. It is possible to determine a car's maximum acceleration from the ground up if one is familiar with the intricate intricacies of the drivetrain, as Larminie and Lowry (2012) do. It's not actually essential to go through the trouble of doing this, as Masias (2018) points out, which is fortunate given that the drivetrain characteristics needed for Larminie and Lowry's method of computation are hard to come by.

1.3. Battery

We require a transportable source of electricity to power the motor of our electric car. This electricity is typically kept in a battery. We shall

examine the essential elements and traits of traction batteries, also referred to as the batteries used in electric vehicles, in this paper we will concentrate on lithium-ion batteries as they are used by almost all electric vehicles on the market today.

Positively charged lithium ions (Li^+ ions) go from the anode to the cathode through the porous separator in a Li-ion battery's normal operation. From the anode to the cathode, a comparable electron current passes through the electrical load. Because it is the most affordable, lightweight, and abundant electropositive, lithium is chosen.

This low-tech solution has shown to be completely transformative. Without it, it's possible that the recent digital revolution—which saw portable gadgets lead the way—would not have taken place. Additionally, the significant advancements in electric vehicles that we are currently witnessing would not have been possible.

1.4. Controllers

Sadly, you can't just connect a motor and a battery and go on a ride. Direct current is produced by a battery at a specific voltage. No motor mentioned in 1.2 will function when linked directly to a battery, with the exception of a brushed-DC motor, which will operate at a single speed when connected to a fixed voltage.

We need to be able to alter the properties of the electricity leaving the battery, whether that means changing its voltage, turning it into alternating current, altering its frequency, or doing all three. Only then will we be able to modulate the speed of a brushed-DC motor and enable any of the other motor types to operate at all.

2. Vehicle Modeling

2.1. Vehicle Battery

In electrical cars the most important part of the vehicle is the battery, vehicle battery can take more than 50% of the weight of the car. In this paper we used some well known equations for the mathematical model. those equations specify many characteristics of the battery pack like state of charge, open circuit voltage, capacity and others which will be seen in details here.

2.1.1. State of charge

There are many existing model for state of the charge of the battery, however in general the state of charge depend on the power consumed by the car, the battery voltage, and the capacity. from equation 1, we can derive the following.[3]

$$soc = soc_0 - \frac{p * \Delta t}{3600 * c * v} \quad (3)$$

Where soc_0 is the initial charge of the battery, C is the battery capacity and P is the power of the battery. The equation can be written in another format as follows since P is equal to $V * we$

$$soc = soc_0 - \frac{i * \Delta t}{3600 * c} \quad (4)$$

The number 3,600 appears in the divisor because the time interval Δt is expressed in seconds.

2.1.2. pack voltage

To write the mathematical model for the pack voltage (battery voltage). Calculations can also be performed assuming that the equivalent circuit for the interface consists of a reaction resistance coupled in parallel with the capacitance and a double layer capacitor. The capacitance value can be used to determine the electrode's surface area. The voltage of a NiMH battery pack (V_{pack}) can be defined as

$$v_{pack} = OCV - IR - \Delta V \quad (5)$$

Where V is the voltage for one battery cell, OCV is the open circuit voltage under no load condition which can be taken from the battery catalogue, i is the battery pack discharge current(A) and v is the voltage change in the battery.

2.1.3. Circuit voltage

From equation number (5) , The polarization model for the NiMH may be defined as

$$\Delta RC \times \frac{d\Delta V}{dt} + \Delta V = we\Delta R \quad (6)$$

$$\text{since } I = I_0 + \left(\frac{d\Delta I}{dt}\right) \times t \\ \text{therefore, } \Delta V = \Delta R \left[(I_0 - \Delta RC \times \frac{d\Delta I}{dt} (1 - e^{\frac{-t}{\Delta RC}})) + \left(\frac{d\Delta I}{dt}\right) \times t \right]$$

Assume, for instance, that the battery pack is at 7% DOD, the NiMH cell's OCV is 1.359 V/cell, R_{batt} is 0.225 W, and ΔR is 0.059 W. So, according to the equation above, ΔRC is equal to 21.3 seconds. As the temperature drops, the polarization resistance rises. The temperature relationship suggests that it might be related to the KOH electrolyte's resistance. As a result, the polarization resistance is dependent on both time and SOC. And when performing the simulation we will further reduce the complexity of this equation to the followings

$$V = e^{-\beta * dt} * V_0 + \gamma * \left(\frac{-i}{\beta} (1 - e^{\beta * dt}) \right) \quad (7)$$

where $\beta = \frac{1}{RC}$ and $\gamma = \frac{1}{C}$.

As it can be seen the current voltage of the battery pack is dependent on the internal resistance of the battery and the capacitance.

2.1.4. Open circuit voltage OCV

The data from the conditional discharge test are used to create the OCV-SOC curve (OCV is the battery voltage under no load condition). The following curve data is what we used in the simulation.

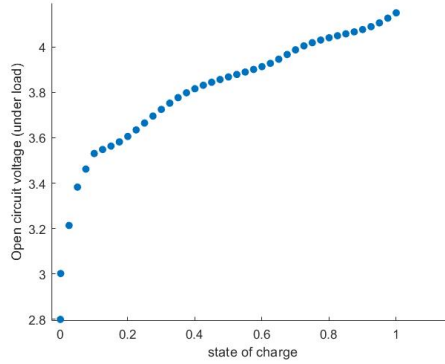


Figure 1: Different open circuit voltages for battery cell

2.1.5. Maximum power

The maximum power of the battery is simply the multiplication of the voltage with the current as follows;

$$P = V_{pack} \cdot n_s \times I \cdot n_p \quad (8)$$

Where n_s and n_p are the numbers of serial and parallel connection of the battery cells respectively.

2.1.6. Battery voltage and battery current

The battery voltage is simply the voltage of one cell multiplied by the number of serial connections in the battery and the battery current is similar to the voltage except that we multiply with the number of parallel connections as follows.

$$V = V_{pack} \cdot n_s \quad (9)$$

$$I = I_{cell} \cdot n_p \quad (10)$$

2.2. Vehicle dynamic

Vehicle dynamics is a branch of engineering that examines how a vehicle moves concerning its intended use. It is a subject that is relevant to a particular class of goods, particularly cars. Theories and techniques from mechanical engineering, machine design, and other disciplines are used in vehicle dynamics. The three main categories of vehicle dynamics are lateral, vertical, and longitudinal dynamics. we shall emphasize the longitudinal dynamics in these papers. Driving dynamics, safety, and increased driver comfort are said to be the three key objectives when creating a car. We are going to keep these three major ideas in mind as we analyze the vehicle dynamics. In this paper, we will construct a straightforward model that takes the driver's input. The output of this model will be the necessary action safely and comfortably, whether it be an acceleration, deceleration, or just the contraction between the driver and the vehicle.

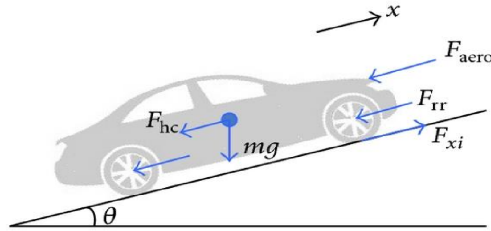


Figure 2: Free body diagram for vehicle showing the elementary dynamical forces on vehicle body [4]

In this part of this paper, the vehicle dynamic will be discussed shortly considering the reaction forces. The first reaction force we will discuss is the air drag force.

2.2.1. Air drag force

Air drag force caused as the name suggests is the drag or the air resistance the vehicle faces during its motion, this force can be modelled as below[2],

$$F_d = \frac{1}{2} \times \rho A C_d \cdot v^2 \quad (11)$$

Where v is the vehicle velocity, ρ is the air density which is equal to $1.225 \frac{kg}{m^3}$, C_d is the drag force coefficient, and A is the frontal area.

2.2.2. Acceleration

From Newton second law,

$$F_{total} = m \cdot a \quad (12)$$

Where F_{total} is the total reaction forces acting on the vehicle body which equal, the subtraction of the forces exerted by the wheels for the drag force caused by the air as can be seen in section 2.2.1 (it acts opposite to the direction of the movement of the vehicle)[2]

$$F_{total} = F_{wheels} - F_{airdrag} \quad (13)$$

Thus,

$$a = F_{total} \cdot \frac{1}{m} \quad (14)$$

2.2.3. velocity

from the velocity definition, acceleration is the first-time derivative of the velocity vector we can get the velocity vector or the scalar term (speed), as follows, $a \cdot dt = dv$ performing the integration we get the following

$$v = v_0 + \int_{t_0}^{t_1} a \cdot dt \quad (15)$$

2.2.4. Position

The velocity is by definition the first time derivative of the position, therefore we can derive the position formula the same as we did with velocity as follows

$$x(t) = x_0 + v \cdot \Delta t \quad (16)$$

2.2.5. front wheel forces/reactions

As we know that a wheel is a rotating object which has a torque that can be calculated through the following

$$T_{frwheel} = F_{frwheel} \times R \quad (17)$$

As we know a wheel is a rotating object which has a torque that can be calculated through the following $F_{frwheel} = T_{frwheel} \cdot \frac{1}{R}$. The reactions forces on the front wheels can be formulated as below, the details can be found in this paper we did[4]

$$F_{frwheels} = \frac{1}{l}(mg \cdot l_1 + h(F_b + f_r \cdot mg)) \quad (18)$$

Where l is the distance between the canters of the front and rear wheels, l_1 is the distance from the car centre to the front wheel, h is the height of the car, F_b is the braking force and f_r is the rolling resistance, you can refer back to figure 2 to see those different parameters.

$$F_b = \frac{w}{g} \cdot a \quad (19)$$

Where w is the car weight force (mg), g is the gravitational acceleration and a is the vehicle acceleration

$$F_{bmax} = \mu \cdot W \quad (20)$$

Where μ is the static friction and w is the weight force, and knowing that the brake force is just the amount required to stop the motion of the vehicle's wheels, we can write the equation for brake forces in the front wheels with the help of (2.2.5)

$$F_{bf} = K_{bf} \cdot F_{frwheel} \quad (21)$$

Where K_{bf} is the front brake force distribution factor which is < 1 .

2.2.6. Back wheel forces

The same thing done for the front wheel can be done for the rear wheel you only need to change the index, the way to model the rear wheel forces is similar to the way used in the front wheels. All the equations used are the following

$$F_{rwheels} = \frac{T_{rwheels}}{R} \quad (22)$$

$$F_{wheels} = \frac{1}{l}(mg \cdot l_2 + h(F_b + F_r \cdot mg)) \quad (23)$$

Where l is the distance between the canters of the front and rear wheels, l_2 is the distance from the car centre to the rear wheels, and h is the height of the car from the centre.

$$F_{br} = K_{br} \cdot F_{wheels} \quad (24)$$

$$K_{br} + K_{bf} = 1 \quad (25)$$

Where K_{br} is the rear brake force distribution factor. You can take a look here for the Matlab model[1].

2.3. Controller

A controller essentially serves as an electric car's computer or brain. The operation of the electric motor is "controlled" or regulated by this computer. Through its energy density, the controller incorporates expected battery range/speed and motor velocities.

A car's range and max speed can be decided by the controller and motor working together to accelerate from 0 to 60 in 6 to 7 seconds (or even less). The controller manages both conventional and automatic drive systems for forward and backward motion, speed regulation, torque regulation or limitation, overload protection, and fault detection.

2.3.1. Best controller solution

No modern electric vehicle uses a DC drive. DC controllers are used, though, by some of the larger conversions. DC is inexpensive and ideal for a conversion on a tight budget. A DC motor also functions for a less expensive conversion. What is currently being developed in laboratories will soon be available to you, and further advancements in solid-state AC controller technology may result in AC motors being used in all future electric vehicle conversions. Let's examine two developments—systems and components—that essentially ensure this result.

One of the most well-liked and potent motor controllers for electric vehicles is the Zilla controller (Zilla), as seen in Figure 3. The power density of the Zilla is unusually high. The Zilla is considered one of the best controllers on the market today by conversion experts and members of the EV community. This controller can give your electric vehicle (EV) the best pickup and torque available (or even on your block). Zilla's concern for safety in their

literature is commendable because it demonstrates that a cheap, effective, and off-the-shelf controller can still be safe. More details are here [5]



Figure 3: Zilla controller Model Z2K-HV [5]

Metric Mind Engineering is another firm that makes premium AC liquid-cooled synchronized and induction three-phase motors for EVs. Various of these motors can generate up to 150 kW at over 400 V and 10,000 rpm. The motor controllers made by the same business have a maximum output power of 212 kW.

2.4. Gearbox

The purpose of the gearbox is to efficiently and effectively match the prime mover output to the vehicle's immediate traction needs, with the inputs being the torque converter model's outputs as follows:

the torque applied to the torque converter's output shaft (Nm) $T_{gr-in} = T_{tc-out}$

Angle of rotation of the torque converter's output shaft (rad/s) $\omega_{gr-in} = \omega_{tc-out}$

the torque converter's output shaft's inertia ($kg \cdot m^2$) $J_{gr-in} = J_{tc-out}$ The relationships between the inputs and the outputs can be described as below [6]

$$\omega_{gr-out} = \frac{\omega_{gr-in}}{g_r} \quad (26)$$

$$T_{gr-out} = g_r \cdot (T_{gr-in} - T_{gr-loss}) = g_r \eta_{g_r} \cdot T_{gr-in} \quad (27)$$

$$J_{gr-out} = g_r^2 \cdot J_{gr-in} + J_{g_r} \quad (28)$$

where η_{g_r} stands for gear efficiency and g_r for gear ratio.

2.5. Motor

Modeling an electric motor involves representing the dynamic behavior of the motor using mathematical equations. These equations can be used to predict the response of the motor to various inputs, such as the applied voltage or current, and to analyze the performance of the motor under different operating conditions.

There are several different ways to model an electric motor, depending on the level of detail and accuracy desired. Some common approaches include:

Equivalent circuit models: These models represent the electric motor as a combination of electrical components, such as resistors, inductors, and capacitors, that are connected in a specific configuration. Equivalent circuit models can be used to predict the steady-state behavior of the motor, but they may not accurately capture the transient response or the effect of mechanical factors, such as rotor inertia and friction.

State-space models: These models represent the electric motor as a set of differential equations that describe the evolution of the system variables over time. State-space models can be used to predict the dynamic response of the motor to various inputs and to analyze the stability and performance of the system.

FEM models: These models use finite element analysis (FEM) to simulate the behavior of the electric motor by dividing the system into small elements and solving a set of equations to predict the response of each element. FEM models can provide a very detailed and accurate representation of the motor, but they can be computationally intensive and may require specialized software. Here are the equations for motor modeling[6].

Output torque:

$$T_{mot} = T_{demand} + T_{spring-loss} + J_{mot} \frac{d\omega}{dt} \quad (29)$$

Constraints

$$T_{mot} \leq Max(T_{mot}) = f(\omega) \quad (30)$$

Lost spin torque:

$$T_{spring-loss} = \alpha_1 \delta(t) + \alpha_2 \omega + \alpha_3 sgn(\omega) \quad (31)$$

Motor voltage:

$$V_{mot} = V_{bus} \quad (32)$$

where J_{mot} is the motor's inertia, T_{mot} is the propulsion torque the motor provides (in Nm), $T_{spin-loss}$ is the torque lost through friction [Nm], T_{demand} is the torque required by the car (in Nm), ω is the motor's angular velocity [rad/s], $maxT_{mot} = f(\omega)$ is the motor's maximum physical torque, α_1 , α_2 , and α_3 are the static friction coefficient, A look-up table can be used to determine T_{mot} , and V_{bus} , which stands for the high-voltage bus voltage.

2.6. Driver

Driving the car in accordance with a predetermined cycle is required when modeling vehicle performance. A PID controller that outputs the locations of the accelerator and brake pedals can simulate the driver. The block diagram in figure 4 shows how a feedback control system looks like, in this diagram we have the input r , e is the error, u is the controller gain, D is the disturbances to our system, and y is the output. Our system here is the velocity of the car to be simulated.

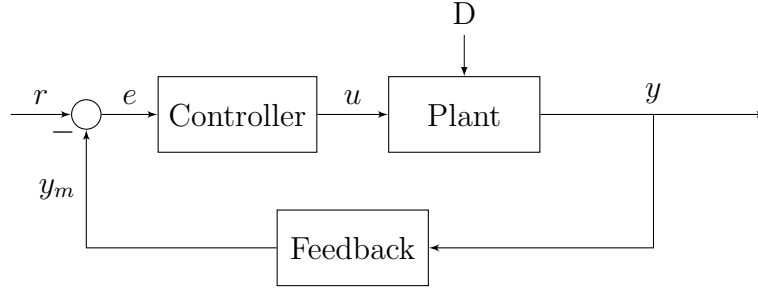


Figure 4: Block diagram for speed control system

2.6.1. PID controller principle

The PID control algorithm's fundamental idea is as follows:

$$u(t) = k(e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d \frac{de(t)}{dt}) \quad (33)$$

$e(t) = V_{desi}(t) - V_{vehicle}(t)$ is the controlled error, $u(t)$ is the controlling variable and it is the sum of the three terms, the error is expressed as the P term $Ke(t)$, the integral of the error is expressed as the I term $K \frac{1}{T_i} \int_0^t e(\tau) d\tau$, and the derivative of the error is expressed as the D term $K \cdot T_d \frac{de(t)}{dt}$. The transfer

function form shown below can be used to illustrate the PID control method provided by Eq.34

$$Y(s) = K(1 + \frac{1}{T_i s} + T_d s) \quad (34)$$

Fig.5 depicts the PID control algorithm diagram. The proportional gain, K , the integral time, T_i , and the derivative time, T_d , are the controller's parameters in the s domain. The proportional P term simply acts in a manner that is proportionate to the control error. The integral I term provides a control action proportionate to the error's time integral, ensuring that the error at steady state is zero.

In reality, several nonlinear factors must be taken into account, such as the motor's maximum traction speed. When a control variable hits its maximum or minimum value, the feedback loop is broken from the perspective of control, and the system instead operates as an open loop. In this situation, the control error will be continually integrated so that the control action will be accumulated if the controller has an integrating action and the control variable exceeds the actuator limitations. As a result, getting the reverse sign of the error will take a lot of time before the control action returns to normal. An anti-wind-up function must be added to the PID algorithm in order to address this issue.[6]

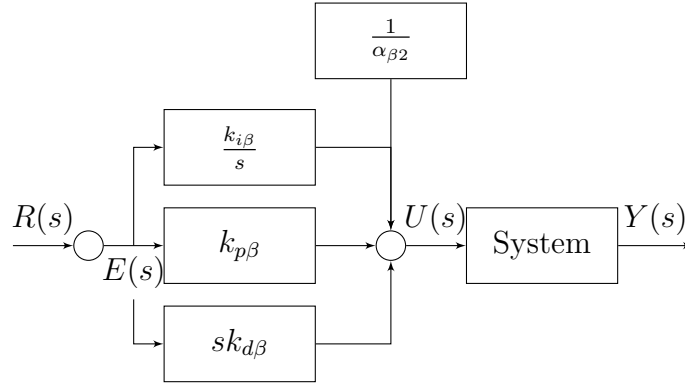


Figure 5: PID controller

2.6.2. Driver modeling

The driver model's inputs are the vehicle speed and programmed vehicle speed, or the driver's desired speed. Its outputs are the percentages of

times the accelerator and brake pedals were used. The physical constraints of the vehicle are taken into consideration by the driver model, which is implemented by a PID controller, as follows:

$$T_{desired} = T_{PID-adjusted} + T_{lost} \quad (35)$$

where $T_{PID-adjusted}$ can be controlled through the PID controller, more details can be found here.[6]

$$T_{lost} = (m_v \frac{dV_{actual}}{dt} + F_{load}) \cdot r_{wh} \quad (36)$$

where

$$F_{load} = F_{rolling} + F_{aero} + F_{grade} \quad (37)$$

$$T_{desired-brake} = \min\{0, T_{desired}\} \quad (38)$$

$$T_{desired-prop} = \min\{0, T_{desired}\} \quad (39)$$

the vehicle's speed V_{actual} (in m/s), The rolling resistance, aero-drag resistance, and grade weight forces are denoted by $F_{rolling}$, F_{Aero} , and F_{Grade} , respectively. $T_{desired-prop}$ The propulsion torque that the vehicle needs is called "demand prop," and the highest propulsion torque that can be achieved at the current vehicle speed is called $T_{max-prop}$ The braking torque that the car demands is called $T_{demand-brake}$.

3. Simulation

After setting all the vehicle parts, and building a model for each one of them, we started to simulate the different parameters together and here you can see the methods used and the results. After setting the initial value for the parameters, such as the vehicle mass, brake force distribution, controller gains, tire radius, different efficiency... etc we can start the simulation as you will see here in this section.

3.1. Necessary battery power

With the help of the previously calculated battery power and the throttle command from the driver as follows

$$P = throttle * P_{req} \quad (40)$$

the fuel cell requested power is what has been used in the simulation, The maximum requested fuel cell (FC) power is the highest level of power that a fuel cell system is capable of providing, as determined by its design and operating conditions. The maximum requested FC power can be affected by a variety of factors, including the size and efficiency of the fuel cell, the availability and purity of the fuel, and the cooling and ventilation systems that are used to maintain the fuel cell's operating temperature, in the simulation it was set to $50kW$ as a maximum.

In general, the maximum requested FC power is limited by the maximum power output of the fuel cell itself, as well as by the capacity of the system's supporting components, such as the hydrogen storage tanks, fuel delivery system, and electrical inverters. The maximum requested FC power may also be constrained by regulatory or safety considerations, such as the need to prevent overheating or to protect against electrical short circuits. The maximum power can be calculated as follows:

$$P_{max} = throttle \times P_{fc-max} + P_{max-battery} \quad (41)$$

where $P_{fc-max} + P$ is the maximum fuel cell power, and $P_{max-battery}$ the maximum battery power refereed in equation 8.

$$P_{braking} = F_{braking} \times R \times 10^{-3} \times K_f \times \omega_f \quad (42)$$

where $F_{braking}$ is the braking force, 19, R is the tire radius, K_f is the proportion of the force given to the front wheels, and ω_f is the angular speed in the front wheels, similar thing can be done for the rear wheel. The 10^{-3} appears here because we converted the power to the unit of KW Therefore we can conclude that:

$$P_{req} = P_{max} - P_{braking} - P_{fc} \quad (43)$$

3.2. Battery output power

As has been illustrated in section(2.5), the generated electrical power can be expressed as follow:

$$P_{elec} = \eta_{regen} \cdot P_{mech} \quad (44)$$

where η is the motor efficiency, the motor generated current is:

$$I_{regen} = \frac{P_{elec}}{V_{bus}} \quad (45)$$

Thus we can calculate the output power based on the equation (43) and the equation (8) to calculate the required current of the battery cell as follows:

$$i = \frac{P_{req}}{V_{battery} \times n_s \times n_p} \quad (46)$$

where n_s and n_p is the battery serial and parallel connections respectively. Hence,

$$P_{out} = v_{battery} \times i \times n_s \times n_p \quad (47)$$

3.3. Output torque

By setting some required angular speed and the required power, we calculated the output torque as follows

$$T_{out} = \frac{P_{req}}{w} \quad (48)$$

Based on the output of this equation, we can use the interpolation to estimate the output motor torque. The interpolation is done between the simulated motor output torque and the calculated one in equation (48). You can use MATLAB Simulink to simulate the output of your motor torque and other characteristics, refer to here to see an example and the steps to simulate one read the file in the (motor-torque.m). [1] By varying the motor power based on equation(44) we can get the following speed curve, and torque curve, see fig6, and fig 7.

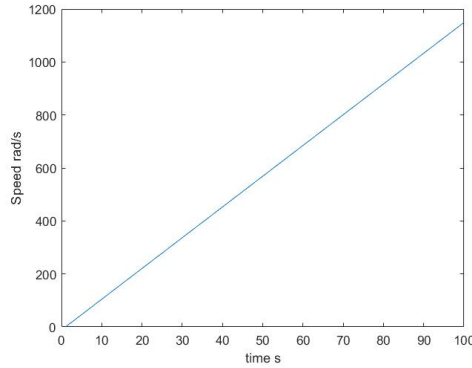


Figure 6: The motor as a linear function with time

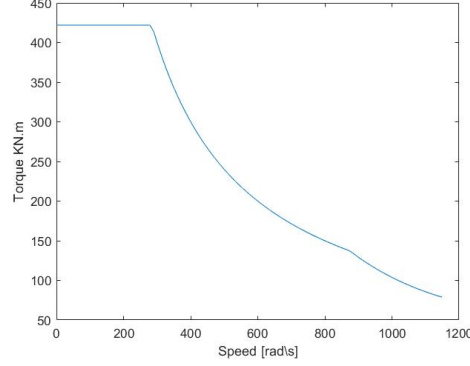


Figure 7: The speed torque motor characteristics of the simulated motor

And from 2.4, we can specify the output torque as stated in equation (27)

3.4. Front and rear brakes

Here we simulated the front and the rear brakes, using the same methods when calculating the reactions on the wheels, except here we are aiming to calculate the torque in braking and the efficiency of the braking operation, for the braking force distribution between front and rear we have a previously built model for this purpose with the help of MATLAB can be found here[1], this model was built for a go-kart car. Also, for the simulation purpose, we imported the MATLAB data, and we considered the position of the brake pedal in percentage to have a good simulation result. In addition, we used interpolation, to model braking torque. The interpolation is done for the pedal position in regards to the brake torque in figure(8) you can see the graph plotted and simulated with MATLAB, which was used later for the interpolation, also we considered at the same time the brake force proportion given to the front or the rear wheels. The brake torque is calculated when the brake command from the driver has been established as can be seen in section(3.6).

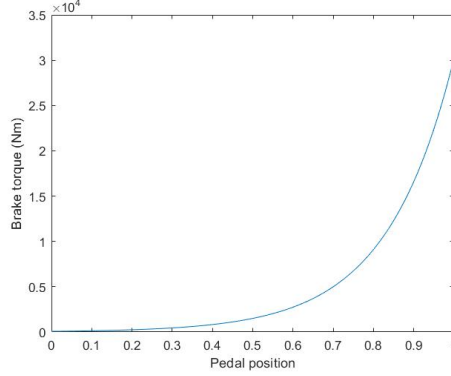


Figure 8: The exponential relation between the brake torque and the pedal position

3.5. Forces and torque in front and rear wheels

In this simulation we can see the reaction forces that arises in the wheels, the results are plotted as a sum of the reactions in the front and the rear. As we know the output torque from the gearbox, which can be seen in section (3.3) and the equation (27), is for the two wheels so we can calculate the forces and the torque in front and rear wheels as follows:

$$T_{front-wheel} = \frac{T_{out}}{2} \quad (49)$$

$$F_{front-wheel} = \frac{T_{out}}{2} \times \frac{1}{R} \quad (50)$$

Where R is the tire radius, T_{out} is the output torque from the gearbox. The similar method can be applied for the rear brakes' torque and force.

3.6. Throttle and brake command

The throttle and brake are both controls that are used to regulate the speed and movement of a vehicle. The throttle is a device that is used to control the amount of fuel or air that is being supplied to the engine, which determines the power output of the engine and the speed of the vehicle. The brake is a device that is used to slow down or stop the vehicle by applying pressure to the wheels.

In most vehicles, the throttle is controlled by a pedal or lever on the dashboard or steering column, and the brake is controlled by a pedal on the floor of the vehicle. The throttle and brake are often used together to control

the speed and movement of the vehicle, especially when driving in traffic or navigating through tight turns or other challenging situations.

It is important to understand how to use these controls properly and safely, as they are crucial for maintaining control of the vehicle and avoiding accidents. Always pay attention to the road and your surroundings when driving, and use the throttle and brake in a controlled and smooth manner to ensure the safety of yourself and others. For example if the driver want to reach certain velocity then he should increase the throttling, same if we want to decrease the speed we apply the brake command. Using the PID driver model to simulate the vehicle operations, speed, acceleration, or braking, see section (2.6). the figure(9) shows the schematic of our block diagram for controlling the desired outputs from the driver either a torque output, speed, or acceleration.

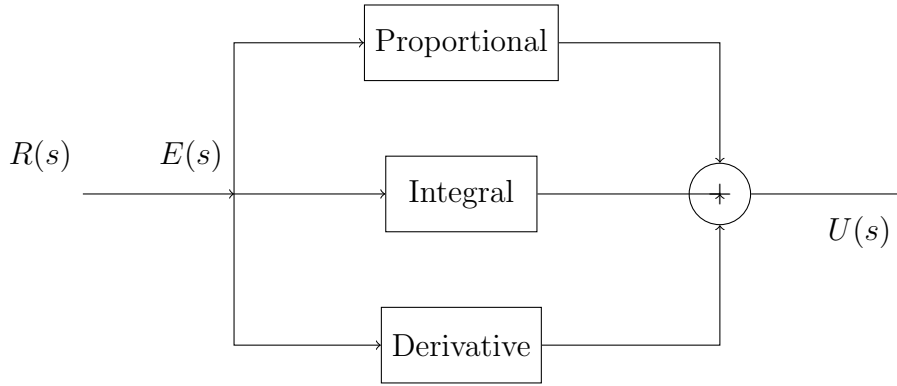


Figure 9: The schematic shows the PID controller used in the simulation to reach the desired outputs

from fig 5, fig 4, and fig 9 we can see the controller used for the driver simulation, the controller used as mentioned before is a PID controller, here you can see the equation that was used to control the speed, and at the same time establishing the brake and the throttle command as follows:

$$v_i = v_{i_0} + K_i \times v_{error} \times dt \quad (51)$$

$$v_d = \frac{(K_d \times v_{error}) - v_{d_0}}{dt} \quad (52)$$

$$v_p = K_p \times v_{error} \quad (53)$$

where v_i , v_d , and v_p are the integral, the derivative, and the proportional velocity terms respectively, K_p , K_i , and K_d are proportional, integral, and the derivative gain factors respectively, $v_{error} = v_{desired} - v_{actual}$. Hence, the throttle is simply the sum of all these correction factors.

$$throttle = v_i + v_d + v_p \quad (54)$$

and the brake is similar to the throttle command, the only difference is that it will have a minus sign indicating that we need to reduce the speed.

$$brake = throttle \quad (55)$$

3.7. Output velocity

With the help of MATLAB we created a desired speed to reach with the mathematical model we built, and to see if the controller we used will insure that our output speed will remain within the desired speed. The mathematical model for speed prediction can be seen in equations (15), (14), and (13). The following figure 10 shows the desired speeds we wanted to maintain, this speed is based on the FTP-75 drive cycle test, A drive cycle is typically represented by a series of data points which plots vehicle speed against time. Driving cycles are produced to assess the performance of vehicles in various ways, including fuel consumption and pollutant emissions.

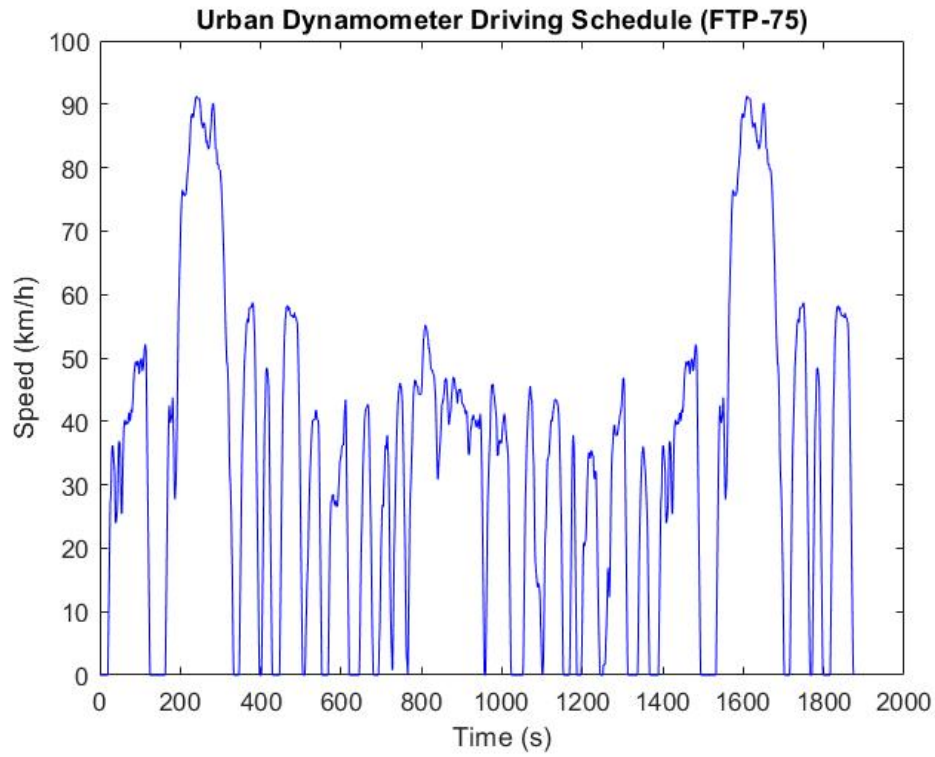


Figure 10: The desired speed (based on FTP-75) that has been used for our model

The cycle's fundamental characteristics include the following: Time: 1877 seconds Traveled a distance of 11.04 miles (17.77 km) Speed on average: 34.12 km/h (21.22 mph). Maximum speed: 91.25 km/h (or 56.7 mph).

4. Results

4.1. Velocity

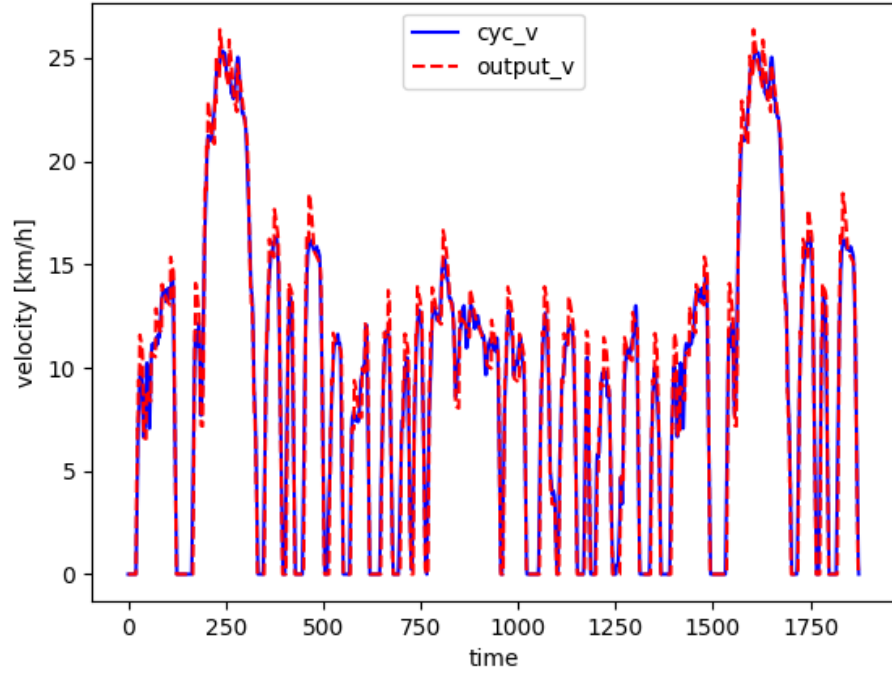


Figure 11: Output velocity vs target velocity

From the simulation results, we can see that our model was able to maintain the speed in the requested domain, the plots show different inputs modelled one and FTP-75 desired speed (cyclic velocity).

4.2. Wheel forces

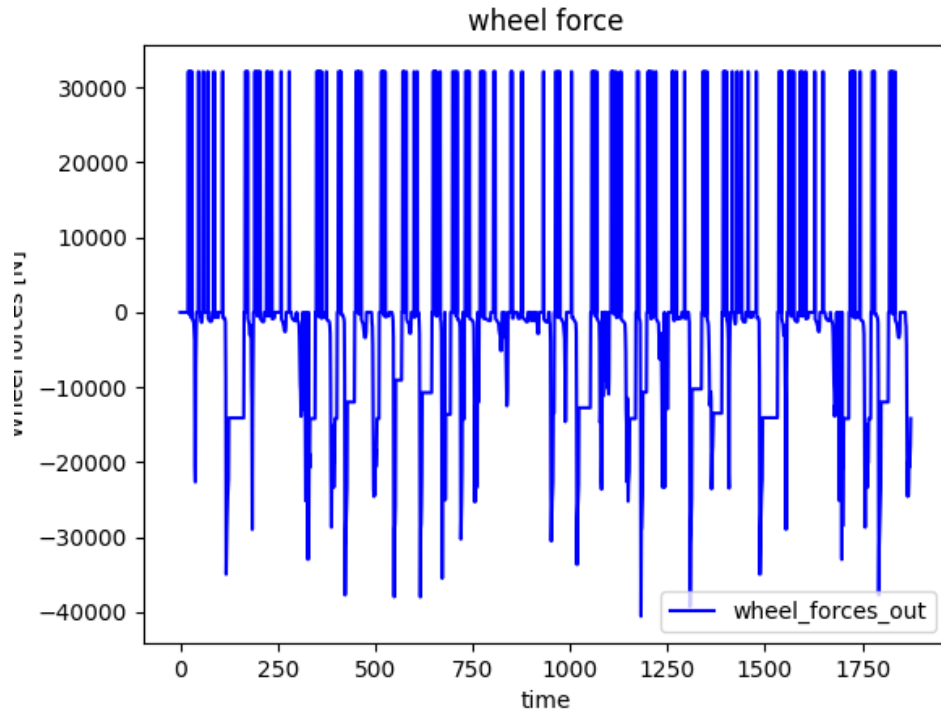


Figure 12: Output wheel forces of the front and rear wheels during the simulation

In this simulation, we can see the reaction forces that arise in the wheels, the results are plotted as a sum of the reactions in the front and the rear. What can be concluded about the results is that our model was able to reduce the reactions, also the reaction forces are somehow stable and vary during

4.3. Torque

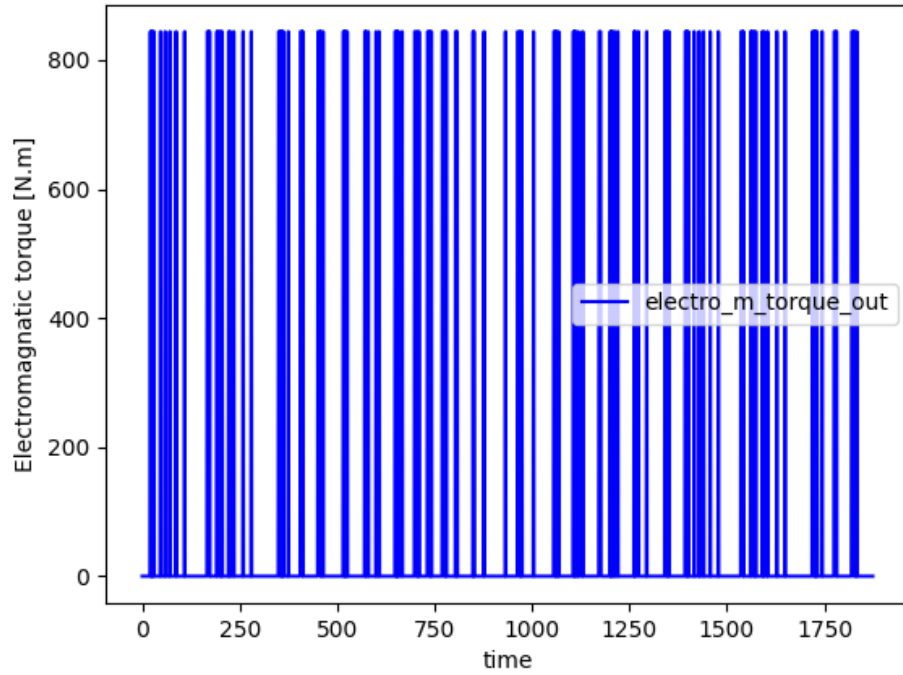


Figure 13: The electromagnetic torque produced by the motor during the simulation

In the simulation of the vehicle output torque plotted above we can see how our model was able to keep the torque constant during braking or acceleration processes.

4.4. Requested battery power

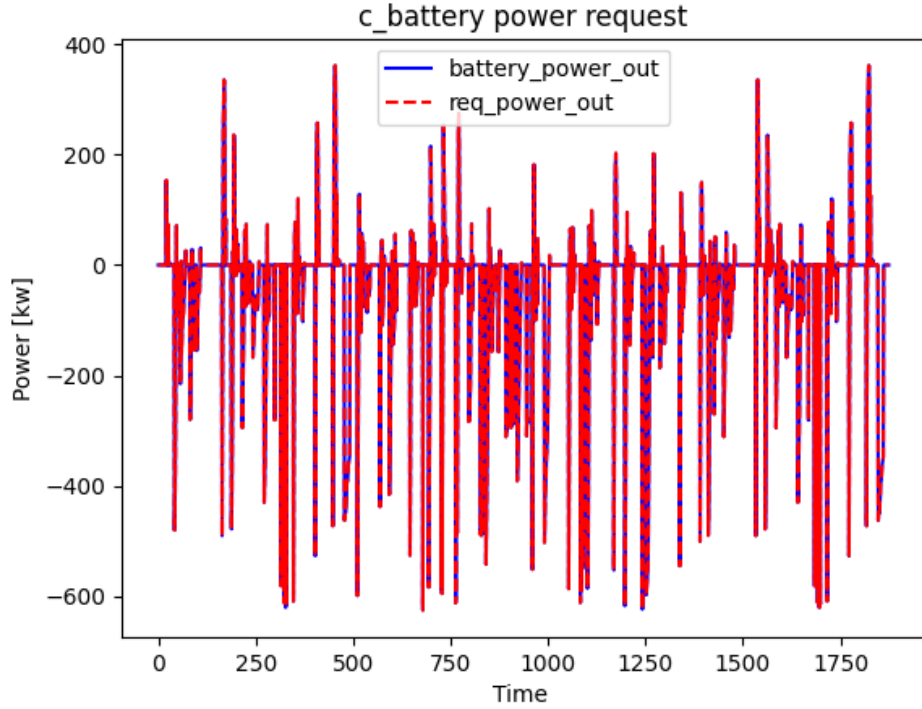


Figure 14: output battery power vs the requested power

In the simulation above we can see the output and requested power, which was calculated based on the throttle and braking commands, in the vehicle measured in KW, from the results the maximum is around 400 KW, (negative power refers to the power lost in case of braking). It is also clear that the model satisfied the requirements. Output power and requested power are nearly the same, which is a great result.

4.5. Throttle and brake commands

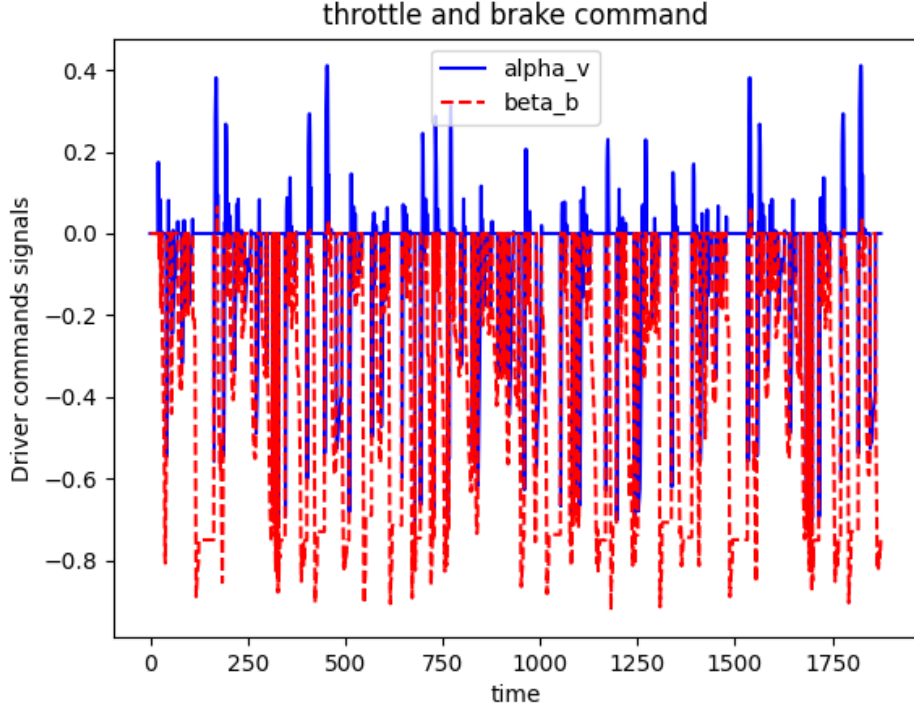


Figure 15: the throttle and braking commands signals from the driver

In this simulation we can see different drivers' command varies between braking and throttling concerning time, α denotes the throttling while β denotes the braking. These commands can be understood as accelerating in case of a throttle or decelerating in case of braking (those throttling and braking commands are used to calculate the required power and other power-related stuff).

4.6. Wheels torque

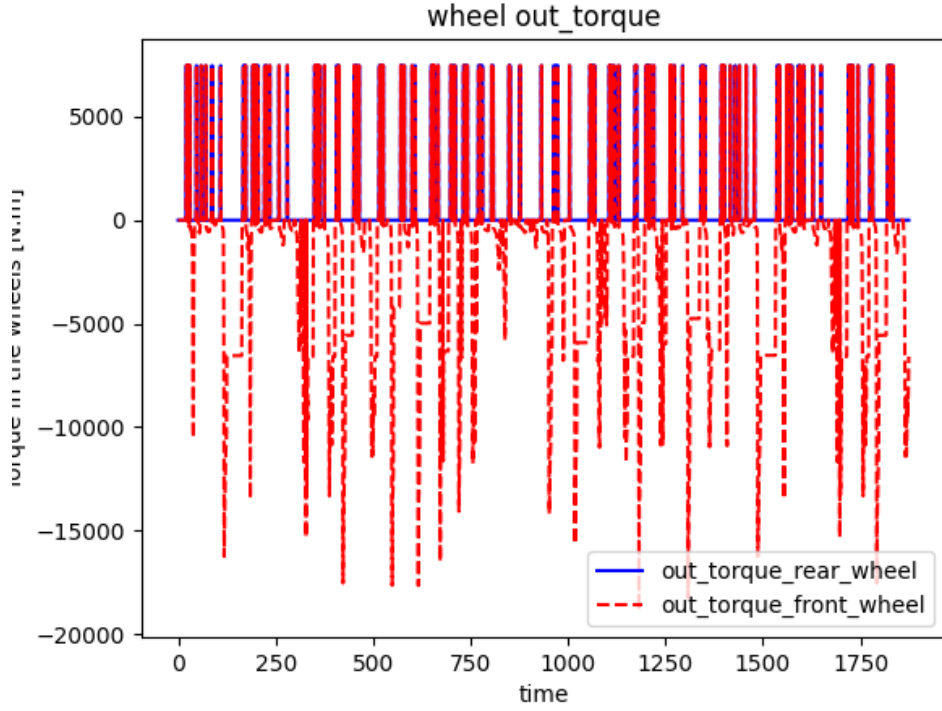


Figure 16: The torque generated by the battery with our model, in the front and the rear wheels

From the previous simulation results, we can see that our model was able to bring enough torque to the wheels during different acceleration, or battery power supply, what else can be seen here is that most of the generated torque was in the rear wheels, as it is well-known that when accelerating most of the loads transfer to the rear wheels. And it can be calculated as seen in the equations illustrated in section (2.2)

4.7. Brake torque

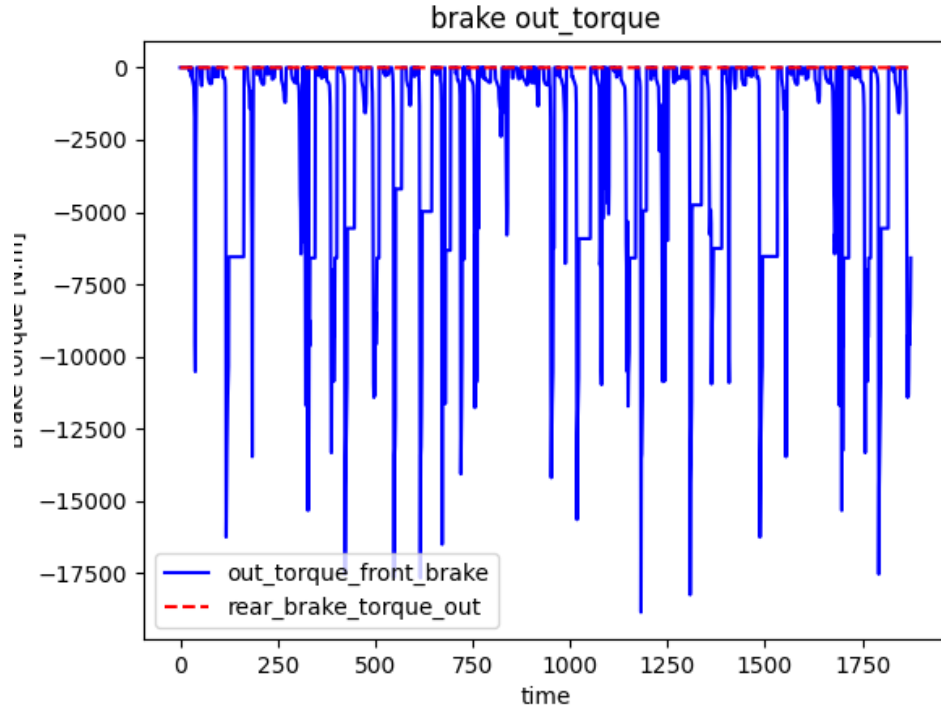


Figure 17: output torque in front and rear brakes

as it can be seen from the simulation plot, the results obtained by our model for the braking torque vary as battery power varies and speed of the car varies as well, what can be seen as well that most of the battery torque was in the front wheel due to the fact that when braking the load transfer occurred in the front wheel, most of the vehicle load transfer to the front [4].

4.8. Overall results

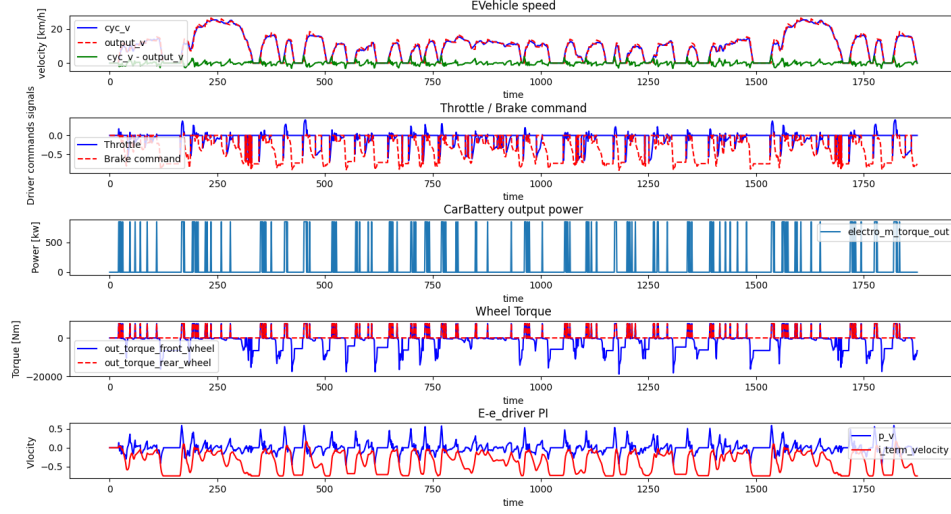


Figure 18: Different simulated parameters

As seen from the previous data and results this model works very well and can be used later for e-vehicles design. However, it can be said that this model needs to be corrected and updated for better performance, for the future we are planning to build a new updated model, and with the help of machine learning, we can build a model that will specify, and correct the errors in the model and also update the value of the parameter including the controller gains to have a suitable model. In the updated model for future work and with help of parameters optimization we will aim to reduce the vehicle cost and increase its efficiency.

5. Conclusion and future work

This model generally shows accurate results, and is able to simulate different parts at the same time we can tell which part of the vehicle needs adjusting and which one is not. However, the python program built for the simulation is limited as we need to have a previous simulation the for some parts of the vehicle first with MATLAB Simulink, in the future work the the program built will be able to model and simulate all the vehicle's parts with GUI, graphical user interface, in addition to the future work mentioned in section (4.8). Also one of the interesting results to clarify is that the PI based

driver model showed better results rather than using PID model as can be seen in figure(18)

This built model uses python and Matlab at the same time to generate the final simulation, if you want to use this model you have to start by using MATLAB Simulink to simulate the type of the electric motor you have and get the Torque graph with the angular speed characteristics. You can use MATLAB control toolbox, the Motor Control Toolbox is a package that includes functions and models for designing and simulating electric motor control systems. It includes the "motor" function and other functions related to motor modeling and control.

You also need to have your battery ocv-soc curve in order to use this model, you can get one by using the mapped battery in MATLAB, A mapped battery is a type of battery that has been characterized in detail in order to understand its performance and behavior under different operating conditions. The process of mapping a battery typically involves collecting data on a variety of parameters, such as the open-circuit voltage (OCV), the terminal voltage, the current, and the temperature, as a function of some independent variable, such as the state of charge (SOC) or the time elapsed since the battery was last charged.

The data obtained from a battery mapping process can be used to create various types of plots and charts that help to visualize the performance of the battery. For example, you can use the data to create an OCV curve, which shows the relationship between the OCV and the SOC, or a discharge curve, which shows the relationship between the terminal voltage and the current during a discharge process.

Also you can choose one of cycle velocity and run your simulation based on it. cycle velocity is a term that is often used in the context of testing and evaluating the performance of vehicles, particularly electric vehicles (EVs). It refers to the speed at which a vehicle is driven during a specific test cycle, such as the Federal Test Procedure (FTP) or the New European Driving Cycle (NEDC).

Test cycles are standardized driving patterns that are used to simulate real-world driving conditions and evaluate the performance of vehicles under different conditions. Cycle velocity is an important parameter in these tests, as it determines the average speed of the vehicle over the course of the test and can affect the vehicle's energy consumption, emissions, and other performance characteristics.

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