PROJECT 2 REPORT

HYBRID ELECTRIC VEHICLES

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ABSTRACT

The primary objective of the second project is to analyze the acceleration characteristics of a Prius mild hybrid vehicle. The main aim is to accelerate the vehicle as rapidly as possible without violating any physical constraints.

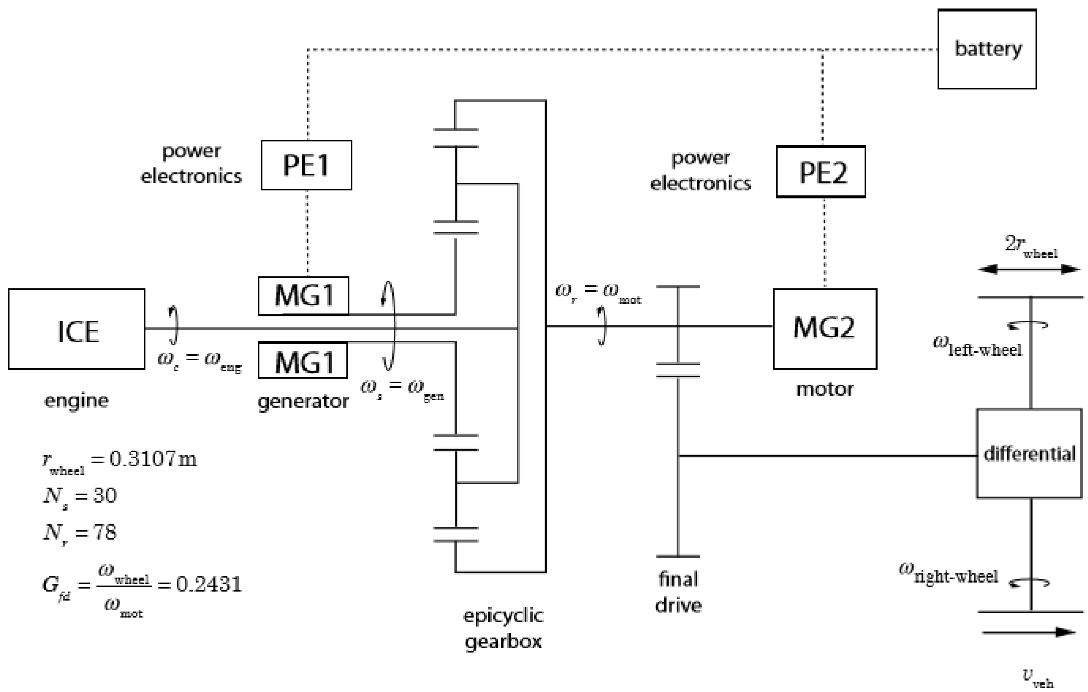
To analyze the vehicle performance, the Simulink model of the Prius mild hybrid electric vehicle is developed. The vehicle is started with a full throttle to analyze how fast it moves for the corresponding time limits.

INTRODUCTION

A hybrid electric vehicle is a type of hybrid vehicle and electric vehicle that combines a conventional internal combustion engine system with an electric machine system. The presence of the electric machine system is intended to achieve better fuel economy and lesser carbon dioxide emission than a conventional vehicle.

The Toyota Prius is a full hybrid electric automobile developed by Toyota and manufactured by the company since 1997. In this project we perform experimental analysis on the acceleration characteristics of the Prius drivetrain. We try to determine how much time it takes for the Prius to go from 0-60 miles per hour. We also try to calculate the energy derived from the battery, energy derived from the engine and the kinetic energy of the vehicle during the process.

The figure below gives the basic Prius drive train architecture.



PRIUS DRIVE TRAIN ARCHITECTURE

VEHICLE PARAMETERS

Since the various properties determine the performance of the vehicle individually, they are selected beforehand. The table below gives the full throttle torque limits of the engine with respect to the speed.

speed (rpm)	Torque(N-m)
1000	76
1198	84
1502	91
1888	97
2502	103
3000	105
3500	107
4000	110

FULL THROTTLE TORQUE LIMIT

The table below summarizes all the important parameters required in building the Simulink model of the Prius.

Parameter	Symbol	Value
vehicle mass	M_{veh}	1361 kg
generator inertia	J_{gen}	0.02 kg·m^2
motor inertia	J_{mot}	0.05 kg·m^2
engine inertia	J_{eng}	0.1598 kg·m^2
wheel radius	r_{wheel}	0.3107 m
rolling resistance coefficient	C_0	0.00475
aerodynamic drag coefficient	C_D	0.26
frontal area	A_F	2.33 m^2
battery capacity in kW-hr	E_{batt}	1.7 kW-hr
minimum engine power	$P_{\text{eng,min}}$	5 kW
maximum engine power	$P_{\text{eng,max}}$	57 kW
initial SOC	SOC_{init}	0.6
target SOC	SOC^*	0.6
maximum SOC	SOC_{max}	0.82
minimum SOC	SOC_{min}	0.38
maximum battery power	$\|P_{\text{batt,max}}\|$	21 kW
maximum motor power	$\|P_{\text{mot,max}}\|$	50 kW
maximum generator power	$\|P_{\text{gen,max}}\|$	30 kW
maximum engine speed	$\omega_{\text{eng,max}}$	5,000 rpm
minimum engine speed	$\omega_{\text{eng,min}}$	1,000 rpm
maximum motor speed	$\|\omega_{\text{mot,max}}\|$	6,500 rpm
maximum generator speed	$\|\omega_{\text{gen,max}}\|$	10,000 rpm
maximum motor torque	$\|T_{\text{mot,max}}\|$	400 N-m
maximum generator torque	$\|T_{\text{gen,max}}\|$	240 N-m

PARAMETER TABLE

ENGINE DATA

This table gives us the values of the engine power in watts(W), engine torque in Newton meter (N-m) and fuel consumed gram per kilo watt hour(g/kw-hr) with the corresponding values of engine speed in revolutions per minute (rpm).

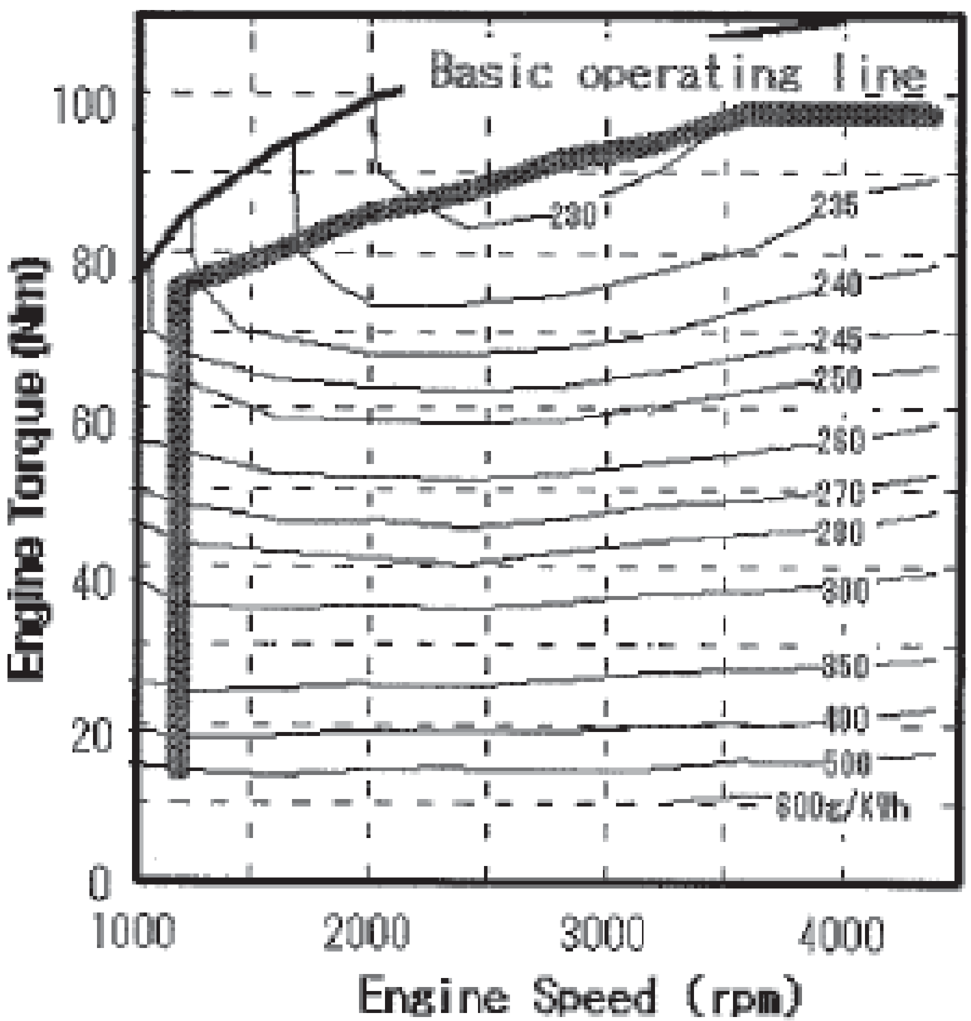
All the parameter data are a rough estimation of the information provided by Toyota on the Prius 2004 model

Speed (rpm)	Torque (N-m)	bsfc (g/kw-hr)	power (W)
1178	14	500	1727
1172	18	400	2209
1160	24	350	2915
1166	34	300	4152
1178	43	280	5305
1166	48	270	5861
1172	54	260	6628
1184	63	250	7811
1172	67	245	8223
1184	74	242	9175
1281	76	240	10195
1688	80	235	14142
2210	86	230	19904
2830	91	225	26969
3510	97	230	35655

ENGINE DATA TABLE

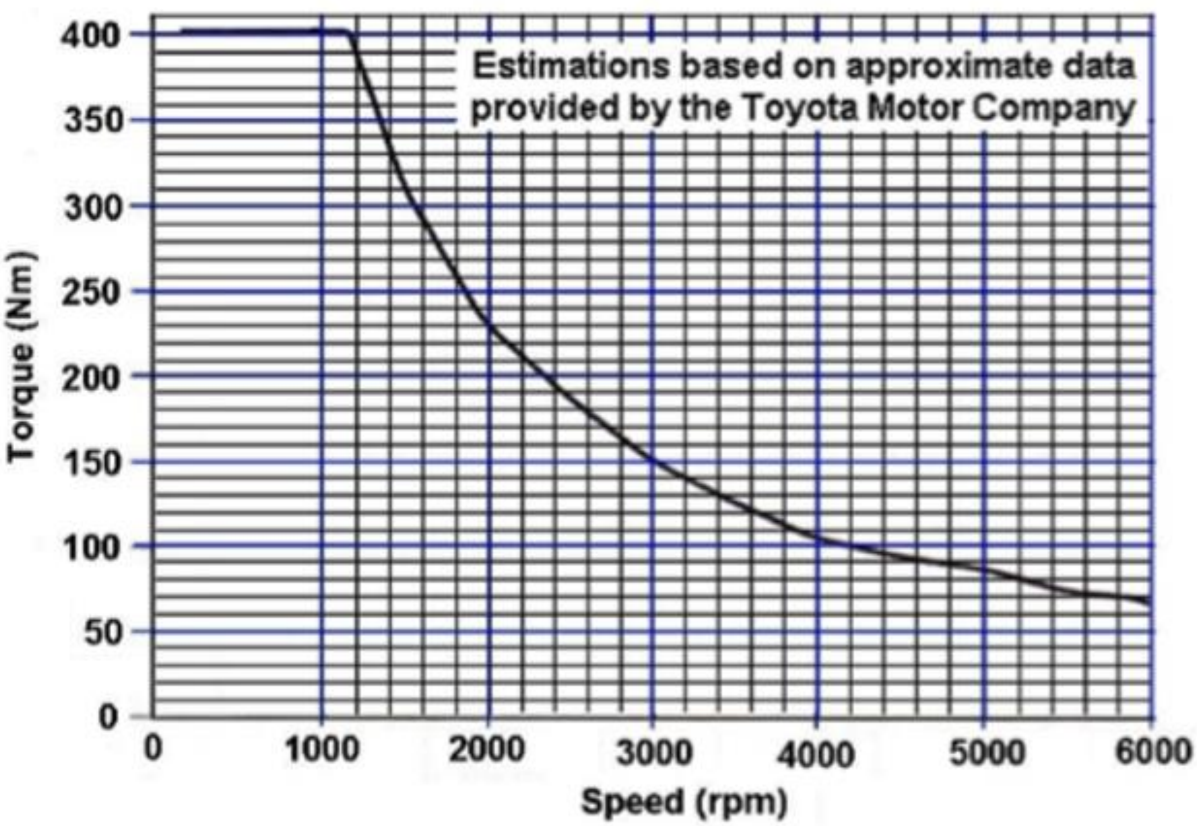
ENGINE CURVE

The engine of the vehicle is operated along its optimum brake specific fuel consumption (BSFC) characteristic graph. If the vehicle runs based on the BSFC curve then it is having optimal fuel efficiency. The maximum torque vs speed characteristics of the engine are depicted by the engine curve.



MOTOR CURVE

Like the engine curve the motor curve gives the maximum torque vs speed characteristics of the Prius motor.



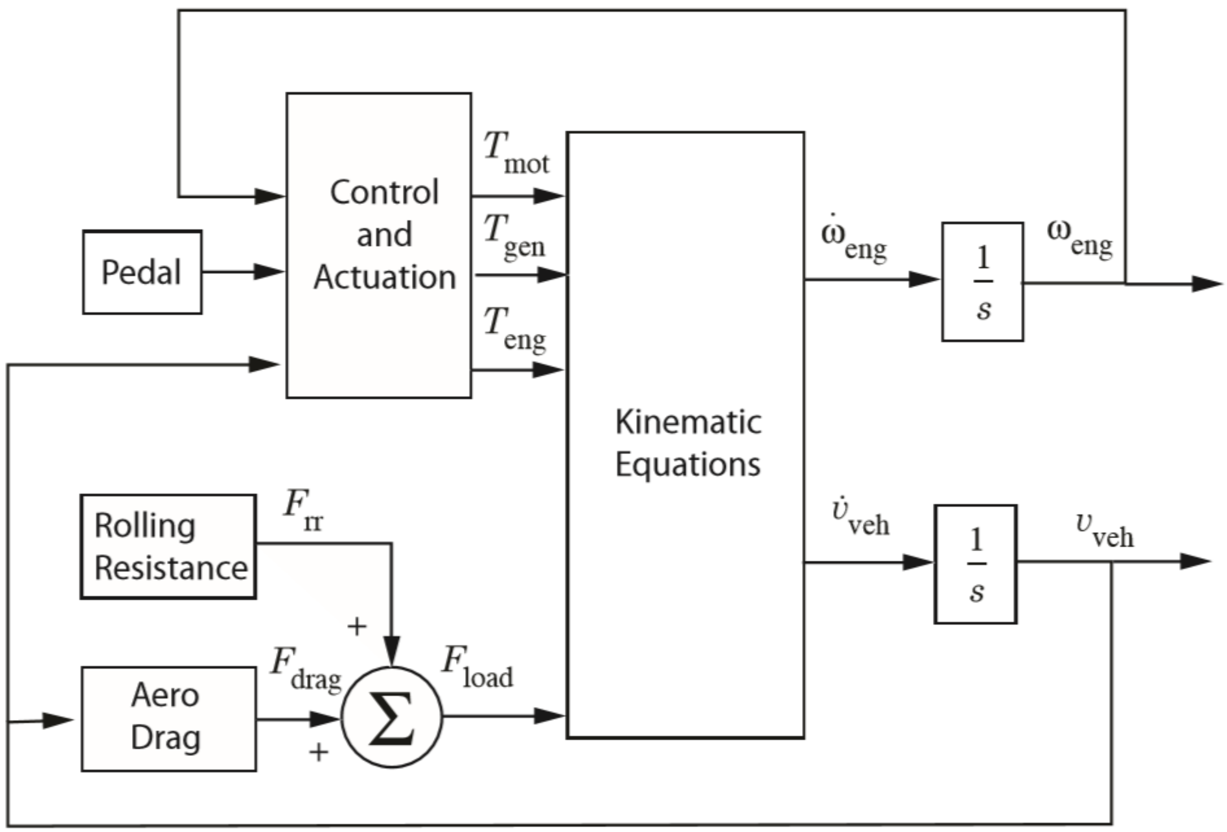
MOTOR CURVE

TOP-LEVEL DIAGRAM AND SIMULINK REPRESENTATION

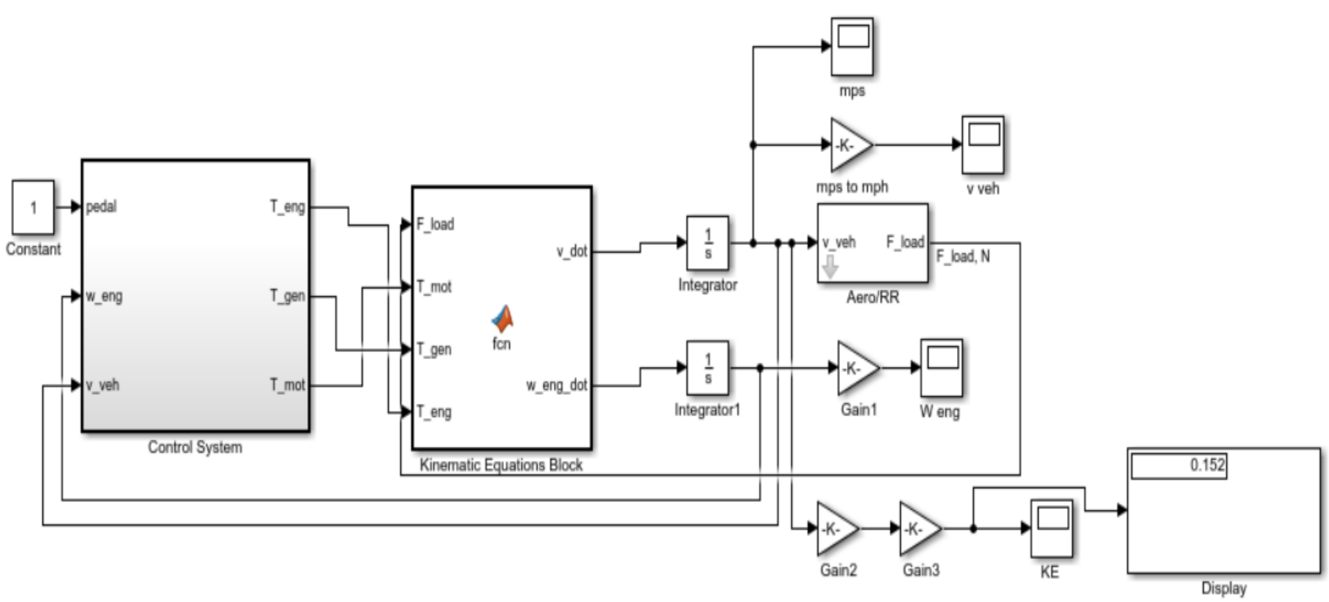
The top-level block diagram includes four important blocks.

1. Kinematic Equations Block
2. Control and Actuation Block
3. Rolling Resistance Block
4. Aerodynamic Force Block

The top-level diagram and its Simulink representation are depicted below.



TOP LEVEL DIAGRAM



SIMULINK DIAGRAM

KINEMATICS EQUATIONS BLOCK

The kinematic equations block takes in the engine torque, motor torque, generator torque from the control and actuation block. It also takes in total force as an input. It utilizes the kinematic equations to calculate the values of vehicle acceleration and engine angular acceleration which are integrated to get vehicle velocity in miles per hour(mph) and engine speed in revolutions per minute (rpm). The vehicle velocity and the engine speed are fed back into the control and actuation block as inputs.

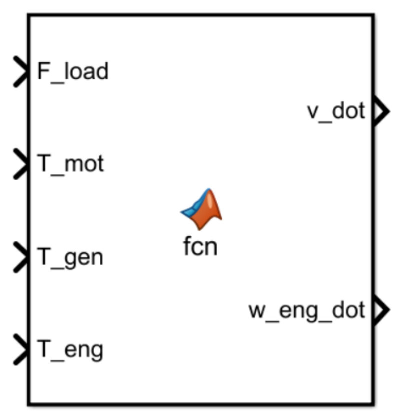
The kinematic equations used are given below.

$$T_{\text{eng}} + T_{\text{gen}} \frac{N_s + N_r}{N_s} = \widehat{J}_{\text{eng}} \dot{\omega}_{\text{eng}} - K \dot{v}_{\text{veh}}$$

$$-F_{\text{load}} - T_{\text{gen}} \frac{N_r}{N_s} \frac{1}{G_{fd} r_{\text{wheel}}} + T_{\text{mot}} \frac{1}{G_{fd} r_{\text{wheel}}} = \widehat{M}_{\text{veh}} \dot{v}_{\text{veh}} - K \dot{\omega}_{\text{eng}}$$

The rolling resistance and aerodynamic blocks when summed give the value of the total load force which is in turn put as an input into the kinematic equations block.

The block representation of kinematics equations is given below



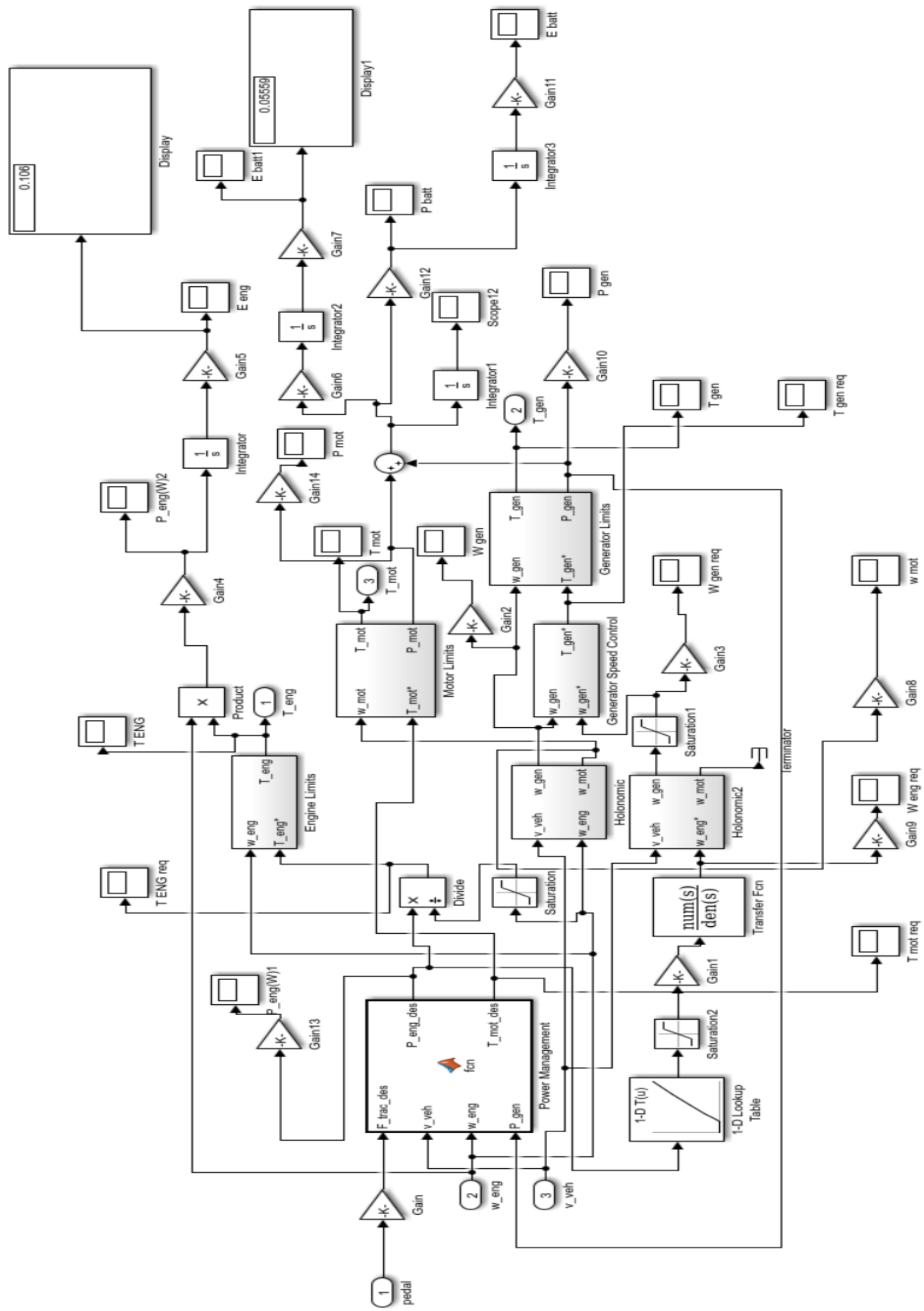
Kinematic Equations Block

CONTROL AND ACTUATION BLOCK

The control and actuation block takes in the vehicle velocity, engine speed and pedal which is a constant of one as its inputs. The value of pedal is kept one as the vehicle is made to run at full throttle from the very beginning. The outputs are the engine torque, motor torque, generator torque.

The Simulink diagram of the control and actuation block diagram is given below

There are many subdivisions within the control and actuation block.



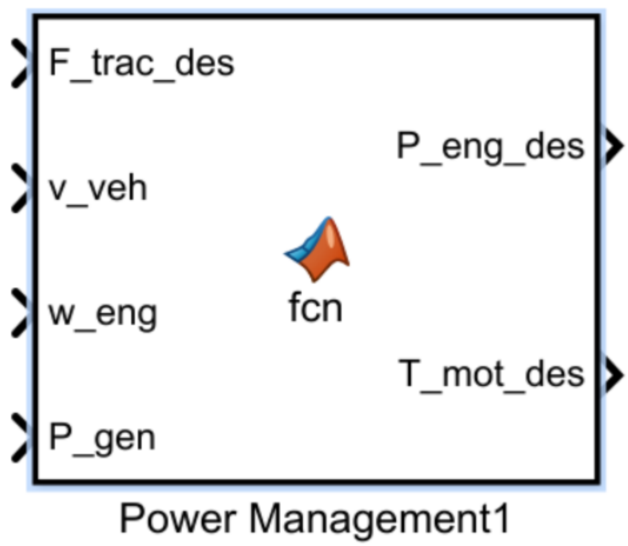
SIMULINK DIAGRAM

The important ones are:

1. **Power Management Block**

This block takes in the maximum tractive force, vehicle velocity, engine speed and generator power and utilizes the power management algorithm to produce the desired engine power and the desired motor torque.

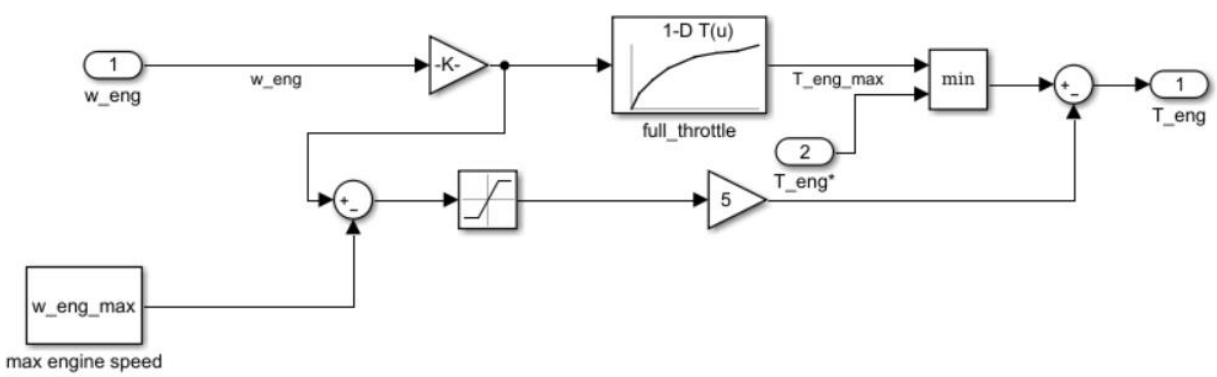
The block representation of power management is given below



2. **Engine Limits**

In this block we compare the desired engine torque with the maximum engine torque obtained from the full throttle torque limit and choose the minimum value to get the engine torque.

The block representation of engine limits is given below

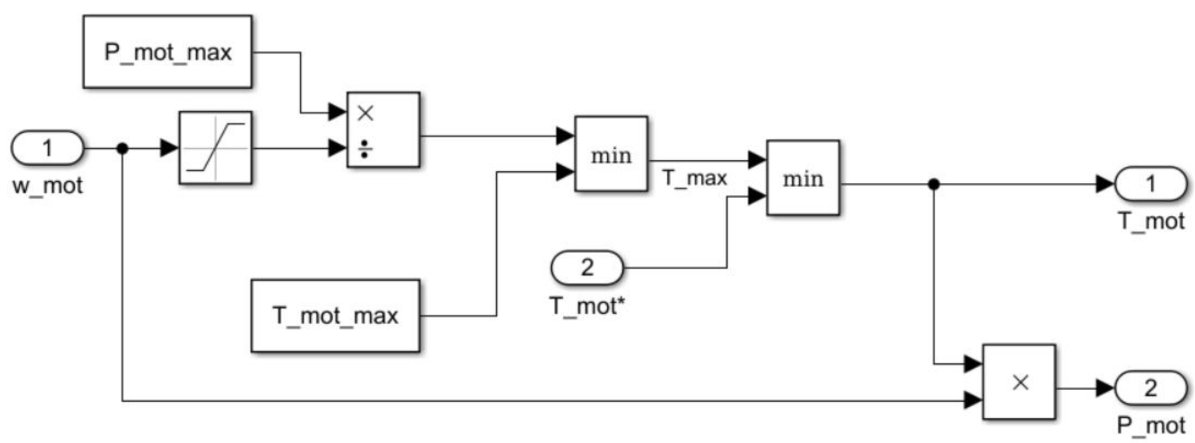


ENGINE LIMITS

3. **Motor Limits**

In this block we take in the desired motor torque and the motor speed as the inputs and calculate the motor torque and the motor power.

The block representation of motor limits is given below

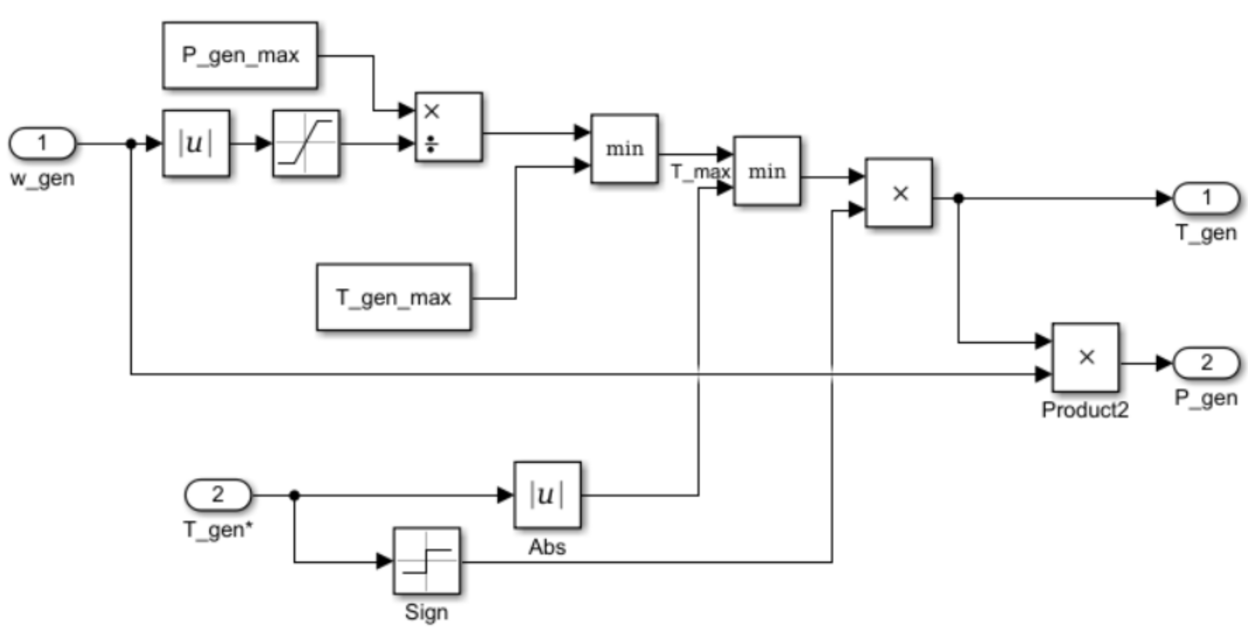


MOTOR LIMITS

4. Generator Limits

This block takes in the generator speed and desired generator torque from the speed limits block to give out the generator torque and the generator power.

The block representation of generator limits is given below

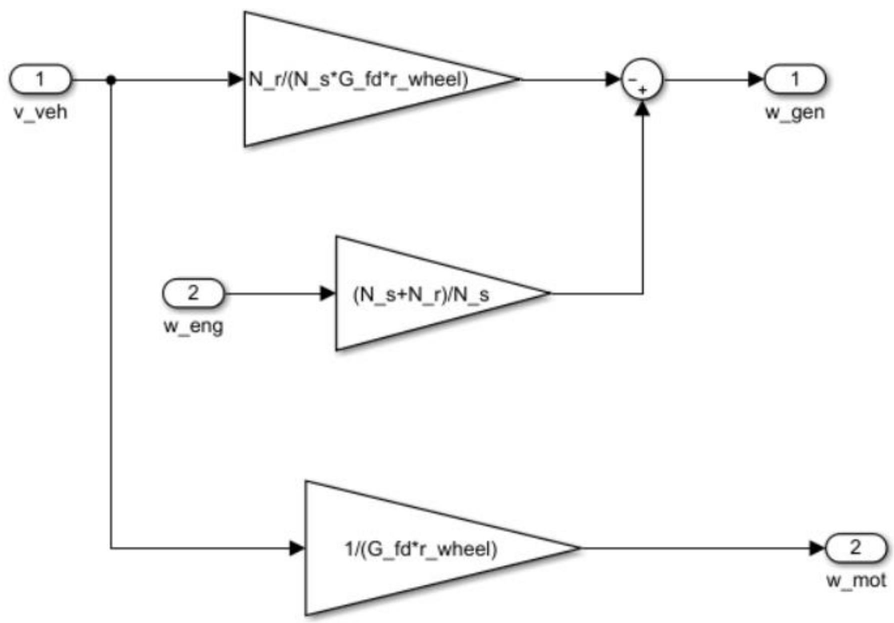


GENERATOR LIMITS

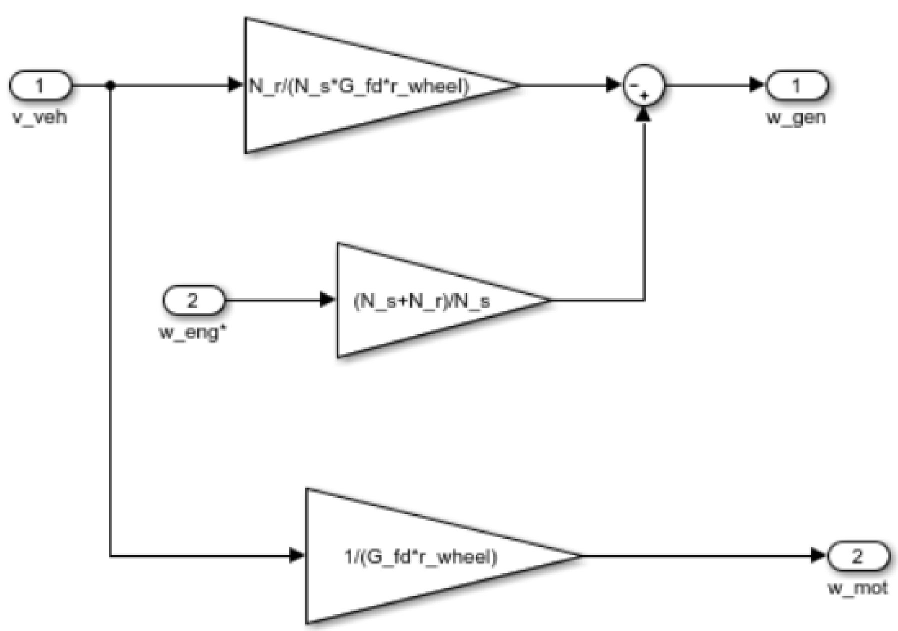
5. **Holonomic Blocks**

We use two holonomic blocks in our model where one computes desired generator and motor speeds using the optimum engine speed graph and the other computes the practical generator and motor speeds.

They have similar circuits but take in different inputs. The block representation of both the holonomic blocks is given below



HOLONOMIC BLOCK 1

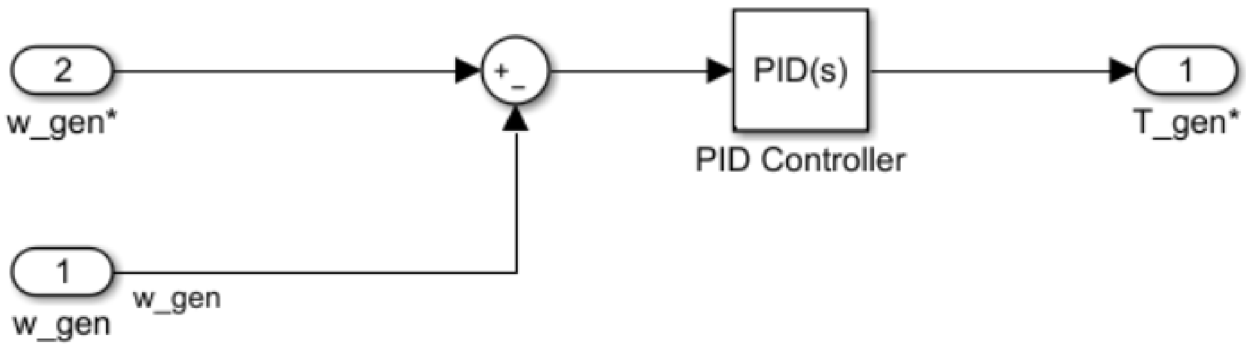


HOLONOMIC BLOCK 2

6. **Speed Control**

This block compares both the desired generator speed and the actual generator speed using a PID controller to give out the desired generator torque

The block representation of generator speed control is given below



GENERATOR SPEED CONTROL

ROLLING RESISTANCE AND AERODYNAMIC DRAG BLOCKS

They compute the rolling resistance force and the aerodynamic drag force and when summed it will equal to the total load force.

The equations used by these blocks are given below

$$F_{rr} = -C_f M_v g \cos\left(\frac{\alpha\pi}{180^\circ}\right)$$

ROLLING RESISTANCE FORCE

$$F_{ad} = 0.5\rho C_d A v^2 \operatorname{sgn}(v)$$

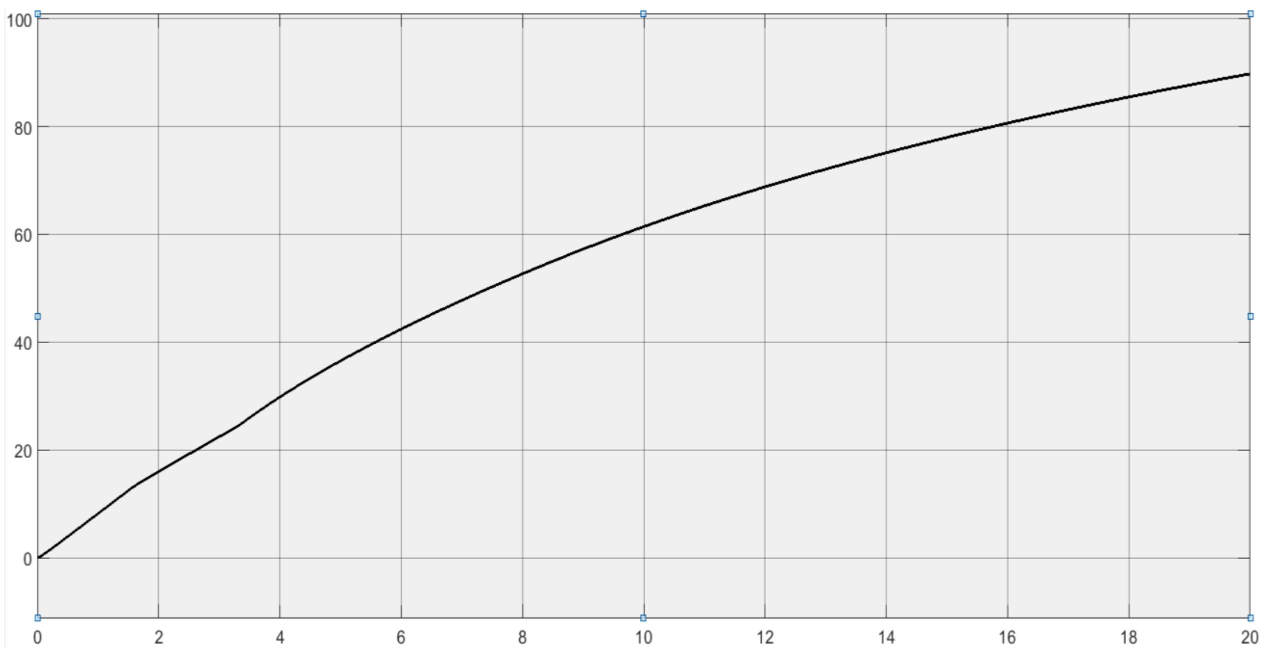
AERO DYNAMIC DRAG FORCE

RESULTS AND DISCUSSIONS

The variables are plotted against time in seconds. For the sake of simplicity, the time interval of all plots is taken to be 20 seconds.

1. **Vehicle velocity**

Our main aim of the project is to get the acceleration characteristics of the Prius model. To do that we "hit the peddle to the mettle" as in we drive the vehicle at full throttle from the start. The objective is to calculate how quickly the vehicle reaches the 60 miles per hour. The graph of vehicle velocity is depicted below.

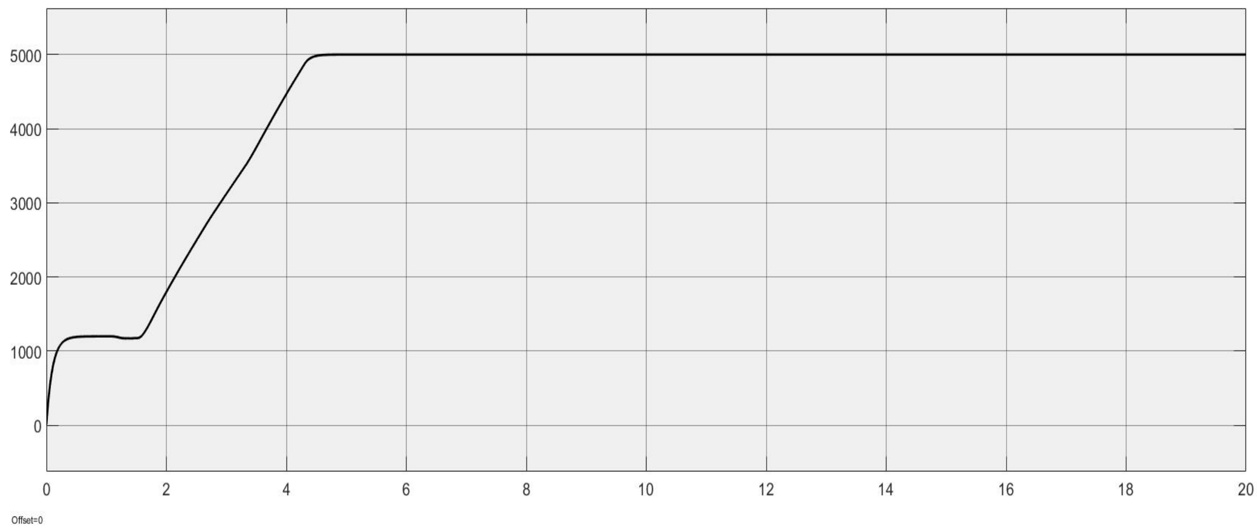


VEHICLE VELOCITY IN MILES PER HOUR VS TIME IN SECONDS

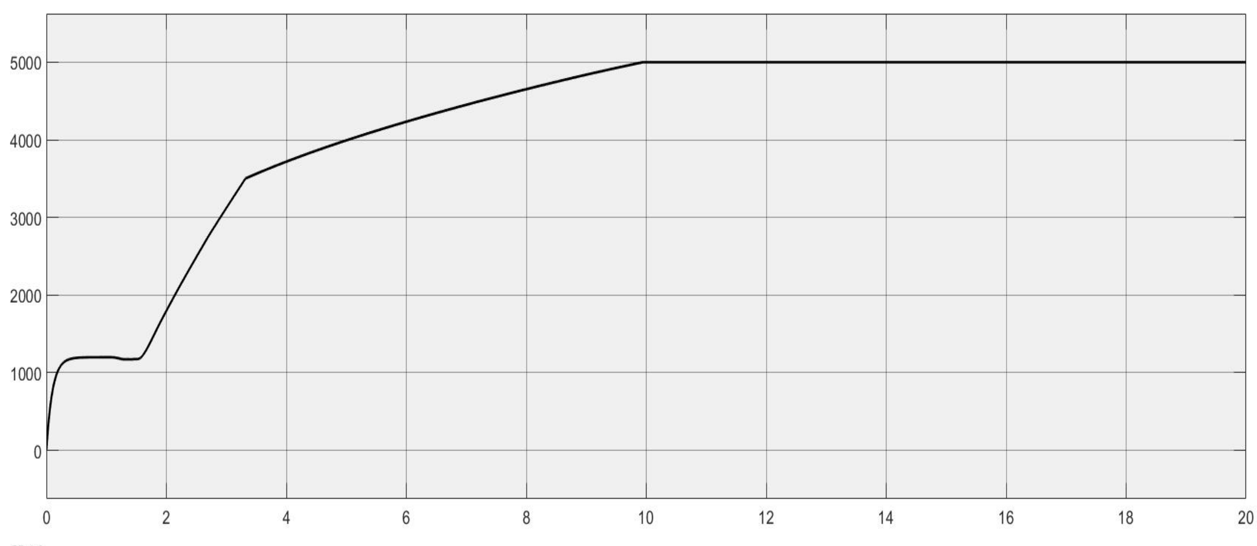
As we can see from the graph above the vehicle takes about 9.8 seconds to go from 0 to 60 miles per hour. This is dependent on a lot of factors. The total mass of the vehicle is taken to be the sum of weights of the car, driver and the battery. This sums up to 1461 kilograms. The velocity keeps on increasing continuously until it reaches its maximum value after which it becomes constant.

2. **Engine Speed**

The engine speed is obtained using the kinematic equations and is then feedback to the control and actuation block. The maximum and minimum engine speeds have been set to 5000 rpm and 1000 rpm. The comparison of engine speed desired and the practical engine speed is given below.



ENGINE SPEED DESIRED IN RPM VS TIME IN SECONDS

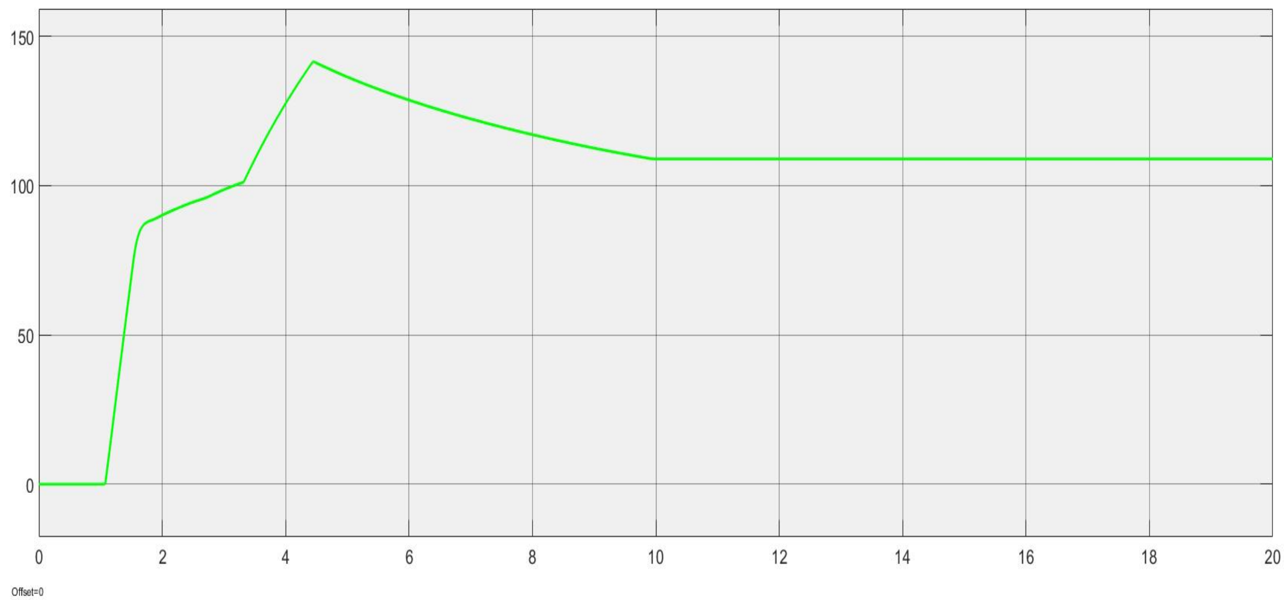


ENGINE SPEED PRACTICAL IN RPM VS TIME IN SECONDS

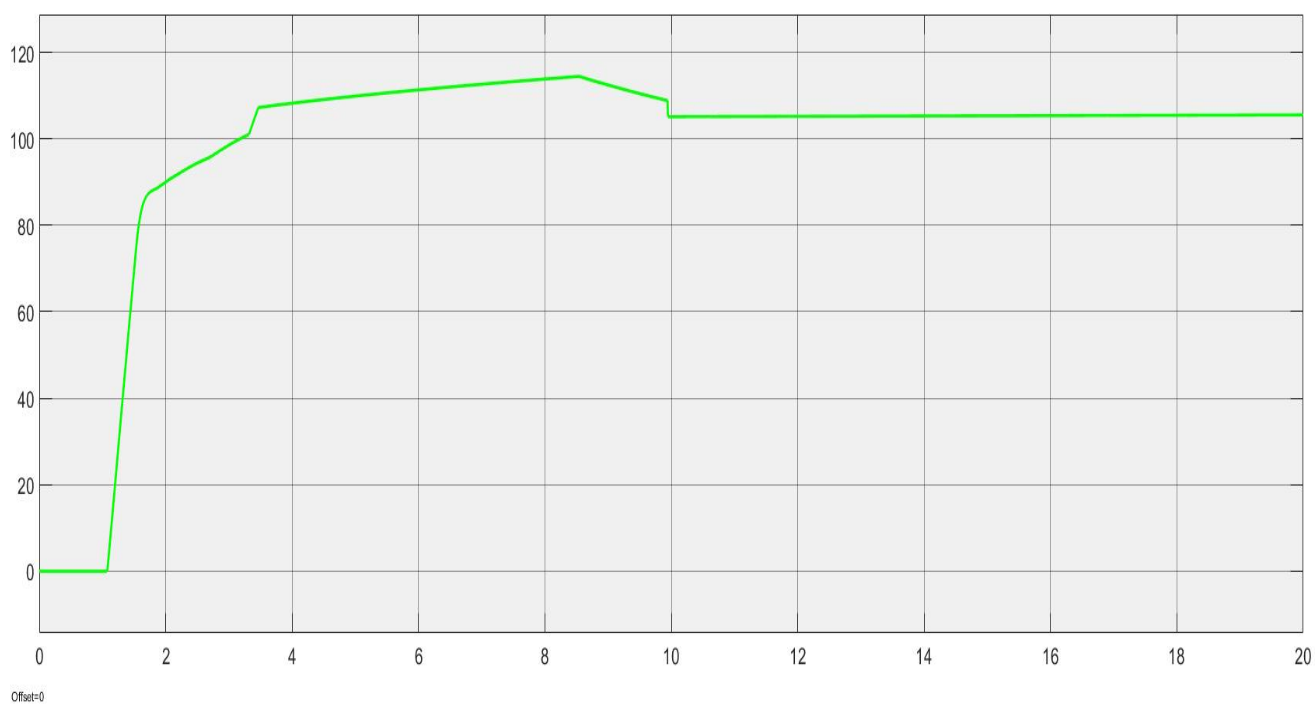
As we can see from the above figures both the components lie within the required limits. Its desired that the engine speed reaches its maximum value of 5000 rpm just after 4 seconds. But it happens at around 10 seconds as it takes more time for the engine to power up at reach its maximum speed value. We can also notice that the engine speed remains constant at 5000 rpm after the vehicle hits the 60-mph mark.

3. Engine Torque

The engine torque is calculated using the engine limits block where the maximum engine torque is compared to the desired engine torque and their minimum value is chosen to be the practical engine torque. The graphical representation of the desired engine torque and the practical engine torque is given below.



DESIRED ENGINE TORQUE IN NEWTON METER VS TIME IN SECONDS

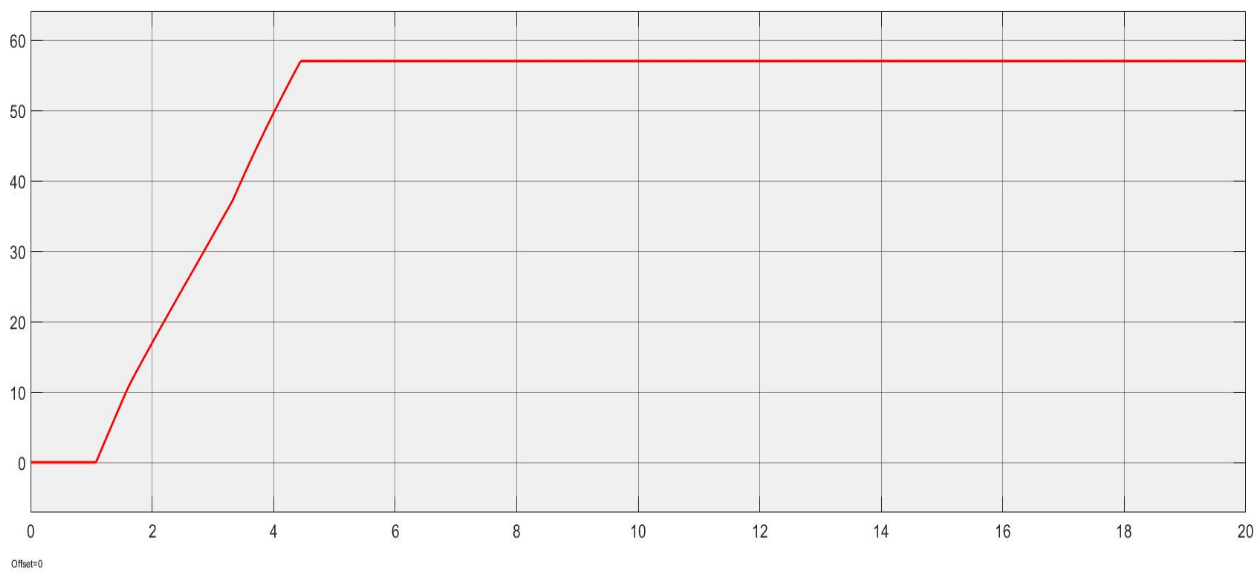


PRACTICAL ENGINE TORQUE IN NEWTON METER VS TIME IN SECONDS

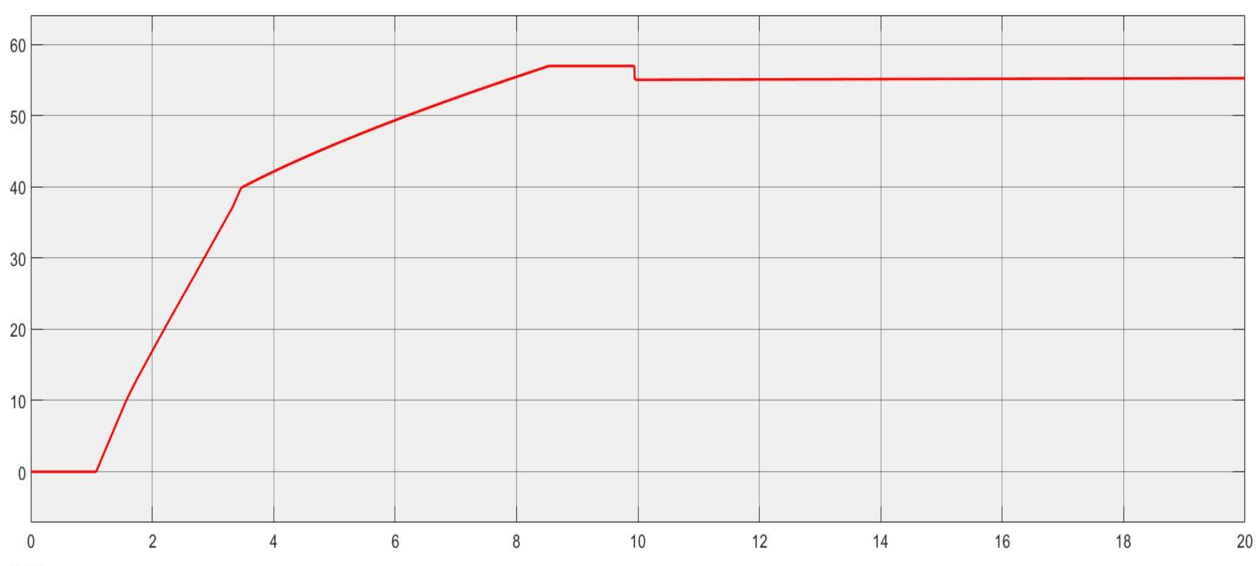
It can be observed that the desired maximum value of the torque is 148 N-m but , it reaches only 116 N-m before becoming constant at 108 N-m as required. This is because of certain engine limitations which don't allow the engine to function at such high torque rates to prevent damage. The engine torque also becomes constant after the vehicle hits the 60-mph mark. Otherwise the practical engine torque resembles the desired value.

4. Engine Power

The engine power is calculated directly by the multiplication of engine torque and engine speed. The maximum and minimum engine power values have been set to 57 Kw and 5 Kw. The comparison of engine power desired and the practical engine power is given below.



DESIRED ENGINE POWER IN KILOWATTS VS TIME IN SECONDS

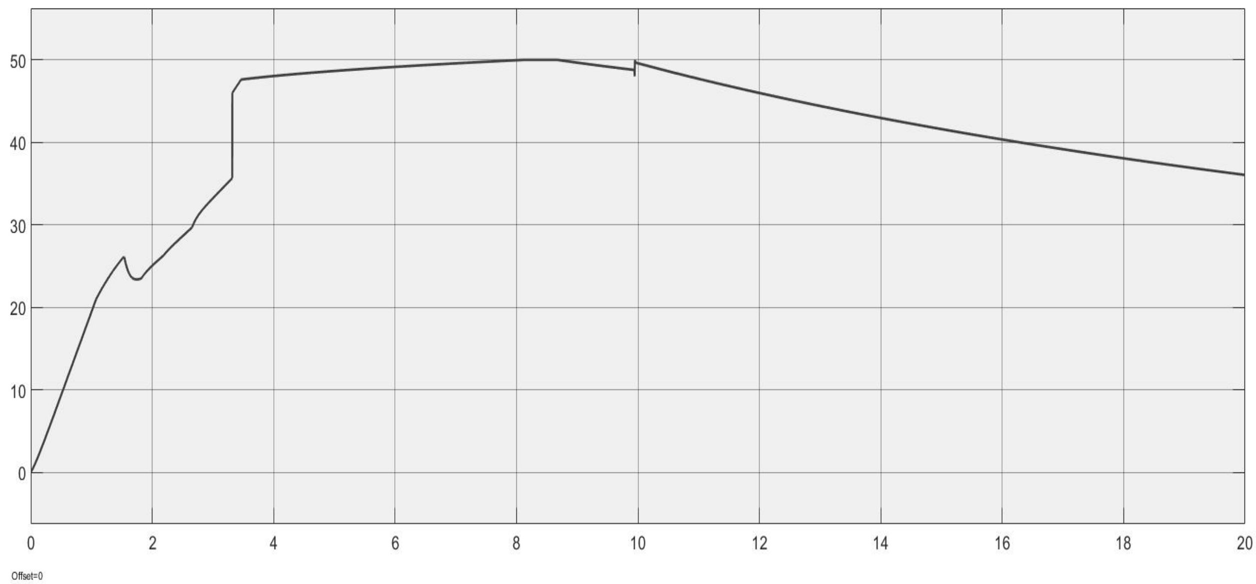


PRACTICAL ENGINE POWER IN KILOWATTS VS TIME IN SECONDS

The practical and the desired engine values certainly stay within the limits. Both become constant after the vehicle reaches the 60-mph mark. The practical engine power takes a slight dip and becomes constant at 55 Kw as compared to 57 Kw which is the desired value. This is to prevent physical damages to the engine by running it at maximum powers for extended periods.

5. Motor power

The motor power is obtained using the motor limits block by multiplying the motor torque and speeds. The maximum motor power value has been set to 50 Kw. The graph of motor power is depicted below.

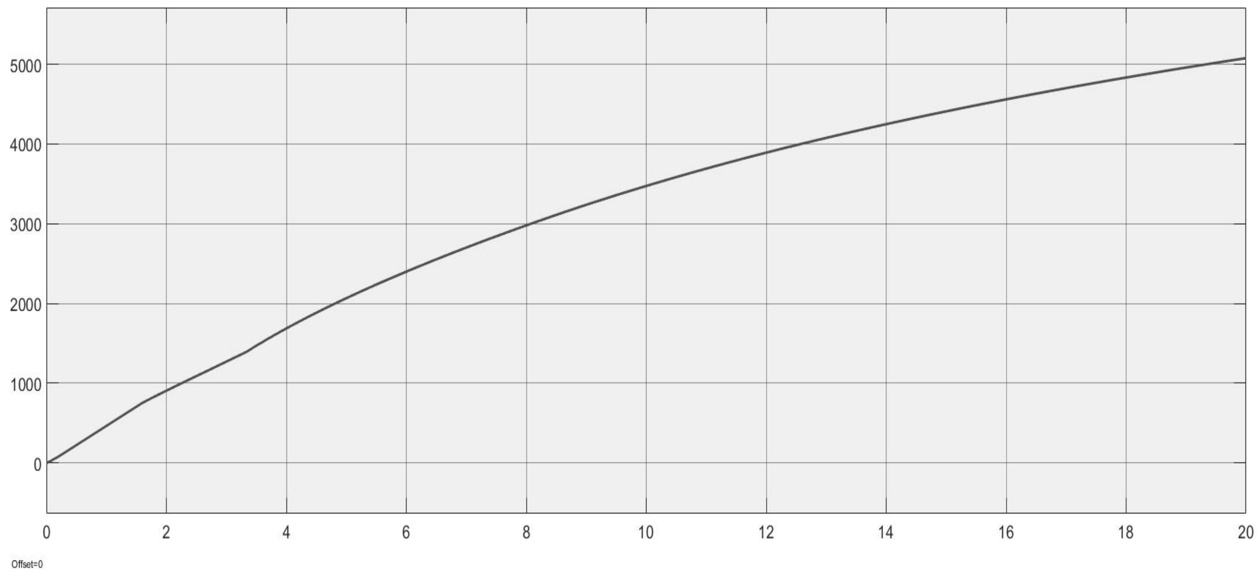


PRACTICAL MOTOR POWER IN KILOWATTS VS TIME IN SECONDS

The motor power keeps rising till it reaches its maximum value of 50 Kw and then starts dipping down. The dipping starts once the vehicle hits 60-mph.

6. Motor Speed

The motor speed is obtained using the holonomic blocks. The maximum motor speed has been set to 6500 rpm. Both the practical and the desired motor speeds look alike. Hence, we provide the graphical representation of the practical motor speed.

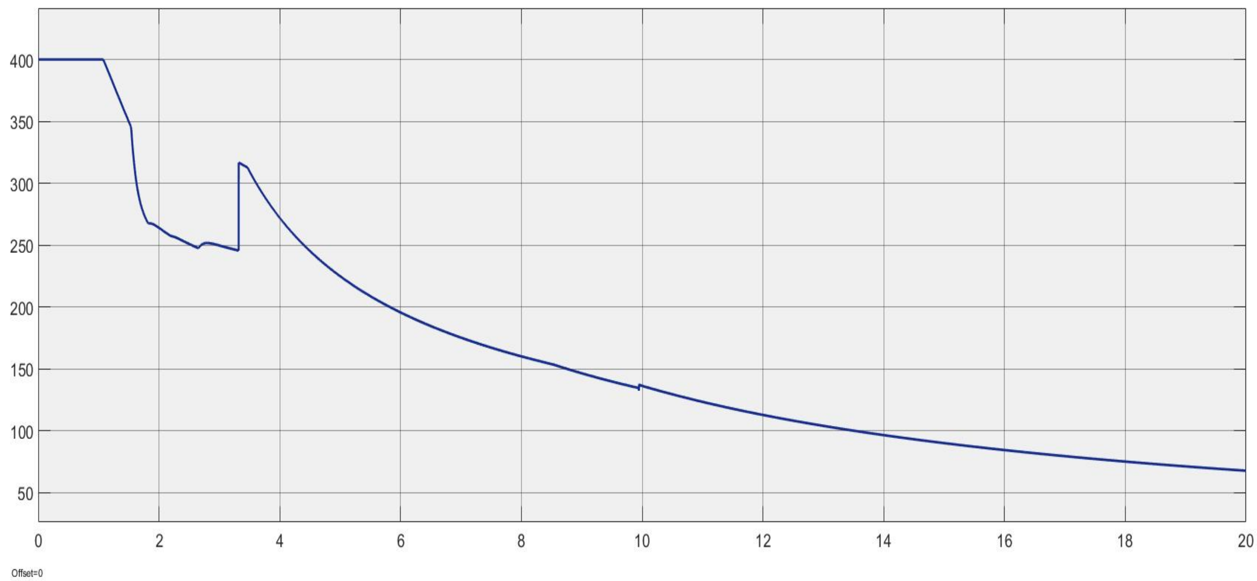


MOTOR SPEED PRACTICAL IN RPM VS TIME IN SECONDS

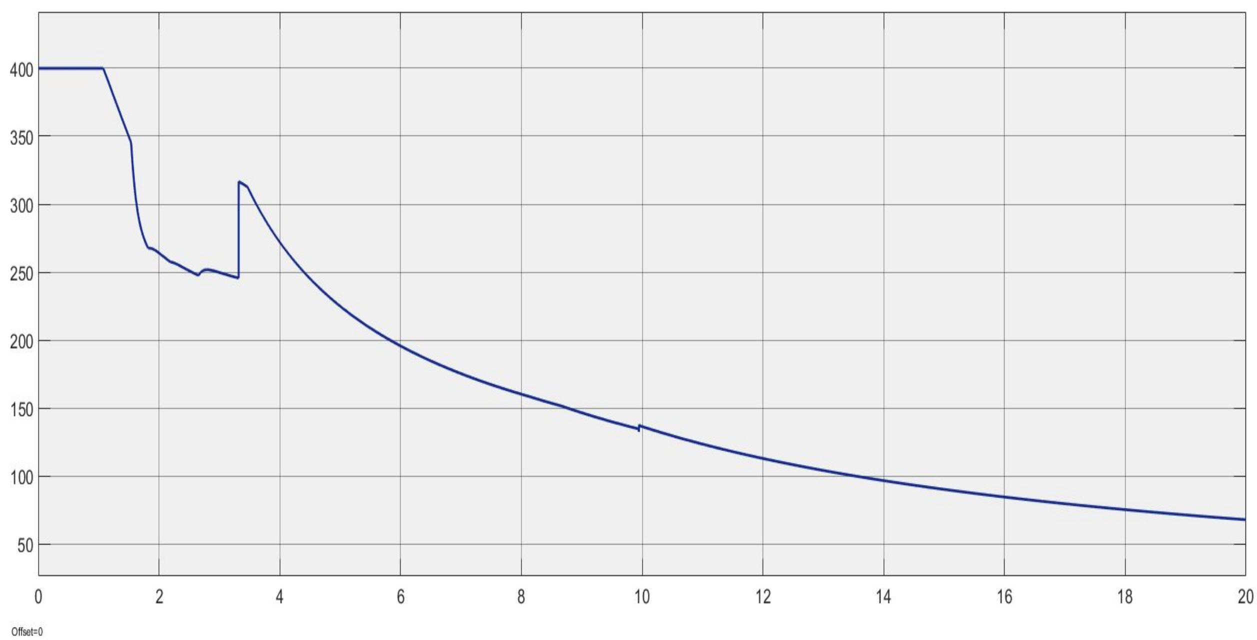
The motor speed keeps increasing until it reaches it maximum value of 6500 rpm after which it becomes constant.

7. Motor Torque

The motor torque is calculated using the motor limits block where the maximum motor torque is compared to the desired torque and their minimum value is chosen to be the practical motor torque. The graphical representation of the desired motor torque and the practical motor torque is given below.



DESIRED MOTOR TORQUE IN NEWTON METER VS TIME IN SECONDS

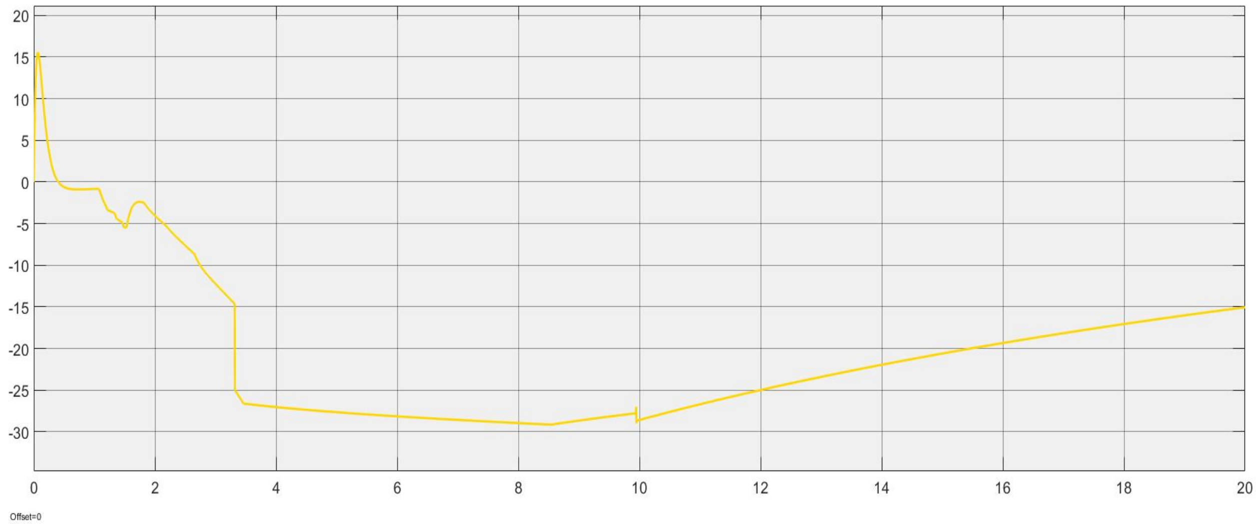


PRACTICAL MOTOR TORQUE IN NEWTON METER VS TIME IN SECONDS

Both the practical and the desired motor torques start at the maximum value of 400 N-m and keep on decreasing. The slope gets higher once the vehicle hits the 60-mph mark.

8. Generator Power

The generator power is obtained using the generator limits block by multiplying the generator torque and speeds. The maximum generator power value has been set to 30 Kw. The graph of generator power is depicted below.

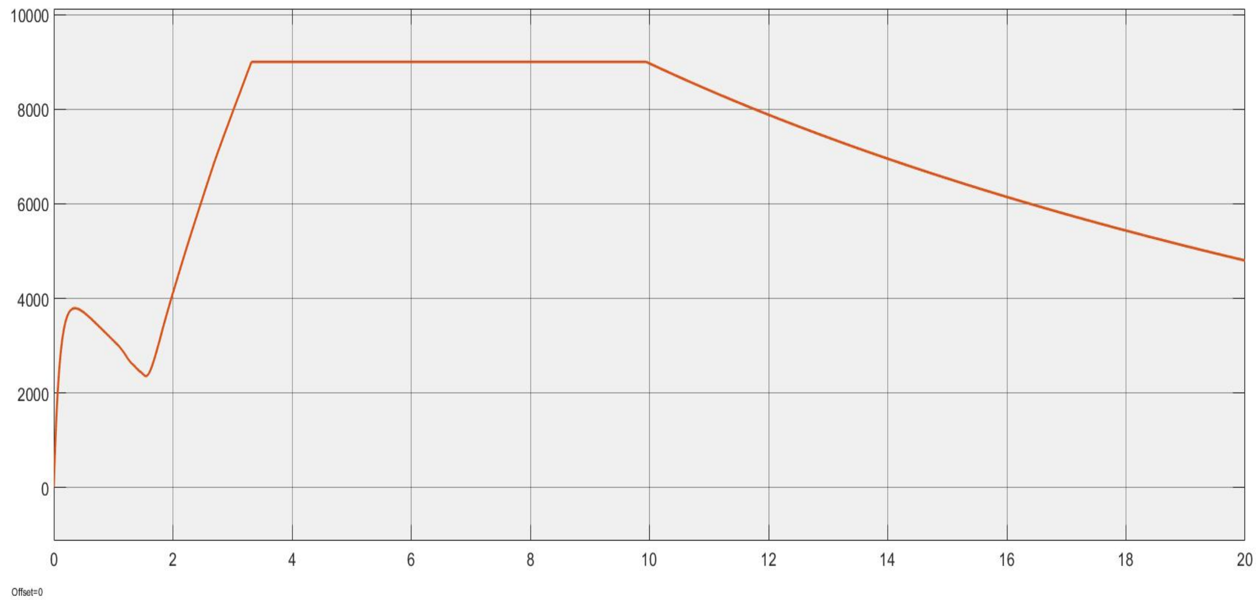


PRACTICAL MOTOR POWER IN KILOWATTS VS TIME IN SECONDS

As we can see from the graph the generator power stays within the limits of +30 and -30 Kw. It starts decreasing from the beginning and reaches its negative minimum of -30 kw at the time when the vehicle is travelling at 60-mph. It starts increasing after that point.

9. Generator Speed

The generator speed is obtained using the holonomic blocks. The maximum generator speed has been set to 9000 rpm while its desired at 10000rpm. This is done to limit the generator speed from crossing 10000rpm. Both the practical and the desired generator speeds look alike. Hence, we provide the graphical representation of the practical motor speed.

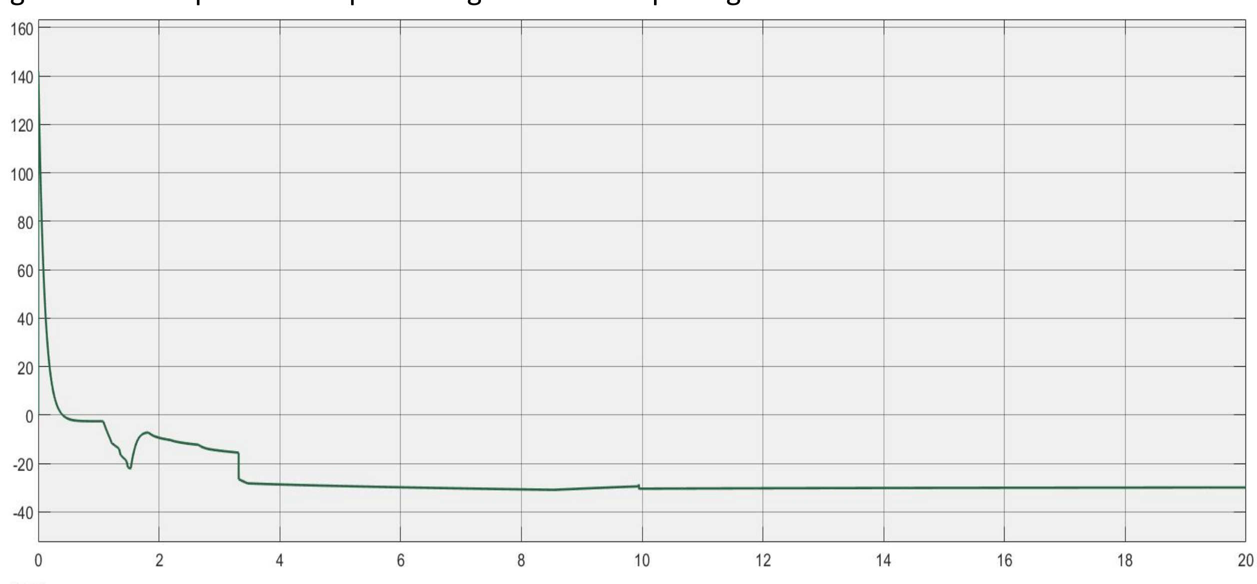


MOTOR SPEED PRACTICAL IN RPM VS TIME IN SECONDS

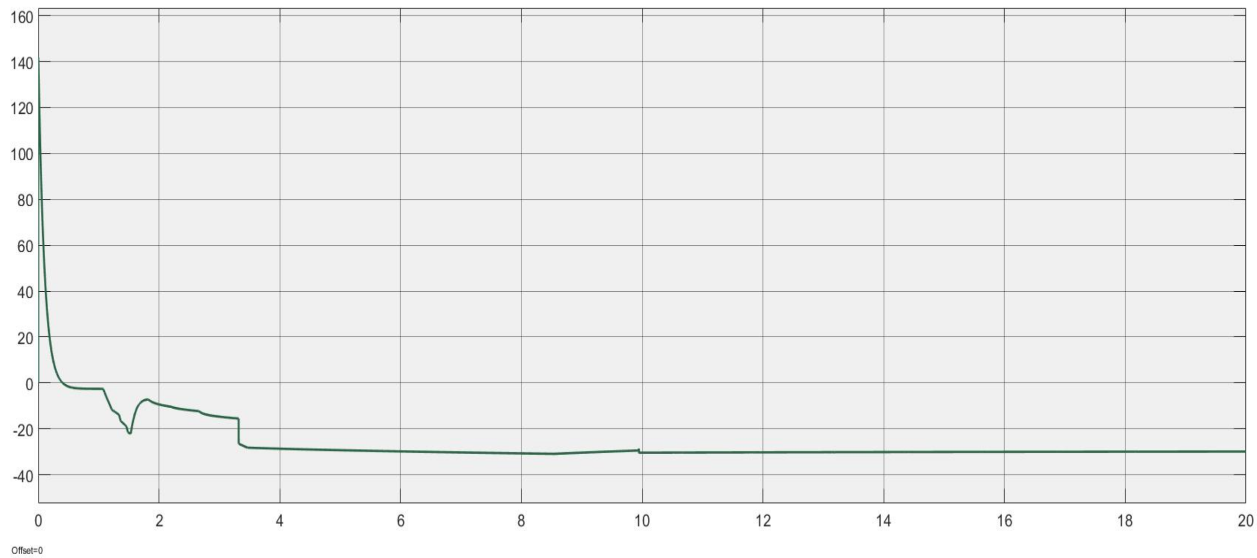
The generator speed increases till it reaches 9000 rpm and becomes constant. It stays constant until the vehicle reaches 60-mph after which it starts decreasing.

10. Generator Torque

The generator torque is calculated using the generator limits block where the maximum generator torque is compared to the desired torque and their minimum value is chosen to be the practical generator torque. The graphical representation of the desired generator torque and the practical generator torque is given below.



DESIRED GENERATOR TORQUE IN NEWTON METER VS TIME IN SECONDS

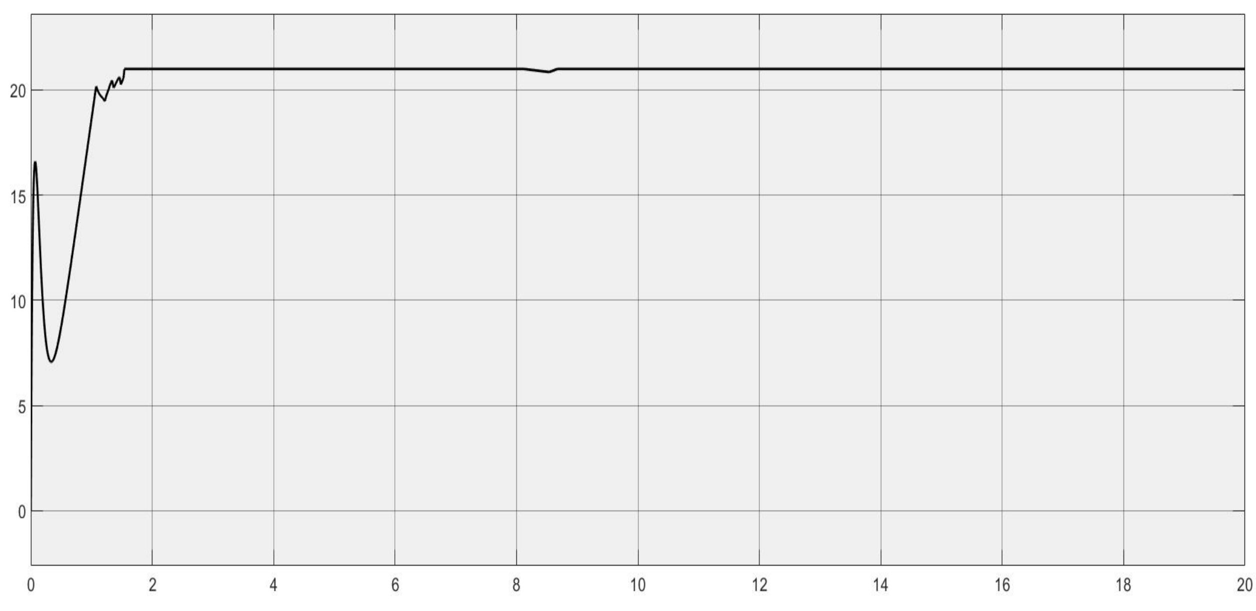


PRACTICAL GENERATOR TORQUE IN NEWTON METER VS TIME IN SECONDS

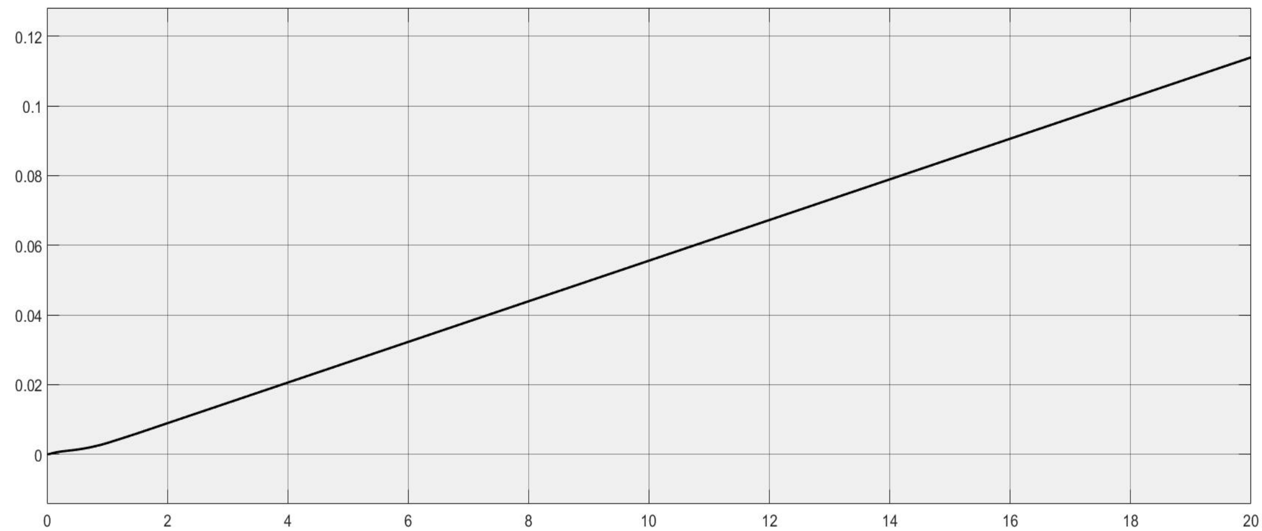
Both the practical and the desired motor torques start at 140 N-m and keep on decreasing. The become constant at -30 N-m and continue that way.

11. Electrical Energy Consumed from the Battery

To get electrical energy from the battery we need to calculate the electric machine power. This is done by summing the motor and the generator powers. Then we integrate the power to get our energy in Kw-hr. The graphs depicting both the battery power and the battery energy are given below.



BATTERY POWER IN KILOWATTS VS TIME IN SECONDS

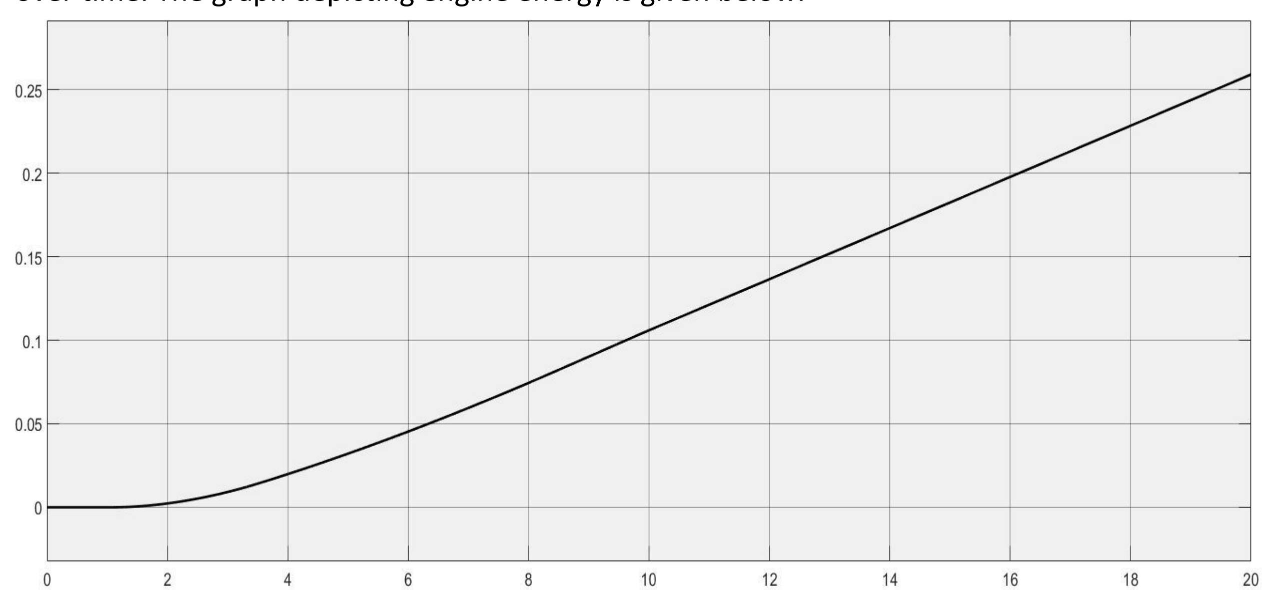


BATTERY ENERGY IN KILOWATT HOUR VS TIME IN SECONDS

We notice that the battery power remains constant at its maximum value of 21 Kw while the battery energy keeps on growing. The energy derived from the battery when the vehicle reaches 60-mphs is equal to 0.05559 Kw-hr.

12. Engine Energy

Like the battery energy the engine energy is also calculated by integrating engine power over time. The graph depicting engine energy is given below.



ENGINE ENERGY IN KILOWATT HOUR VS TIME IN SECONDS

The engine energy keeps increasing from the start. The energy derived from the engine when the vehicle reaches 60-mphs is equal to 0.106 Kw-hr. And the kinetic energy of the vehicle is 0.152 Kw-hr when the vehicle hits 60-mph. It is calculated using the equation

Kinetic Energy = ½ * Mass of vehicle * (vehicle velocity)^2 where the mass is 1461 kg and the velocity is 27.27-m/s.
The sum of engine and battery energies at 60-mph equal the kinetic energy of the vehicle.

CONCLUSIONS

The model was successfully built and its acceleration characteristics were noted. All the required parameters required were plotted and calculated.