Electric Vehicles (EVs):
A Study on Its Many Principles, Interior Functioning and Modeling Through Software Simulation

A Thesis
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BRAC University
By

Mohammad Saadman Alam-15110006
Khondaker Nazib Murshed-15121029
Zunayed Mahmud-15121010
Tonmoy Roy-15121013

Supervised by
Dr. A. K. M. Abdul Malek Azad
Professor
Department of Electrical and Electronic Engineering
BRAC University, Dhaka

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DECLARATION

We hereby declare that research work titled "*Electric Vehicles (EVs): A Study on Its Many Principles, Interior Functioning and a Presentation of their Respective Simulink Models*" is our own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged/referred.

Signature of
Supervisor

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Dr. A. K. M. Abdul Malek Azad

Signature of
Authors

……………
Mohammad Saadman Alam

……………
Khondaker Nazib Murshed

……………
Zunayed Mahmud

………………..
Tonmoy Roy

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ABSTRACT

Electric Vehicles (EVs) are at its most pivotal point in history in terms of popularity, development and regular consumer usage. The preferred mode of transport currently consists of conventional gasoline chambered vehicles and hybrid electric vehicles (also known as electrified vehicles), which use the gasoline vehicles in addition to batteries which supply electricity for locomotion. These batteries may be plug-in hybrid vehicles (PHEVs) or normal hybrid vehicles (HEVs). In our thesis research, we will, however, be focusing on Battery Electric Vehicles (BEVs) which eliminates the use of gasoline chambers altogether and relies solely on the power of a battery and the electricity produced by it. These BEVs can be plugged into sockets where they are charged for later use. We are now in a day and age where the fossil fuels are in rapid decline, and very soon in a matter of 33 years, in other words by the year 2051, our natural oil reserves will have depleted. In our research we have done a complete study on the different parts of an electric vehicle. A study on different types of forces acting on the vehicle while travelling on the road was done. Moreover, the different types of motors used in an Electric Vehicle was studied along with their controlling strategies. It is evident; therefore, an alternate method is required to power these vehicles, one which is more efficient as well as environmentally friendly. This transportation problem can be resolved by renovating the way automobiles functions, and it seems that electric vehicles (as opposed to electrified vehicles) are the answer. There are several advantages associated with using electrically powered cars which include zero pollution as opposed to exhaust pollution and carbon emissions from traditional vehicles, lower levels of noise pollution. This paper describes how an electric vehicle works in order to give a broad overview and insight on their functioning. It also includes the modelling of an Electric Vehicle and also the corresponding simulation results. In a comparative study in between the electric vehicle and the conventional vehicle we have put forward the importance and necessity of electric vehicle in the modern times. Therefore, this thesis paper will give a complete idea of the functioning of an electric vehicle which are supported by relevant simulation results.

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ABBREVIATIONS

EV - Electric Vehicle
PHEV - Plug-in Hybrid Electric Vehicle
HEV - Hybrid Electric Vehicle
BEV - Battery Electric Vehicle
IC - Internal Combustion
ADVISOR - Advanced Vehicle Simulator
AEB - Automatic Emergency Braking
UPS - Uninterrupted Power Supply
LiCoO2 - Lithium cobalt oxide
LiFePO4 - Lithium iron phosphate
LiMn2O4 - Lithium manganese-oxide
LiNiO2 - Lithium nickel-oxide
LiPF6 - Lithium hexafluorophosphate
BLDC - Brushless DC Motor
PMSM - Permanent Magnet Synchronous Motor
IM - Induction Motor
EMF - Electromagnetic Force
DTC - Direct Torque Control
FOC - Field Oriented Control
PWM - Pulse Width Modulation
PI - Proportional Integral
SOC - State of Charge
UDDS - Urban Dynamometer Driving Schedule
HWFET - The Highway Fuel Economy Test
ECE - Elementary Urban Cycle
UDC - Urban Driving Cycle
EUDC - Extra European Driving Cycle
MVEG - Motor Vehicle Emissions Group
NEDC - New European Driving Cycle

CHAPTER 1

Introduction

1.1 Introduction to Electric Vehicles (EVs)

Electric Vehicles (EVs) are vehicles of the very near future. They are already being used quite prevalently at present, however, they are yet to be perfected and mastered. They are indeed quite far from the stage that deems them to be a must-have or a necessity over the other options available in the market. For starters, the initial cost of battery electric vehicles (BEVs) can get quite expensive when compared to their traditional internal combustion (IC) counterparts. It can be predicted quite well enough though, and with a high degree of certainty, that this situation will go on to be ameliorated due to economies of scale. Currently, the lithium-ion batteries, those which are used to power our everyday electronics such as phones, laptops and so many more devices, seem to be the market dominating battery technology. Further improvements to these batteries are a hot area of research at present, and so, we can expect these batteries to get even more efficient and powerful while their prices drop. Using these batteries in automobiles, for example, will drive the batteries' demand up and force the production of these batteries to go higher. With an increased number of firms involved with the production and manufacturing of these batteries in bulk, and due to more competition amongst them, and greater overall supply in the market, the prices will inevitably drop until an equilibrium point is reached. We can expect the prices of these BEVs to drop year after year in the long run when all the major automobile companies start to phase out their traditional IC vehicles, and this is bound to happen, as fossil fuels are running out and quite rapidly so. Zero pollution and little to no noise are already a consumer favorite concept and a strong marketing tool used in the automobile industries. To get a clearer picture of where the automobile industry stands, the current scenario of the automobile industry can be compared and seen as analogous to the price to demand ratio of PCs in the early 1990s following up to 2010 and beyond. Initially the price was very high, but soon after, there was a massive decline in their price despite the computers' power and efficiency increasing so much more than it had initially been. It is quite possible for a similar trend to appear in the automobile industry as a revolution of this scale has not occurred in transportation for quite some time now. In section 1.2, we shall look into a brief history pertaining to transportation and vehicles that has occurred in the past and led up to the point we are at presently, but before that the present situation has been presented.

At present, there are three kinds of Electric Vehicles, simply put, the Hybrid Electric Vehicles (HEVs), the Plug-in Hybrid Electric Vehicles (PHEVs), and the Battery Electric Vehicle (BEVs). At hindsight it may seem that the plug-in hybrid or PHEVs are a good option as they use both an internal combustion engine and a battery which stores electrical energy to provide kinetic energy to the vehicle for moving forward as well when necessary, however, the problem here is that this makes the car very heavy and it makes it a little bit of both and cannot operate at its maximum capability, as it otherwise could have, were the vehicle stand-alone, that is, if the vehicles were either fully internal combustion (like traditional vehicles), or fully relying on the battery. This leaves us to the last option, the battery electric vehicle (BEVs). This is the system that should be utilized and made the focus of automobile industries. This is because upon the integration of all the technologies uncovered over the past decades, such as the latest communication technologies, the internet, computerization, satellite communication and so much more alongside a mode of operation with an electric interface and electric power will open up a window in unparalleled transportation technology unlike any that has ever been present before *and* high efficiency.

1.2 A Brief History on Transportation

If we look into history, we can find that the concept of Electric Vehicles is not groundbreaking and recent, but rather we can find that this dates back to as far as the mid-19th Century. All kinds of prototypes for Electric Vehicles such as the Electric model cars were already around in the late 1820s [1]. Until the 20th century, the land speed record is known to be held by Electric Vehicles before other kinds of engine technologies took the helm [2]. The first scale model electric vehicles were created in between the years of 1828 and 1835, and soon after there were a stream of crude and impractical Electric cars. It wasn't until the year of 1870 that an Electric car of real potential came into being [3]. By the year of 1900, after the first Electric car came into existence, these electric vehicles were gaining strong popularity amongst the urban users. They appreciated for its simplicity and the dearth of the black smoke pollution that was present in vehicles at that time. These Electric vehicles took the US roads by storm covering one third of its traffic in their first decade. However, by this time, the first gas-electric hybrid car was invented; none other than by the great Ferdinand Porsche. This vehicle came to be known as the Lohner-Porsche Mixte [4].

In the year of 1912 Henry Ford then brought about the internal combustion engine's revolution [5]. It was both affordable and a reliable car for the masses as it outperformed these early electric vehicles both in terms of range and speed. As the market spiked, the age of the internal combustion engine was truly underway and we were entering the fossil fuel era for powering automobiles.

By the year of 1935, Electric Vehicles which were on the road were completely gone. However, during the second half of the 20th century, as the price of fuel was escalating interest into electric vehicles was emerging yet again [5]. The 1990's was the time where the potential for electric vehicles was re-investigated. It was at this time, that research restarted at a rapid pace and automobile manufacturers took notice. The ionic vehicles General Motors EV1 and the Toyota Prius came into the market with an electrically powered infrastructure, where the former was fully electric while the latter being a full hybrid electric vehicle. The general motors EV1 had failed to secure profits using the nickel metal hydride batteries for powering their vehicles and so by 1999 they shut down its assembly line, however, it had made remarkable strides into automobile engineering, and were they to use the Lithium ion batteries as opposed to the nickel metal hydride batteries, even today these vehicles would have, quite arguably, been the best in the market and all around. Unfortunately, battery technology as innovated by the remarkable Tesla Motors was not around at the time. Nevertheless, the world has learnt a great deal from GM and they are worthy of praise for such an attempt into automobile engineering. Toyota, on the other hand, perhaps understood that we were not ready (back in the 1990's) for fully electric vehicles, maybe taking note from GM's EV1, and ought for a different method of approaching the problem of power. They took the approach of the hybrid electric model, where both the IC engine would be there alongside an alternative electric battery and they were incredibly successful with that idea. Its production line, for instance, has been open from 1997 up to present day.

The IC engine was a brilliant discovery or invention by Henry Ford and without this kind of engine we would have a far less reliable means of transportation were we to rely on the early day Electric Vehicles to slowly advance into today's time. The Electric Vehicle of today will be so much more empowering in comparison to the early day's ones due to the sheer amount of technology that has been innovated over the last century. These electric vehicles can have all of that integrated into one complete package. Satellite communication, internet, self-driven vehicles, vehicles communicating with one another; the potential for enhancement into the vehicles of today seem to be limitless, where on the early electric vehicles, range and speed was of prime concern and limiting. At the time, before both World War I and World War II, it was indeed both unforeseeable and unpredictable for Henry Ford to see a future dominated by IC engine vehicles in such a sheer number that the fossil fuels powering these vehicles would itself diminish. We are however at that day and age where these fossil fuels will inevitably fade and vanish, and so, a sustainable solution must be brought about. In order to take a step forward, it is often necessary to look backwards rather than wildly innovate something radically different than what the natural convention is, and history has, more than once shown us the next steps and prescribed potential courses of actions into the future.

1.3 Motivation

As mentioned previously in 1.1, the advantages Electric Vehicles can deliver are immense. EVs for, for instance, will require only a power outlet to fully charge batteries. As such, gas stations would be rendered to be inessential, and no gasoline also means no harmful air pollutants being released – an environmental solution. This also minimizes the cost of operating these vehicles making it economically viable too. Electric motors, furthermore, require only one gear for all speeds and they can indeed be powerful through proper designing. EVs approximately produce 40 percent less CO_2 and O_3 than conventional vehicles, even after considering and factoring in the CO_2 and other harmful pollutants released into the atmosphere by the power plants necessary to deliver the electricity needed to power up these vehicles.

The main and most pressing issue with regards to the feasibility of EVs are primarily their high costs and sub-par battery economy. Tesla Motors have made tremendous strides in this respect and hopes to make a difference. Their innovation has made batteries, in the recent year, to not only be cheaper, but also to recharge more quickly, and it's with these low costs they hope to achieve more than their competitors' in the race to the next generation of transportation which is that of Electric Vehicles.

As for the race to Electric Vehicles, several of the leading automobile manufacturers had chosen larger battery cells as fewer of them would be necessary, as well as reducing its complexity and cost, however, Tesla Motors have, unconventionally, chosen the very popular Li-ion batteries as their base of battery development. The formers’ packs did contain more energy overall, but they posed to be more lethal and dangerous as well while having a lower energy density. As a result, less energy dense battery materials – materials which are more resistant to fire could be used (as done by Tesla Motors). In order to offset lower energy density, automakers chose flat cells as they can be packed together densely, however, cells such as these eventually did end up costing more to manufacture [6].

Tesla, upon choosing smaller cylindrical cells, did save more on the cost of manufacture as a result as opposed to other automakers. This is because, for the laptop industry, the costs of these cells had been already driven down. Even more so, Tesla was able to use the most energy-dense materials for batteries which were available. The reason for this is simple. Smaller cells are less dangerous. High energy dense batteries also do drive down material costs. What Tesla did is, they wired together thousands of separate cells instead of wiring hundreds of larger ones. JB Straubel, CTO (Chief Technical Officer) had also invented a kind of liquid cooling system which is able to snake its way in between cells, thereby removing heat quickly enough so that the heat produced by one cell cannot interfere with the others.

Smaller cylindrical cells also granted Tesla the flexibility of packaging cells. In the case of a collision also, the large, flat cells could deform and thus result in a fire. This means that the battery must be kept out of harm’s way, even in the event of a collision. The only other place possible to reduce such a kind of casualty is the passenger or cargo space. Tesla, however, says that their EVs have passed crash tests with flying colors, that is without their cells deforming, or their coolants leaking. This kind of engineering is remarkable on Tesla’s end and worthy of applaud [6].

The motivation and purpose of ours and this thesis stands to be learning the technology behind Tesla’s battery pack and gaining insight into great engineering, as well as to get a better picture and understanding of the automobile industry. Our motivation is to inform more people on how Electric Vehicles as a whole function, so that even after fossil fuels will have depleted, transportation is not only sustained, but made even better, safer and cleaner making life easier for everybody.

1.4 Problems with the traditional IC vehicles

The problems with the traditional IC vehicles are innumerous. For instance, they run primarily on fossil fuels. These fossil fuels, on the other hand, have accumulated over the course of millions of years but today we are closer than we ever were in any point of history to its depletion. Every day we are creeping more and more close to the time where fossil fuels will no longer be. It has been estimated that fossil fuels will run out by the year 2051, about thirty years from now. Transportation, however, has existed from the beginning of time, from the invention of the wheel to horse carriages to automated vehicles using petrol, and everything in between. Transportation has been there well without the need of burning fossil fuels for several millennia throughout history and it has been constantly evolving. Vehicles at present must be manufactured and technology improved substantially so that the reliance on fossil fuels decrease over time and eventually, and ideally, stop entirely. The answer to this is renewable energy and harnessing the power of nature to power our modes of daily transportation. This is why Electric Vehicles seem to be a prominent answer. As for IC engines the problems include increased noise pollution, ejection of harmful pollutants into the atmosphere from the burning of fossil fuels, requiring large scale gas stations overall, higher maintenance costs for both daily usage and the long-term; they include many more. Most of these situations can be, at the very least, reduced substantially by using the more efficient and cleaner Electric Vehicles.

1.5 Thesis Overview

This thesis looks into the operation of Electric Vehicles and presents its working and principles in a way that can be comprehended by everybody. Electric Vehicles, namely battery-electric vehicles using lithium-ion battery modules and packs are well on their way to dominate the streets outside in the very near future. Here we look into the principles by which these lithium ion batteries work as well as the motor/controller of the Electric Vehicles. The automotive industry changes rapidly, and today and with every passing day, the changes made to these automotive vehicles is on the exponential rise. It is therefore imperative that we all know how these vehicles function and the principles under which they operate.

1.6 Summary of the Following Chapters

The next chapter, Chapter 2, looks into some model specific parameters of present day Electric Vehicle models. Chapter 3 then gives an overview of how Electric Vehicles are constructed and the main principles upon which they function. Chapter 4 and chapter 5 then go into more details, outlining two of the most important components of these vehicles; namely, how the popular Li-ion batteries are constructed and how the motor/controller of Electric Vehicles function. Chapter 6 then discusses all the dynamics of Electric Vehicles; the forces acting upon them and how they are overcome. Upon understanding all the theory presented in Chapters 3, 4, 5 and 6; Chapter 7 then delves into the results of simulations of each component part using the two software: MATLAB Simulink and ADVISOR (Advanced Vehicle Simulator). Chapter 8 then concludes our thesis.

Chapter 2

Selected Existing Models of Pure Electric Vehicles

With the advancement of time every major car manufacturing company have shifted towards the production of Electric Vehicles in mass level. The increasing demand and the immense positive response from the buyers have led the companies bring changes to the car models and they have always put their effort in enhancing the performance of the vehicles and overcome the drawbacks to offer a better experience to the customers. Moreover, the companies being liable to the nature are inclining towards electric vehicle production to contribute to the environment with least amount of toxic emissions. We have discussed few of the Electric car models which are presently in production.

2.1 Nissan Leaf

Fig. 2.1 Nissan Leaf [7]

The Nissan Leaf is an Electric Vehicle which has scored the record sales across all pure electric vehicles up to present day. With slightly over seven years, the Nissan Leaf reached 300,000 in global sales. Its sales started from 2011 and being a first generation pure electric vehicle truly makes this feat remarkable.

The Nissan leaf is priced at $29,990 as of 2018. This 2018 model is more refined over its earlier day versions. It houses a greater power, battery range while also improving aesthetically by looking better both inside and outside as compared to the original model of the Nissan Leaf.

The full specifications that the redesigned 2018 Nissan LEAF uses are:

- A higher capacity 40-kWh Li-ion battery which delivers a 40 percent increase in range and is now improved to 150 miles compared to the previous model
- A 37 percent increase in horsepower and 26 percent more torque which gives up to 147 hp and 236 ft-lbs respectively, allowing for a stronger acceleration from the all-new e-powertrain
- Standard 6.6-kW onboard charger
- Level 1/Level 2 charge cable (standard on SL, available on S, SV)
- More confident and secure handling
- Standard Automatic Emergency Braking (AEB), available Automatic Emergency Braking with Pedestrian Detection
- Available Nissan ConnectSM with Navigation featuring Apple CarPlay™ and Android Auto™
- Enhanced Nissan Connect EV telematics
- All-new exterior and interior styling [8]

It also has the ProPILOT Assist which is a single-lane “hands-on” driving assistance technology. After being activated, the car can automatically maintain distance with the vehicle which is in front of it. This is done using a speed and distance preset by the driver. In addition to that, it can also provide steering assistance in order to assist the vehicle and keeping the vehicle centered in its lane. For instance, if the car in front stops, the ProPILOT Assist system can automatically apply the brakes to help bring the vehicle to a full stop if necessary [8].

2.2 Tesla Model S

Fig. 2.2 Tesla Model S [9]

The Tesla Model S is the first fully electric sedan type vehicle [10], it has a unique combination of performance, safety and efficiency to make it stand apart from its competitors. This model is currently acquiring the highest safety ratings and has also the crown of the longest range of the electric vehicles presently in production [10].

This model among the other production EVs has two motors both in the rear and the front wheel which independently controls the torque and for this reason gives a better traction than all the conventional vehicles where a tradeoff is made between the fuel efficiency and enhanced traction [10].

2.2.1 Design

In the Tesla Model S which was first produced in the year of 2012 has a three phase, four pole AC induction motor, which provided the vehicle with 460hp or about 310kw of power [11]. The model also has a 601 Nm motor which is present in the rear side of the vehicle and has a copper rotor [11]. At the time of release of the Tesla Model has it had a feature which was second to none of having a drag coefficient C_d which is 0.24 and was lowest than any other production cars of its time [12]. Having a very low drag coefficient the vehicle always had an upper hand over its own type competitors and the conventional vehicles as well. The P85D model variant of the tesla model S having dual motors onboard produces an acceleration of 0-97 km/h in only 3.2 seconds [13].

2.2.2 Battery

The battery of the Tesla Model S is claimed to have the energy density as much as twice of its close competitor the Nissan Leaf, however in terms of the driving range it outruns the Nissan Leaf in numbers, the driving range of Tesla Model S is said to be more than twice of that of Nissan Leaf [14], the driving range value typically depends on many factors such as drag coefficient, motor efficiency, rolling resistance and also the weight of the vehicle. The P85D version of the Tesla S model which has 85kwh battery weighing about 540kg contains 7104 lithium ion battery cells which are spread into 16 modules and they are wired in series [15]. In each of the module there are about 6 group which contains 74 cells and they are wired in parallel, they are then connected in series in between them [16]. The battery pack performance is backed up by a guarantee of eight years and also of unlimited mileage [17], [18]. The Tesla Model S has an inbuilt heating or also can be said cooling circuit to keep the temperature of the motor, the controller and also the battery in their optimum temperature rating [19]. The heat dissipated from the motor or rather known as the waste heat is used to keep the battery warm in cold conditions as it does not reach its optimum working capacity until a certain temperature [20].

2.2.3 Drawbacks

As it may seem that the Tesla Model S is the best car in production, it also has few drawbacks. In the older version a complaint has raised that the power dissipates, roughly about 4.5kwh was drained overnight and caused a problem for the users [21]. There have also been complaints about consumption of more power per km than the expected power consumption in few of the variants of the model [22].

2.3 Chevrolet Volt

Fig. 2.3 Chevrolet Volt [23]

The Chevrolet Volt is a purely electric vehicle until a certain value of the battery, the battery value is determined to a threshold, whenever the battery power drops from fully charged to that predetermined value it turns on the internal combustion engine and the vehicle traverses.

2.3.1 Drivetrain

The Chevrolet Volt has a primary motor or generator which provides a fair amount of acceleration at lower ranges and also helps in energy production from the regenerative breaking. This provides a maximum output of about 111kw [24]. There is also a secondary motor which mainly acts as a generator and helps produce about 55kw of energy, on the other hand there is an internal combustion engine present which gives about 63kw power when the battery reaches a certain predetermined value [24].

2.3.2 Battery

The battery of Chevrolet Volt weighs about 197kg, there are about 288 lithium ion cells arranged in nine modules. For the battery pack to stay cool, there is a separate cooling system which works independently for the battery pack [24], [25].

2.3.3 Performance

The Chevrolet Volt reportedly has a top speed of 160km/h [26]. On various road tests it has appeared that the Volt reaches 0-97km/h acceleration within 9.2 seconds, however it takes 9 seconds to reach the same acceleration value if the motor is supplied help from the internal combustion unit during propulsion [27].

2.3.4 Drawbacks

The major drawback of the Chevrolet Volt may be the driving range on its all electric mode, it is known to travel about 40-80km once fully charged, however this range is also dependent to some extent on the driving technique, driving terrain and also the temperature at which the vehicle is operating [26], [28].

2.4 BMW i3

Fig. 2.4 BMW i3 2018 [29]

This vehicle is special in the pursuit of EVs in the sense that it’s a major automotive brand, well established and well trusted, who have started developing EVs in the year 2013 while its sales commenced in 2014.

The BMW i3 is powered by a 33 kWh lithium-ion battery pack mounted under the passenger compartment with a 170-horsepower, 184-lb-ft of torque synchronous electric motor [30]. The power is sent to the rear wheels via a single-speed transmission, enabling the i3 to sprint from zero to 60 mph in 7.2 seconds. Top speed is reached at 93 mph [30].

The i3 doesn't have to be fully electric: An optional 650cc, 34-horsepower two-cylinder gasoline-burning range extender works like a generator to provide the battery with additional charge [31]. The range extender only kicks in when truly needed and it does not send power directly to the i3's drive wheels [31].

Without the range extender, The BMW i3 is a premium EV best suited to urban motoring due to its 97-mile range. An optional range extender can be attached which is a 650cc, 34-horsepower two-cylinder gasoline-burning range extender, which works like a generator to provide the battery with additional charge. The range extender only kicks in when truly needed and it does not send power directly to the i3's drive wheels. With the range extender, i3 drivers can expect something closer to 180 miles. A full charge is available in four and a half hours when the car is plugged into a home charger [30].

The BMW i3 weighs in around 2961 lbs or 1343 kg. As for the Propulsion of the BMW i3, its engine and fuel type is Electric with a power delivery of 170 hp at 4800 rpm. The torque it delivers is 184 lb-ft (250 Nm) and it gets this power from a rear wheel drive system. The Transmission of this vehicle is 1-Speed and automatic as it usually is for EVs. This vehicle is priced at $44,450 [31].

Several noted likes for this vehicle from buyers include it having:

- Smooth acceleration
- Agile urban handling

- Simple, elegant interior
- One-pedal driving
- Range extender option [32]

While some DISLIKES mentioned is:

- It lacks BMW's traditional dynamism
- The rear seat is compromised and
- The range pales compared to newest rivals [32]

Table. 2.1 Monthly Sales of BMW i3 in USA [33]

Month	2014	2015	2016	2017	2018
January		670	182	382	382
February		1089	248	318	623
March		922	332	703	992
April		406	814	516	503
May	336	818	696	506	424
June	358	551	608	567	
July	363	935	1479	601	
August	1025	792	1013	504	
September	1022	1710	391	538	
October	1159	986	442	686	
November	816	723	629	283	
December	1013	1422	791	672	

Table. 2. 2 Monthly Sales of BMW i3 in Europe [34]

Month	2014	2015	2016	2017	2018
January	476	649	939	1858	1865
February	710	683	814	1523	1626
March	1135	1154	1149	2014	2278
April	922	810	903	1574	1892
May	709	838	648	1676	
June	769	789	606	1746	
July	793	746	588	1404	
August	673	1094	1352	1129	
September	706	1025	2348	2198	
October	662	1043	1770	1789	
November	682	1383	2075	2109	
December	811	1637	1807	1990	

Chapter 3
Construction of Electric Vehicles

3.1 Basic Insight

An Electric Vehicle (EV) can be constructed and differentiated from conventional vehicles by the help of three main electrical components, while most other components, such as the tires, windshields, aluminium body framework, tail-lights seats etc. are similar to those of traditional vehicles. The key difference of these other components is that they ought to be made lighter yet stronger to allow for higher speeds and accelerations.

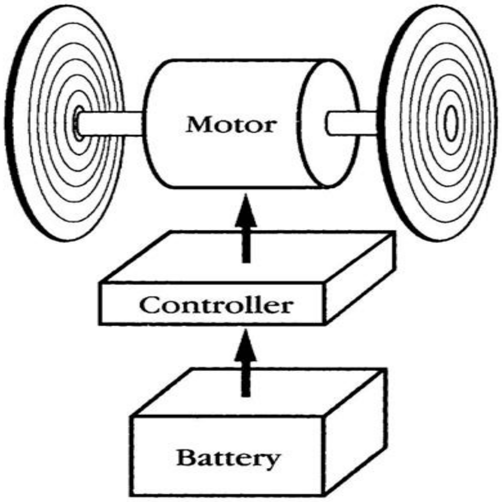


Fig. 3.1 Simplified Block diagram of Electric car [35]

The three components which when working together in tandem, allows for movement and differentiates it from conventional vehicles are:

i) The Electric Motor which converts Electrical Energy to Mechanical Energy thereby providing the thrust required to make the car move forward as locomotion.
ii) The Controller Unit which converts DC electricity to AC electricity. This unit also partakes in taking power from the battery and delivering it to the motor and
iii) The Battery which acts as a reserve for power instead of a gasoline fuel tank.

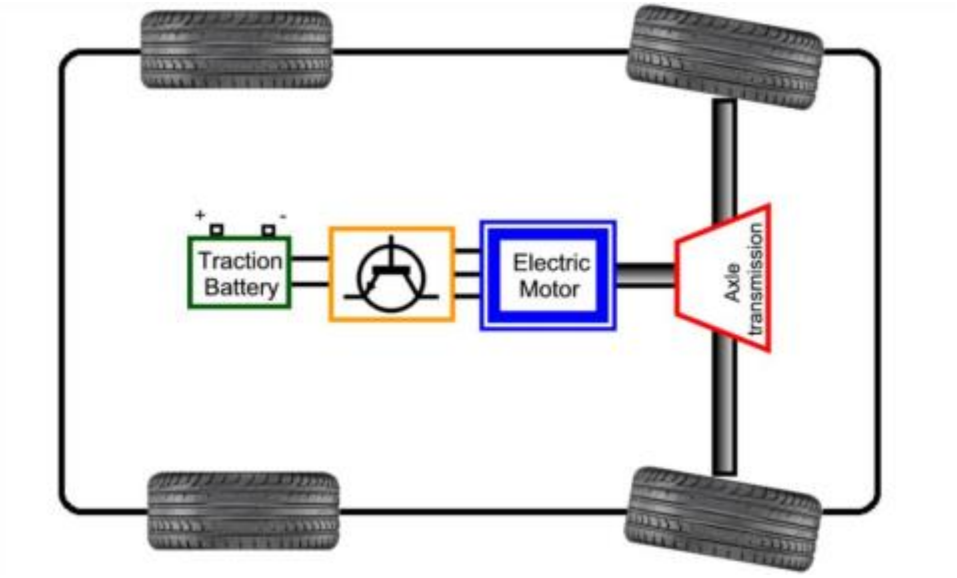


Fig. 3.2 Electric Vehicle Drive Train [35]

Upon pressing the accelerator and by responding to the force being applied on the pedal, the control unit, acting like a brain, takes the required power from the battery and delivers it to the electric motor which then changes the necessary electrical energy into mechanical energy.

From here, we can pose to ask several questions:

- How efficient is this transfer process-The process of converting Electrical Energy from the battery to the Mechanical Energy as output from the motor or IC engine to the overall vehicle.

- What is the actual capacity of the battery being used as the reservoir for power?

- What is the driving range, that is, how far in km, can this EV travel without depleting the battery being used and finally

- How fast is it?

3.2 Types of Vehicles

It is important to note that there are 3 main types of EVs:

- Hybrid Electric Vehicles (HEVs): These Vehicles are using both petrol and electricity as sources of energy coupled with regenerative braking technology, which changes kinetic energy and heat from the wheels while in motion into electricity to be re-used from the battery it holds once again. These hold both a fuel tank as well as a battery as a reservoir for electrical power.

- Plug-in Hybrid Electric Vehicles (PHEVs): These vehicles can be charged with an external charging port to power up the batteries they hold, and also, they have a fuel tank. The two different ways of powering the vehicle, either through the fuel tank, or the battery, can be separated or used independently.

- And Battery Electric Vehicles (BEVs): The final form of the Electric Vehicle is the BEV, which works only exclusively through a battery as the primary and only method of powering up the vehicle. These vehicles are powered up by only an external plug outlet.

3.3 Problems Faced by EVs

In this paper, we will have strict focus on BEVs its functioning as well as how to improve them overall. The problem which needs special care and attention to detail is the overall driving range of EVs which is quite low when compared to regular or traditional vehicles, that is, on one full charge how far the car can travel. In order to resolve this, issue the battery must be improved significantly. Another problem which needs to be addressed is how long the battery takes to get to full charge. Improvement and adjustments to charging stations as well as improvements made to the battery can ameliorate this difficulty.

In order to investigate, we shall be using ADVISOR a MATLAB Simulink Toolbox which allows for an effective analysis on the energy consumption of Electric Vehicles and look at the analysis results that it has to offer. The comparison between select parameters of BEVs, traditional IC vehicles will be of prime focus here.

With the advancement of electric vehicles there has been a few problems arising which have created certain hindrances towards the users. The most avid problem which we can locate in the present times is the driving range of electric vehicles as well as the quick drainage of the battery; people are working hard to find a durable solution to this problem. The use of optimal control to optimize the driving range and average speed can be noteworthy. It helps reducing the operational costs of building cars and also helps to increase the electric vehicle’s range and speed. In recent times people dread they would be stranded in the middle of nowhere with absolutely drained battery. This fear needs to be alleviated and the optimal control application makes it easy to increase the driving range.

Furthermore, we can also focus on the use of single speed gearbox, but this lets the onboard battery to drain very fast. We can always increase the driving range of an electric vehicle with enhanced battery capacities; however, it would deteriorate the already existing problem of excess weight of the vehicle. There has been extensive work done to use the energy efficiently at different gear ratios, the use to a multi speed gear box may play a helpful role to the use of energy, the energy is lost by a great amount when the motor works in non-optimal speed, thus we have to put less pressure on the on-board battery pack, and make efficient use to it to increase the driving range of the vehicle. The use of two speed gear box instead of single speed gear shows a mentionable difference in the battery life. However, charging and discharging electric vehicles still remains a problem for the users, the introduction and widespread use of fast charging is really important to make this user friendly and convenient. The use of various level of chargers have been seen in the recent times, but we have to find a solution to replenish the drained battery in the shortest time possible, without compromising the driving range.

Chapter 4
The Lithium-Ion Battery

4.1 Introduction

Understanding the principles of the modern day lithium-ion battery is quintessential as it helps to power so many of our everyday devices. This ranges from our smartphones, to our laptops, to UPSs (Uninterrupted Power Supplies) and so many more. As of recently, Tesla Motors are now even using these lithium-ion batteries as a base from which power is drawn to propel its vehicles forward utilizing its high-energy density and electrochemical properties while all the same being lightweight and safe. This is indeed worthy of praise and very soon the other automobile industries shall be following suit, and we, the consumers shall begin to see these batteries powering our cars as well in the very near future. This makes it all the more important to understand the properties of Li-ion batteries, how they are made, and the way they function. In doing so, the mystery behind the power-generating aspect of electric vehicles can be realized. This chapter focusses solely and looks into lithium-ion batteries, its properties and its way of functioning, in theory and in details.

4.2 Classification of batteries

There are two kinds of batteries, primary batteries and secondary batteries. Primary batteries are those which we use in remotes and clocks. These are alkaline cells which are made from Zinc and Manganese Dioxide once they have depleted, they can no longer be used [36]. The other type of battery is the secondary batteries which are rechargeable. These lithium-ion batteries are classified as these secondary batteries. In secondary batteries, the electrochemical reaction is reversible and the original chemical compounds can be reconstituted by the application of an electrical potential between the electrodes injecting energy into the cell. Such cells can be discharged and recharged many times.

Fig. 4.1 Lithium-Ion Battery [37]

A lithium-ion battery is constructed by two or more electrochemical cells which are electrically interconnected where each of which contains two electrodes and an electrolyte in between. There is a redox (oxidation-reduction) reaction that occurs simultaneously at these electrodes and thereby is able to convert electrochemical energy into electrical energy [38].

In everyday usage, a “battery” is also used to refer to a single cell. These batteries contain mostly liquid electrolytes but at present solid electrolytes are being thought of being constructed as a means of improvement to the existing model. The electrolytes in the middle are what helps the conduction of ions from one electrode to other electrode, cathode to anode and anode to cathode.

The reason that Lithium is used in electrochemical cells is that it is the lightest of metals and it has a density of 0.534 g/cm^3 and this is less than that of water which has a density of about 1 g/cm^3. Due to this property it can even float on water.

The electrochemical properties of lithium are also excellent as it is highly reactive due to having only 2 shells with a total of 3 electrons. This allows for vigorous reactions to take place. Relating these properties to electric vehicles, we can see that these can give lithium the potential to achieve very high energy and power densities in high-density battery applications for automotive forces propelling the car forward when the user wishes to drive forward.

Lithium batteries, as opposed to Lithium-ion batteries are primary batteries, and here, the lithium metal or the lithium compound used acts as an anode. These batteries are not rechargeable and cannot be reused once its electrochemical potential has been depleted. A typical lithium cell can produce voltages from 1.5 V to about 3 V based on the types of materials used. Common applications of lithium batteries are Pacemakers, Digital Cameras, watches etc. They are used when a long battery life is desired and are used less than alkaline batteries as they can be more expensive [39].

In Lithium-ion batteries a pure lithium metallic element is used as the cathode. These batteries are rechargeable batteries and due to reversible reactions its electrochemical properties can be restored. Due to its rechargeable properties, lithium-ion batteries are considered to be better than pure lithium based batteries as they can serve our purpose to provide power to vehicles over a longer span of time.

4.3 Construction of Lithium-ion Battery

4.3.1 The cathode and the anode

Li-ion batteries are secondary cells connected in series and these consist of a positive cathode and a negative anode. These are the plus and minus terminals on a battery, respectively, during the discharging phase of the cell, that is, when power is drawn from the cell to use a device or appliance and in our case powering electric vehicles. When the battery discharges, for instance, the conventional current which flows out is from the flat end *into* the small circular end, that is, the flat end serves as the positive cathode and the small circular end serves as the negative anode. While the battery charges, however, these roles reverse. The positive terminal, small circular end then becomes the cathode while the negative terminal, the flat end, is the anode. The reason for this is that the flow of the conventional current is considered. In the charging phase the positive conventional current flows from the small circular end to the flat end, where they are serving as the cathode and anode respectively. This is why the terminology of the cathode and anode changes. The roles have, in effect, reversed. As the terms such as cathode and anode can be misleading or confusing in the case for rechargeable batteries, the terminals from here on shall be referred to as the positive and negative terminals. The positive terminal is the circular connector end while the negative terminal is the flat end at the bottom.

4.3.2 Materials used for construction

The positive terminal of regular Lithium-ion batteries is made from Lithium cobalt oxide (LiCoO2) while the negative terminal is made from Carbon or Graphite, an allotrope of carbon [40]. Lithium iron phosphate (LiFePO4), Lithium manganese-oxide (LiMn**2**O**4**), Lithium nickel-oxide (LiNiO**2**) has also been used in the construction of lithium-ion batteries [38]. The reason that these particular types of materials and compounds are used is that they are lithium liberating compounds and being made from electro-active oxide materials also helps in oxidation (loss of electrons) and reduction (gain of electrons). In between the two terminals lies the electrolyte and separator which is comprised of a lithium salt in an organic solution. The lithium salt most commonly used is Lithium hexafluorophosphate (LiPF6) and the organic solution assists this substance to be dissolved completely over a wide range of temperatures [38]. For the proper functioning of the battery or cell, it is necessary that this electrolyte acts as an insulator between the two terminals while being in a liquid state.

4.3.3 The charging and discharging Phases

During the charging phase of the battery, the lithium ions from the positive terminal (the terminal being made from LiFePO4 as an example) move *across* the electrolyte (LiPF6 as an example) from the small circular end to the flat end (graphite or carbon). In doing so, the electrons are compelled to move through an external circuit towards the negative terminal, the reason being; these electrons cannot cross this insulating barrier layer as the ions could when an external voltage is applied. Instead these electrons flow towards the negative terminal due to the difference in potential between the terminals [39]. As the Lithium ions moves through the cell from the positive terminal to the negative terminal, the negative terminal consists of Li+ ions. When the electrons then reach these Li+ ions, they recombine and form the metal lithium. Due to the insulating material that is, the electrolyte in the middle which acts as a separator (LiPF6 dissolved in the organic solvent), the electrons are prevented from this happening directly [39]. As such, it will take the longer route for this to happen, the path with least resistance, that is, the external circuit. As a result of charging, lithium atoms are formed at the negative terminal and they remain there until discharged.

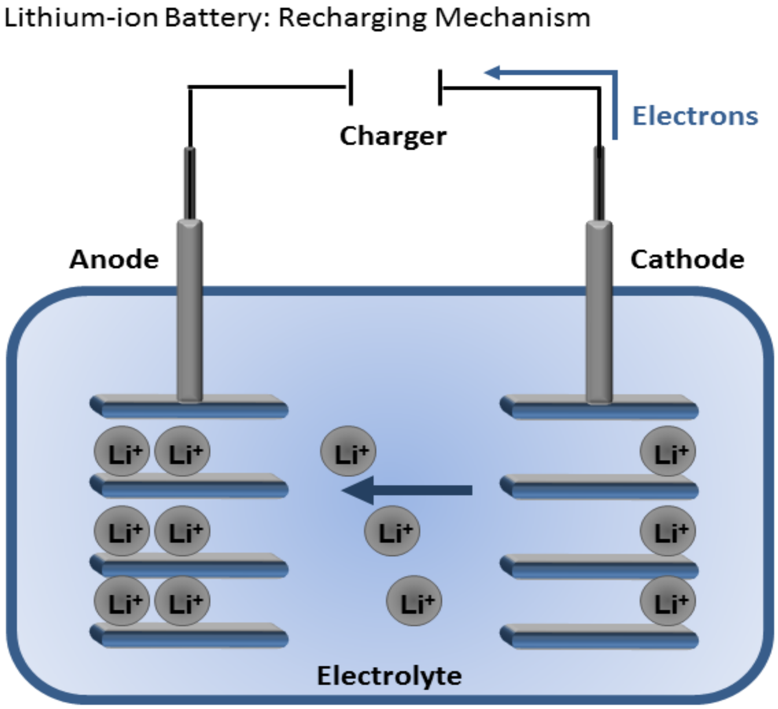


Fig. 4.2 Lithium-Ion Charging Process [40]

It is to be noted that, the cathode here is represented by the flat end of the battery, the negative end, and the anode here is the small circular connector end, the positive end.

When Li-ion batteries are discharged we use their energy to power up electronic devices, or in our case vehicles. For this to happen, the opposite of charging takes place. The stored lithium in the negative terminal then moves across the electrolyte over to the positive terminal. Again the electrons would now be compelled to move through an external circuit over to the positive terminal for recombination into lithium atoms. While these electrons now move through the external circuit, we have our electronic device over there. As these electrons move through our device, our device gets the necessary current to be powered up for utilization.

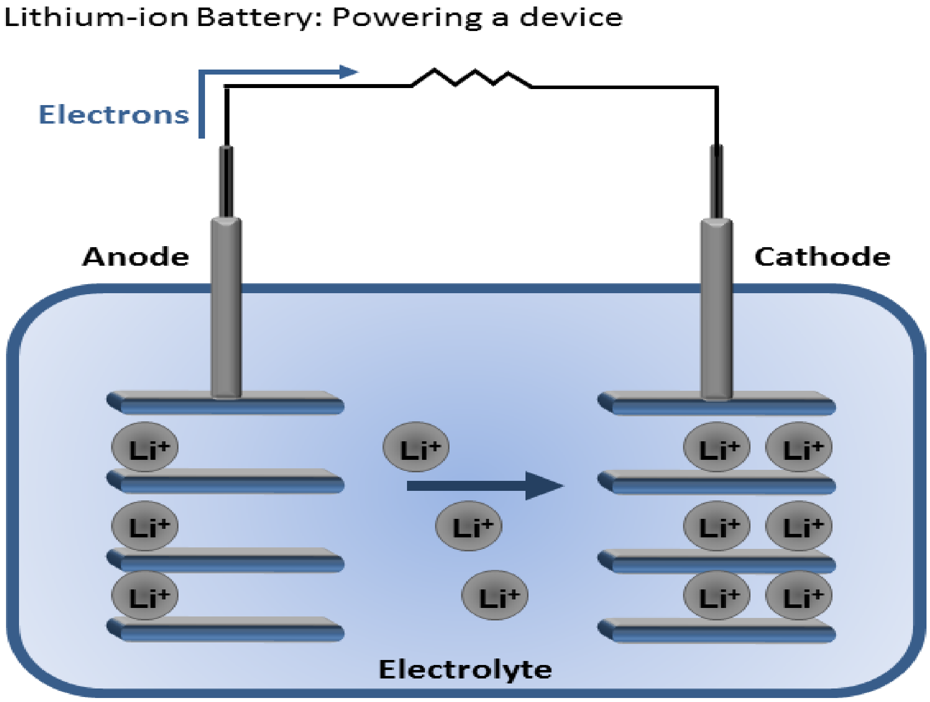


Fig. 4.3 Discharging Lithium-Ion batteries [41]

It is to be noted that, the cathode here is represented by the flat end of the battery, the negative end, and the anode here is the small circular connector end, the positive end.

In this way, Li-ion batteries can be charged and discharged for hundreds of cycles if not more. It is very important, however, that the battery not be discharged completely. If a complete discharge occurs, that is, when all the lithium of the battery gets to the positive terminal, the battery would be rendered unusable. It is for this reason controllers of some sort exists within the device that the lithium ion battery is used. It controls both the charging and the discharging cycles for optimizing the lifetime and capacity of these batteries even though this does make using these lithium ion batteries more expensive than they are already. The volts and current that these batteries can provide is also limited by manufacturers because Lithium itself is very reactive and unless its power is limited, and even after doing so, in rare cases explosions can occur [42].

It is also important to note that even upon being charged fully, Lithium ion batteries self-discharge, however, this is at a very slow rate as opposed to being used by a device. The capacity of a Li-ion battery also decreases over the span of years. This is true for all kinds of batteries, however, the rate at which the capacity of Li-ion batteries decrease is quite low in comparison [42].

4.4 Using Lithium-ion Batteries in Electric Vehicles

As a reference EV, the Tesla Model S uses these Lithium ion batteries exclusively and without the need for any IC engine unit. This vehicle is a fine example of a pure battery electric vehicle. In the Tesla Model S developed by Tesla Motors, they use 16 modules of batteries. Each of these 16 modules uses 7,104 individual cells and these modules are connected to one another in series. The cells contained within each of these modules are connected in parallel. As a result of this, the battery used to power the Tesla Model S can give a total of 85kWhs. The cells that this battery uses are the Panasonic 18650anca cells and the overall weight of the whole battery becomes 1200lbs or 540kgs [43]. This is a very high weight and improvements made to the battery pack, by reducing the weight without sacrificing power is vital and key to improving the performance of Electric Vehicles. This is because a higher weight hinders top speed and acceleration as acceleration is inversely proportional to the mass. Each module of the battery weighs approximately 33.75kgs. The time required to charge the full battery is forty-eight hours given that the volts applied to it are 120V with a current of 15A. If, however, they were to be charged with 240V and 90A this charging time drops to four-hour duration. This can be well achieved if the vehicle were subjected to separate charging stations designed specifically for these BEVs.

The traditional gas stations and pumping stations could then be rendered obsolete just as oil is diminishing rapidly.

Fig. 4.4 Panasonic 18650anca [44]

For these Lithium ion batteries to function optimally, a core temperature must be maintained. For charging this is 0 to 45 degrees Celsius and for discharging it can be -20 degrees to 60 degrees Celsius [45]. Even at lower temperatures, lithium ion batteries outperform the lead acid batteries. In the Tesla Model S for the batteries' optimal temperature to be achieved, an external battery heater was used, however, in the newer Model 3 this temperature was received from the power train itself. What this means is that in the Model 3, even when the vehicle remains parked, the software used in the vehicle can send a request to the powertrain's inverter to power up and pass appropriate currents to the motor so that enough heat is generated to warm up the cells [46]. This eliminates the need for external battery heaters and allows for less weight to be taken up overall by the battery pack.

As for the Panasonic 18650anca, these Lithium ion batteries have high-capacities of 3.4 Ah and 4.0 Ah. These lithium-ion battery cells have an improved nickel-based positive electrode and are used in laptops as well with individual cell sizes being slightly larger than the standard AA battery [47].

The motors which are drawing power from these battery modules are 380hp for the 60kWh model of the Tesla S [11]. The P85D model variant of the tesla model S having dual motors onboard produces an acceleration of 0-97 km/h in only 3.2 seconds from an 85kWh battery [13].

4.5 Future Scope

The future scope of the Lithium ion batteries is immense. Intensive research is currently going on as the demand of rechargeable power is going up exponentially in the present years. As an example, research into solid state lithium ion batteries is under way which uses solid electrolytes. The charge time for these kinds of lithium ion batteries can be done usually in a matter of minutes [48]. The conventional Lithium ion batteries use a liquid electrolyte, but the problem with this is that they require quite large spaces between each cell (20-30 micron) separator per cell, while on the other hand, the solid state lithium ion battery requires just 3-4 micron for separators. Furthermore, the solid state lithium ion batteries can hold up to twice the charge of their liquid counterpart. Even more so, what could make them a quintessential part of electric vehicles in the near future is that they both weigh less and while being more durable, they are not prone to catch fire as their liquid electrolyte counterparts are. This gives them a very essential component in vehicle design as the batteries used in them must be made safe even in the face of a collision. These solid state lithium ion batteries are still well into the research and development phase, however, we can expect that over the years with much research undergone, they will be perfected for regular consumer usage due to the potential these kinds of batteries bring with them [49].

The problem that is being faced in terms of popularizing these solid state batteries into the market is that these batteries can only conduct well in room temperature, however, if we think in terms of driving or the electronics industry, the problem of heat quickly becomes apparent. Whether we drive a car or operate a laptop or a mobile phone, for short or extended durations, heat can disrupt theoretical approaches to problems. With an elevated temperature poor conductance is shown in the solid electrolyte, and trying to boost the ionic conductivity with an elevated temperature could significantly increase the expenses, at least if many cells are involved [49].

4.6 Conclusion

In conclusion, it is quite possible to use several thousand lithium ion cells connected in series, made into a powerful battery, to power up vehicles as opposed to a single large individual battery unit such as nickel metal hydride. With a higher specific energy of 140Wh/kg in lithium compared to a 34Wh/kg in lead acid and 68Wh/kg, lithium ion batteries reign supreme. Moreover, the ideal discharging percentage is very low compare to nickel metal hydride batteries which decay up to 5% a month while lithium ion batteries decay of around 2% of the total capacity in a year. The charging capacity is also very high in lithium ion batteries. To sum up, lithium ion batteries have great potential in terms of powering up vehicles in the future, and of course, other devices. The only drawback is it being relatively far more expensive than the alternate options, however, the future of these batteries seem to be more than promising and research into creating solid state lithium ion batteries could significantly offset the limitation of their being a high cost alternative to powering vehicles.

Chapter 5

Dynamics of the Electric Vehicle

Vehicle dynamics is closely related to the Newton's second law of motion. Whenever a force acts on a mass or a vehicle it accelerates to a certain direction. However, there are various types of forces that acts on a vehicle, only when the net or resultant force on the vehicle is greater than zero the vehicle accelerates. The necessary force required by an electric vehicle comes from the propulsion unit of the vehicle and the force is often known as tractive or traction force. This force has to be greater than the other resisting forces due to gravity air and tire resistance in order to accelerate the vehicle. For an electric vehicle to accelerate it depends on the following factors: [50]

1. The total power that is produced by the propulsion unit of the vehicle
2. The conditions of the road
3. The aerodynamic property of the vehicle
4. The compound mass of the vehicle

5.1 Movement of Vehicle

We can determine the motion of a vehicle if we analyze all the forces acting on it along the direction of the motion of the vehicle. The forces which act on a vehicle while it moves along a slope in depicted in the following picture

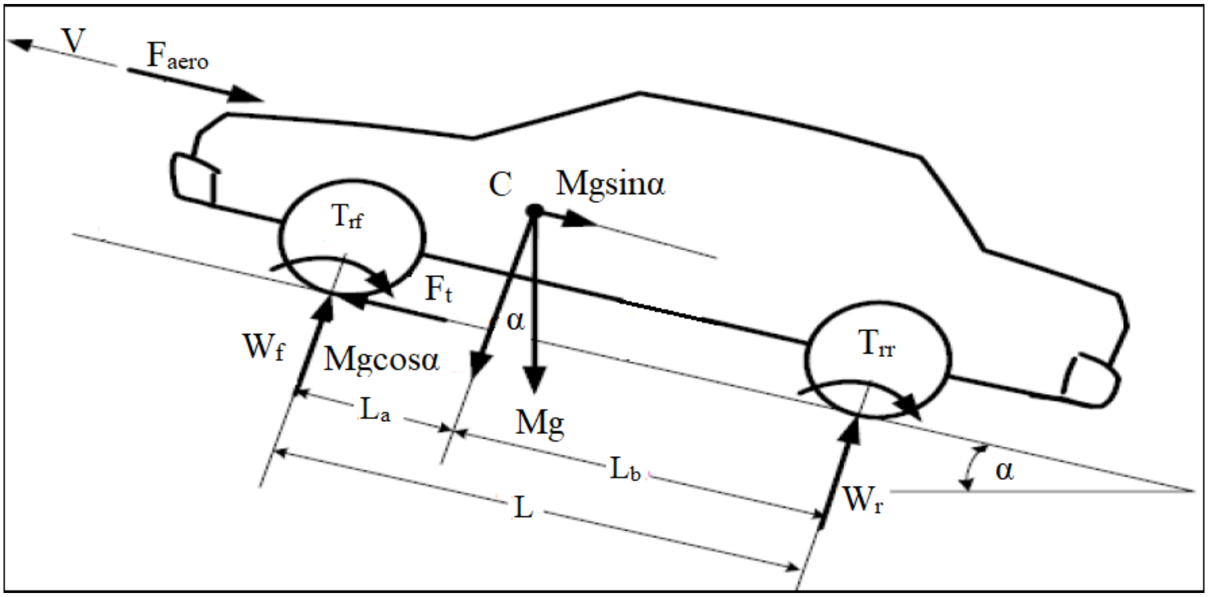


Fig. 5.1 Forces that are acting on a vehicle while going uphill [50]

The tractive force (F_t) which is acting between the tire and the road surface is the reason behind the propelling of the electric vehicle. The tractive force is produced in the propulsion unit and is transferred to wheels through the differentials. During its movement a vehicle faces a number of resistive forces which in turns slows down the vehicle [50]. The most prominent forces are

1. Rolling Resistance
2. Aerodynamic Drag
3. Uphill Resistance

We can express the acceleration of a vehicle from Newton's second law of motion as follows [50]:

$$\frac{dV}{dt} = \frac{\sum Ft - \sum Fresistance}{\delta M}$$

Here the terms are denoted as follows

V= speed of the vehicle

$\sum F_t$= total tractive force (Nm)

$\sum F_{resistance}$= total resistive force (Nm)

M = total mass of the vehicle (kg)

δ = Mass factor, due to the conversion of rotational inertias of the rotational components into the transnational mass

5.1.1 Rolling Resistance

The rolling resistance of a vehicle on road surface is mainly due to the hysteresis in the tire material, in the following figure we can see the force acting on a tire while the vehicle is at rest, while at rest a tire force P acts on the tire and this acts along the straight line downwards at the point of contact of the tire and the road surface. There is also a reaction force along the same very line named as P_z.

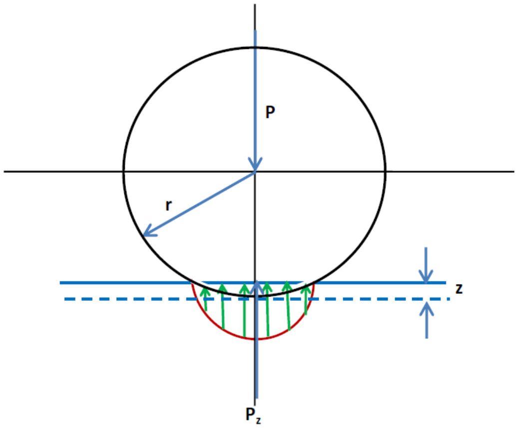


Fig. 5.2 Pressure distribution in the area of contact [50]

The deformation of the tire, z and the force acting on the tire, P has a relationship between them which is shown in the following figure,

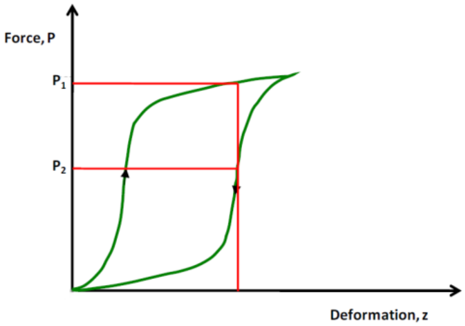


Fig. 5.3 Force acting on the tire v/s Deformation of the tire [50]

In this figure we can see that for the effect of hysteresis, the force, P for the exact same amount of deformation, z is higher during the loading process than the unloading process. Thus, we can say that due to hysteresis the ground reaction forces are distributed asymmetrically.

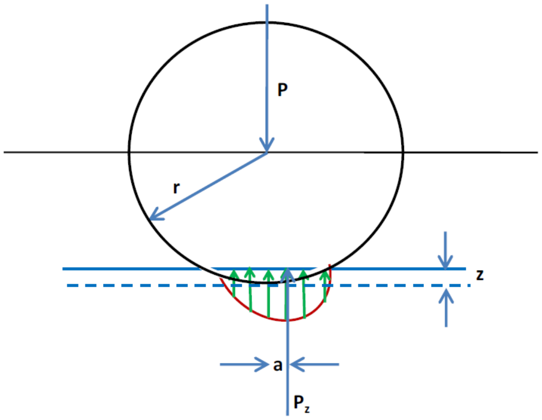


Fig. 5.4 Pressure acting on a rolling tire (Hard Surface) [50]

Here we will try to understand the effects on a rolling tire, while the tire is rolling the part of the tire which is leading is said to be the loading part of the tire and the trailing part is known as the unloading part of the tire. For this reason, a shift in the ground reaction force is noticed, this shift in the ground reaction force creates a moment that further opposes the rolling of the wheels. However, if the surface on which the vehicle travels is soft then the ground reaction force almost completely shifts to the leading part and in result increase the moment.

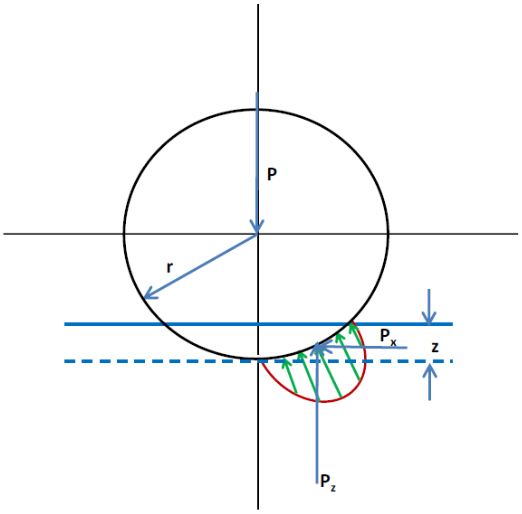


Fig. 5.5 Pressure acting on a rolling tire (Soft Surface) [50]

The moment which is produced when the resultant ground reaction force shifts forward is known as the rolling resistance moment and can be expressed mathematically as follows [50]:

$T_r = Pa = Mga$

Where,

T_r = the rolling resistance (Nm)

P = Normal load acting on the centre of the rolling wheel (N)

M = Mass of the vehicle (kg)

g = acceleration constant (m/s^2)

a = deformation of the tire (m)

To overcome the rolling resistance moment a force acting on the centre of the wheel is required which is denoted as F_{roll}, which is expressed as follows:

$F_{roll} = T_r / r_{dyn} = Pa/r_{dyn} = Pf_{roll}$

Here,

T_r = the rolling resistance (Nm)

P = Normal load acting on the centre of the rolling wheel (N)

r_{dyn} = dynamic radius of the tire (m)

f_{roll} = rolling resistance coefficient

The rolling resistance moment which is developed can easily be eliminated with the help of a horizontal force acting on the centre of the wheel which is in a direction opposite to the direction along which the wheel moves, this force is called the rolling resistance, the magnitude of this force can be calculated with the following formula [50],

$F_{roll} = Pf_{roll}$; Where,

P = Normal load acting on the centre of the rolling wheel (N)

f_{roll} = rolling resistance coefficient

When the vehicle is travelling in an inclined path the normal load, P has to be replaced by its component which is perpendicular to the road surface, thus the previous equation has to be written to new form as follows [50],

$F_{roll} = Pf_{roll}\cos(\alpha) = Mgf_{roll}\cos(\alpha)$

Where,

P = Normal load acting on the centre of the rolling wheel (N)

f_{roll} = rolling resistance coefficient

α = angle of the inclined road (radians)

The rolling resistance coefficient f_{roll} is calculated keeping the following things into consideration,

1. Material of the tire
2. Structure of the tire
3. Temperature of the tire
4. Pressure of the tire when inflated
5. Geometry of the tread
6. Roughness of the road
7. The material used in road production
8. Any type of liquid on the road surface

We can find typical values of the rolling resistance coefficients depending on the conditions of roads and vehicle types as follows,

Table. 5.1 Rolling resistance coefficients, f_{roll} [50]

Conditions considered	Rolling resistance coefficients(f_{roll})
Car tire moving on smooth tarmac road	0.01
Car tire moving on concrete road	0.011
Car tire when on a rolled graveled road	0.02
On unpaved road	0.05
Bad earth tracks	0.16
Loose sand	0.15-0.3

For calculating the rolling resistance coefficients of passenger cars often the following formula is used, which gives us accurate result up to the point when the vehicle speed is below 128 km/h

$$f_{roll} = 0.01(1+\frac{V}{160})$$

Where,

V= the speed of the vehicle (km/h)

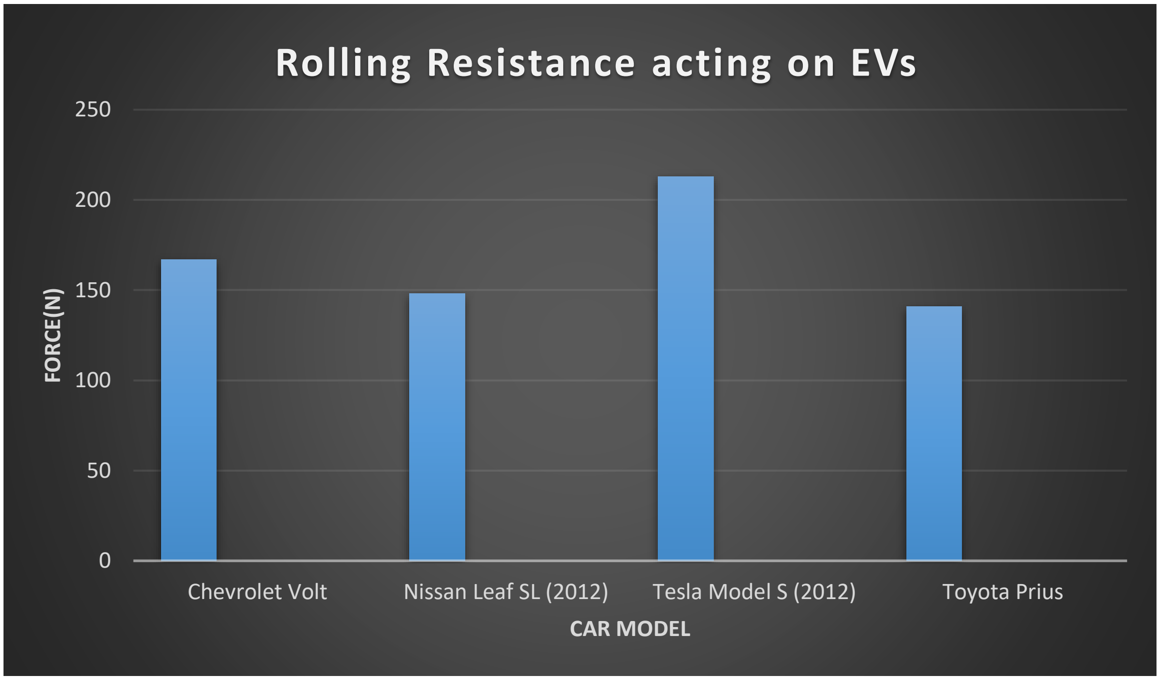
From the formula of the rolling resistance force we can easily see that the force is dependent on the mass of the vehicle to a great extent, the acceleration due to gravity, g is constant and the rolling resistance coefficient f_{roll} is also a negligible value, thus depending on the mass of the car the force varies, we have considered the rolling resistance coefficient for car tire on smooth tarmac road (0.01) and have calculated the rolling resistance force for different types of electric vehicles [50]

Table. 5.2 Calculation of F_{roll} for various EVs [53]

Vehicle Name	Weight of the vehicle (kg)	Acceleration constant (m/s^2)	Rolling resistance coefficient	**F_{roll} (N)**
Chevrolet Volt	1708	9.8	0.01	**167**
Mercedes Benz CLA 250	1530			**149**

Nissan Leaf SL(2012)	1520	9.8	0.01	**148**
Tesla Model S(2012)	2170			**213**
Toyota Prius	1442			**141**

From the above calculations we can conclude that the rolling resistance is more on the vehicle having the higher mass.

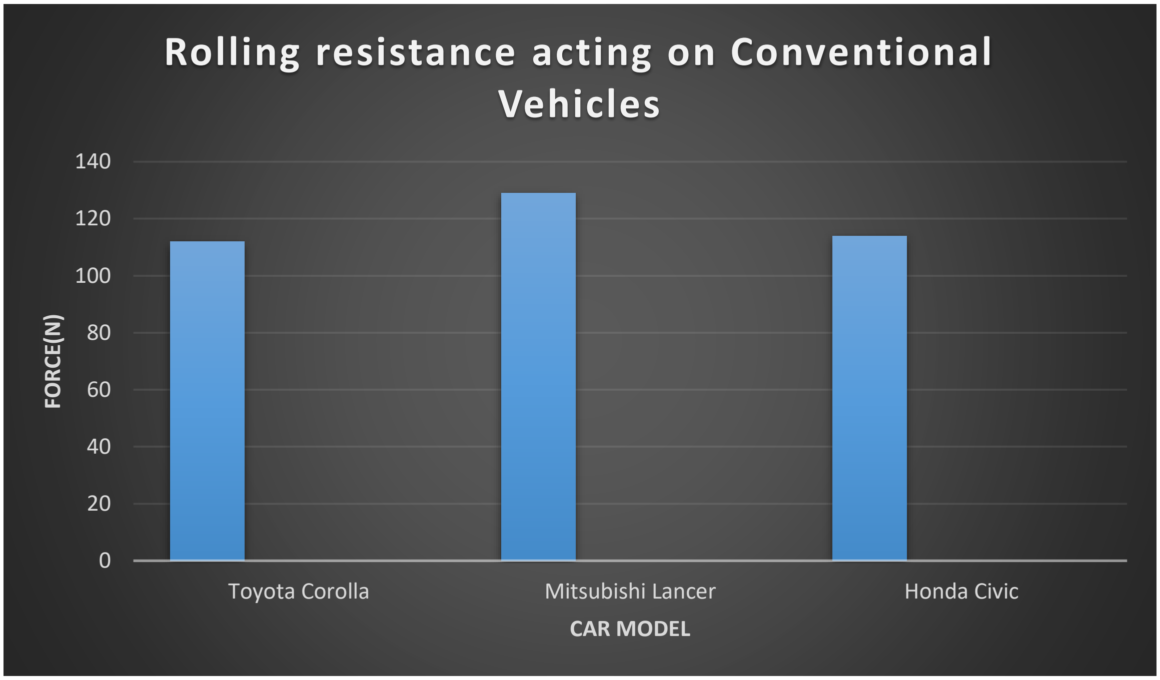


Here we see the rolling resistance force on the conventional vehicles,

Table. 5.3 Calculation of F_{roll} for various conventional vehicles [51]

Vehicle Name	Weight of the vehicle (kg)	Acceleration constant (m/s^2)	Rolling resistance coefficient	**F_{roll} (N)**
Toyota Corolla	1147	9.8	0.01	**112**
Mitsubishi Lancer	1325			**129**

Honda Civic	1173	9.8	0.01	**114**



Thus we can see that since the electric vehicles have a slightly higher weight than the conventional vehicles thus the rolling resistance forces working on it are greater than the forces working on the conventional vehicles.

5.1.2Grading Resistance

While a vehicle is travelling, it may travel in slanted path, whenever it travels a slope going up or coming down there is always a component of force which is acting downwards.

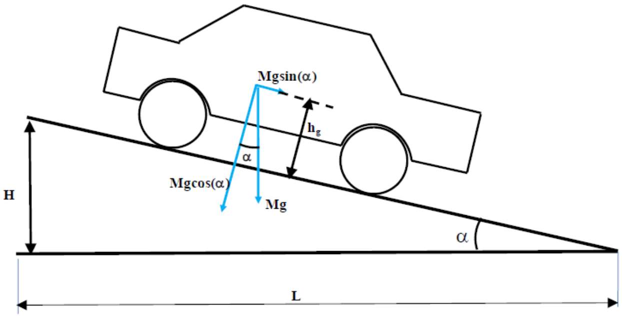


Fig. 5.6 Vehicle on inclined surface [50]

When the vehicle is travelling up a slope the component of the force opposes its forward movement but on the other hand if the vehicle travels downward this component of the force adds to the vehicle movement. The grading resistance is often denoted as follows [50],

$F_{grad} = Mg\sin(\alpha)$

Where,

M = mass of the vehicle (kg)

g = acceleration constant (m/s^2)

α = road angle (radians)

In many cases the tire rolling resistance and the grading resistance are combined together and they are called the road resistance. We can then express the road resistance as follows [50],

$F_{road} = F_{roll} + F_{grad} = Mg\{f_{roll}\cos(\alpha) + \sin(\alpha)\}$

Where,

M = mass of the vehicle (kg)

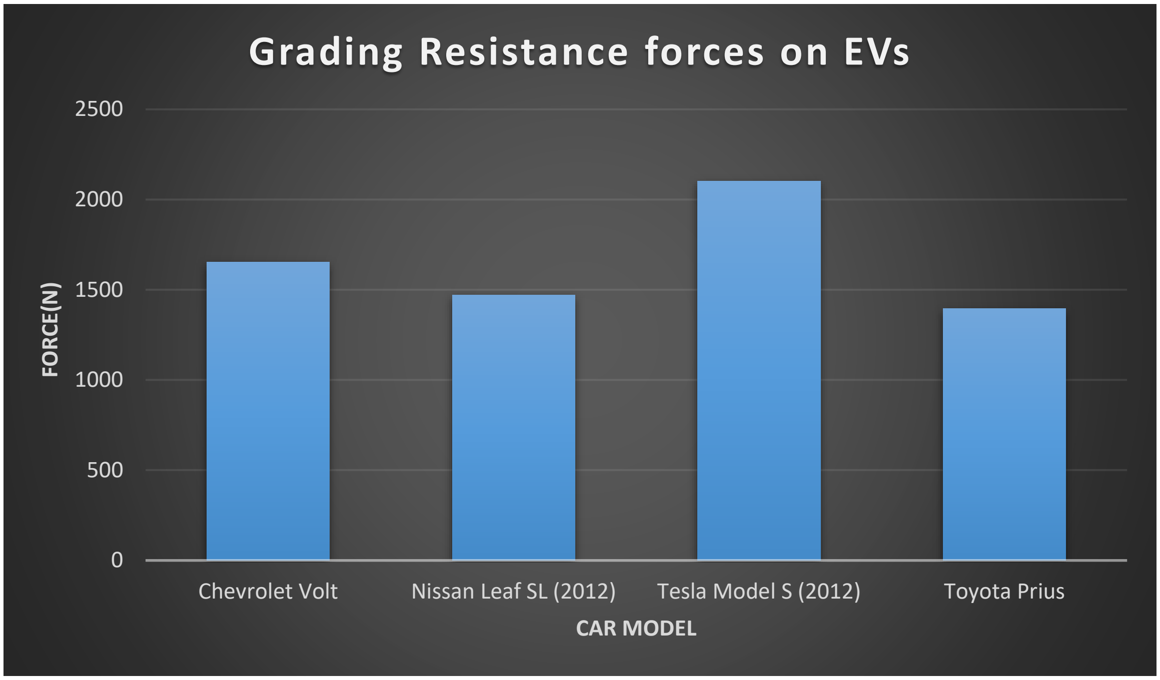
g = acceleration constant (m/s^2)

f_{roll} = rolling resistance coefficient

If we want to calculate the grading resistance of a vehicle we have to consider a certain value of the road inclination, let us consider a 10% slope which is roughly 5.71 degrees and 0.099 in radians. [54]

Table. 5.4 Calculation of F_{grad} for various EVs [53]

Vehicle Name	Weight of the vehicle (kg)	Acceleration constant (m/s^2)	Road Angle(radians)	**F_{grad} (N)**
Chevrolet Volt	1708	9.8	0.099	**1654**
Mercedes Benz CLA 250	1530			**1482**
Nissan Leaf SL(2012)	1520			**1472**
Tesla Model S(2012)	2170			**2102**
Toyota Prius	1442			**1396**



5.1.3Aerodynamic Drag

Aerodynamics helps us to know about the air flow around or through objects. Air is a thin type of fluid and this has prominent effects on the acceleration, top speed, efficiency and also the handling of any vehicle [50].

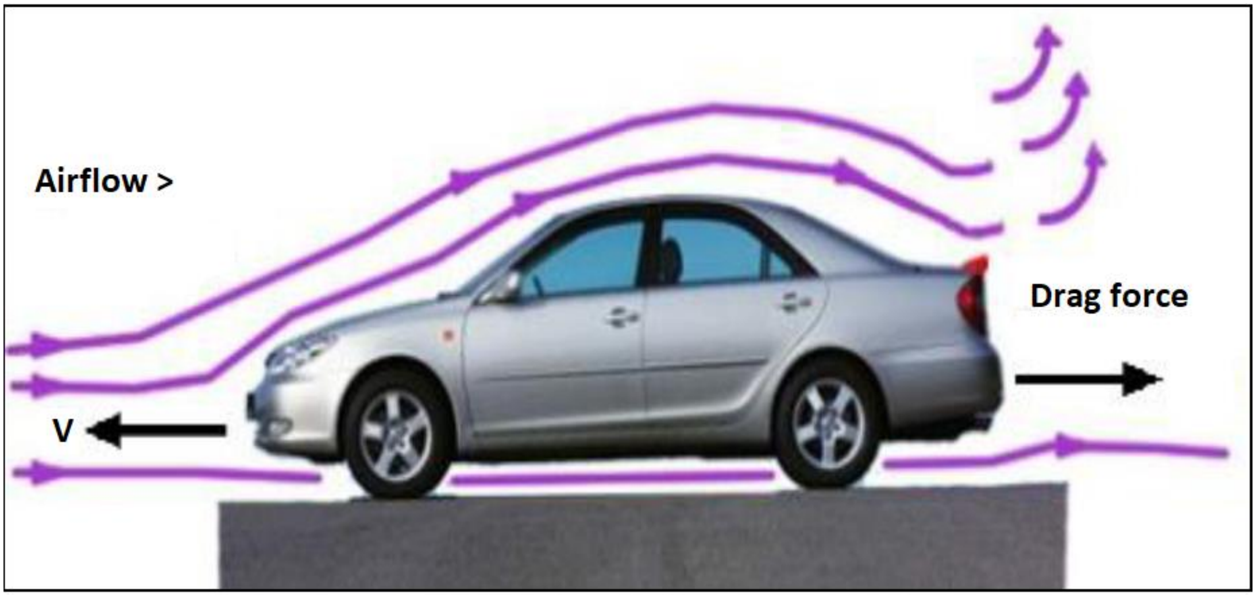


Fig. 5.7 The drag force due to air flow acting on a car [55]

When a vehicle travels at a higher speed on road it faces a resisting force, this resisting force is known as the aerodynamic drag force. However, there are two reasons acting behind this aerodynamic drag force [50], they are

1. Shape drag
2. Skin effect

The shape drag of the vehicle depends on the shape of a particular vehicle, whenever a vehicle is moving forward it presses the air which is present in front of it, since the vehicle travels at a certain high value of speed the air cannot move out rapidly and the air pressure increases. For this reason, high air pressure is developed at the front of the vehicle. On the other hand, as the vehicle is travelling forward it is creating an empty space behind it, the air cannot fill this empty space instantaneously as well, and thus a low pressure area is developed behind the vehicle. So, we see that two different types of pressure areas are created at the front and back of the vehicle while it is travelling forward. The high air pressure area at the front of the vehicle resists the motion of the vehicle by pushing the vehicle and creating an opposite force to the direction of travel of the vehicle, an on the other hand the low air pressure zone at the rear end of the vehicle drags the vehicle backwards which is also a force in the opposite direction of the motion of the vehicle.

The air which is close to the body of the vehicle traverses almost at the speed of the vehicle. Whereas the air away from the vehicle is static, in between these two layers of air the air molecules have a great difference in the range of speed. Due to having a great range of difference of speed in between the two types of air molecules a frictional force occurs, for this frictional force another component of aerodynamic force is developed and this is often known as the skin effect of the aerodynamic drag force. The aerodynamic drag is often expressed by the following formula [50]:

$$F_{aero} = \frac{1}{2}\rho A_f C_d (V+V_w)^2$$

Where the notation denotes,

ρ = density of air (kg/m^3)

A_f = frontal area of the vehicle (m^2)

V = speed of the vehicle (m/s)

V_w = speed of wind (m/s)

C_d = drag coefficient

From the formula of aerodynamic drag we can see that the density of air, scalar multiple of 0.5, are constant and also the frontal area and the drag coefficient are fixed values for a particular type of vehicle, thus the force on the vehicle depends on the speed of the vehicle and also the speed of the wind, we have selected few vehicles and have used their drag coefficient and frontal area parameters and have studied the chance of aerodynamic drag force on them at different speed of the vehicle and the wind, the vehicles are Tesla Model S(2012), Toyota Prius(2014) and Nissan Leaf SL(2012), Mercedes Benz CLA 250, Chevrolet Volt [53]

Table. 5.5 Aerodynamic force calculation of EV at 0m/s wind velocity

Name of the vehicle	Density of air (kg/m^3)at 25˚C	C_dA_f (m^2)	V (m/s)	V_w (m/s)	**F_{aero} (N)**
Chevrolet Volt	1.18	0.62	20	0	**146.32**
Mercedes Benz CLA 250		0.65			**153**
Nissan Leaf SL(2012)		0.72			**170**
Tesla Model S(2012)		0.575			**136**
Toyota Prius	1.18	0.575	20	0	**136**

Table. 5.6 Aerodynamic force calculation of EV at 3m/s wind velocity

Name of the vehicle	Density of air (kg/m^3)at 25˚C	C_dA_f (m^2)	V (m/s)	V_w (m/s)	**F_{aero} (N)**
Chevrolet Volt	1.18	0.62	20	3	**193**
Mercedes Benz CLA 250		0.65			**202**
Nissan Leaf SL(2012)		0.72			**224**
Tesla Model S(2012)		0.575			**179**
Toyota Prius		0.575			**179**

Table. 5.7 Aerodynamic force calculation of EV at 5m/s wind velocity

Name of the vehicle	Density of air (kg/m^3)at 25°C	C_dA_f (m^2)	V (m/s)	V_w (m/s)	**F_{aero} (N)**
Chevrolet Volt	1.18	0.62	20	5	**228**
Mercedes Benz CLA 250		0.65			**239**
Nissan Leaf SL(2012)		0.72			**265**
Tesla Model S(2012)		0.575			**212**
Toyota Prius		0.575			**212**

From the above calculations it is eminent that the wind velocity has a notable effect on the vehicle, keeping the velocity of the types of vehicle same we have varied the values of the wind velocity they face while travelling and the and we can see the different amount of forces acting on the vehicles, the force acting on the vehicle also reduces the amount of velocity with which it travels.

Table. 5.8 Aerodynamic force calculation of Conventional Vehicle at 3m/s wind velocity

Name of the vehicle	Density of air (kg/m^3)at 25°C	C_dA_f (m^2)	V (m/s)	V_w (m/s)	**F_{aero} (N)**
Toyota Corolla	1.18	0.61	20	3	**143**
Mitsubishi Lancer		0.63			**149**
Honda Civic		0.64			**151**

From the comparison of the aerodynamic drag force between EV and conventional vehicles we can see that there is not much difference since this value mostly depends on the aerodynamic drag coefficient and also the frontal area of the vehicles, the electrical vehicles are now being developed with very less drag coefficient, presently the production car Tesla Model S has the least value of drag coefficient which is 0.23. [53]

5.2 Total Driving Resistance

The traction force to be supplied from the propulsion unit F_t has to be greater than the combined resistive forces and thus the vehicle will move forward. The $F_{resistance}$ thus stands as the combination of F_{roll}, F_{aero} and F_{grad}.

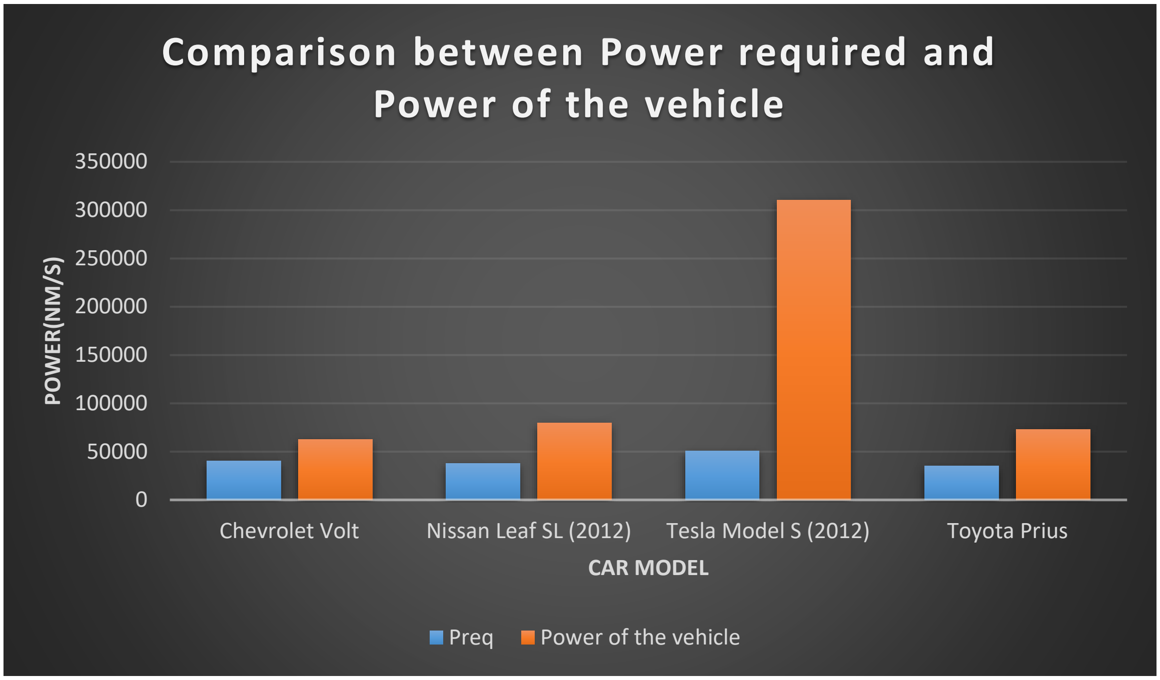
If we want to find the power required then, $P_{required} = F_{resistance}V$

From the above calculations we can find the total resistance that an Electric vehicle faces while it is traveling on the road

Table. 5.9 Comparison between $P_{required}$ and the Power of the vehicle [53]

Name of the Vehicle	Rolling resistance, F_{roll} (N)	Grading resistance F_{grad}(N)	Aerodynamic resistance F_{aero}(N)	Total Resistance, $F_{resistance}$(N)	Velocity, V(m/s)	**$P_{required}$ (Nm/s)**	**Power of the vehicle(Nm/s)**
Chevrolet Volt	167	1654	228	2049	20	**40980**	**62664**
Mercedes Benz CLA 250	149	1482	239	1870		**37400**	**155168**
Nissan Leaf SL(2012)	148	1472	265	1885		**37700**	**79822**
Tesla Model S(2012)	213	2102	212	2527		**50540**	**310336**
Toyota Prius	141	1396	212	1749		**34980**	**73108**

Here, the parameter $P_{required}$ denotes the minimum power that an electric vehicle requires to overcome the resistive forces and help the car to traverse smoothly, we can see that the $P_{required}$ in compared to the power of the vehicle is very less, thus the vehicle can easily overcome the resistive forces and face no hindrance during travel, we have considered the velocity of the vehicle to be 20m/s same as like the value we used in other calculations.



5.3 Simulation

We have taken help of MATLAB Simulink to find the effects of the aerodynamic drag on different types of the electric vehicle. For each type of vehicle we have changed the speed of the wind and have seen the effect of aerodynamic drag on the vehicles, the vehicle Simulink model is as follows,

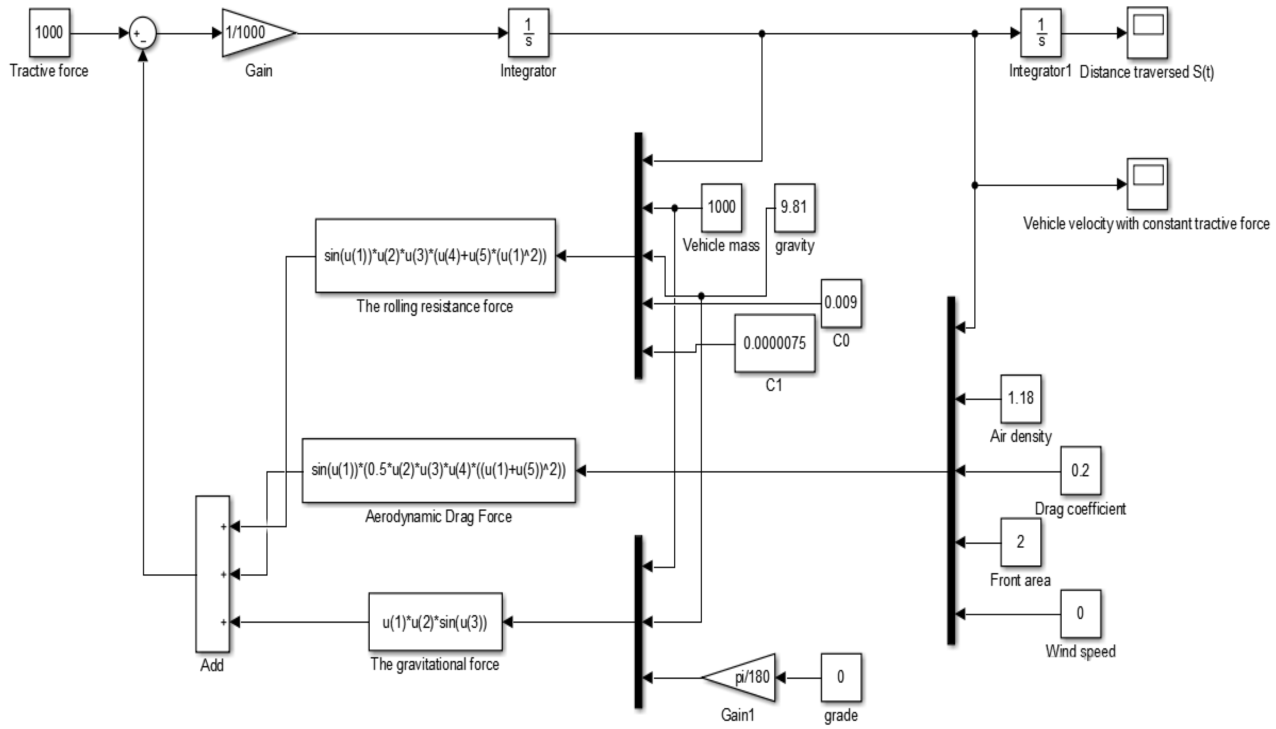


Fig. 5.8 Simulink model of the vehicle

5.4 Simulation Results

The speed of the wind parameter has been changed to see the effect on the vehicle speed, we can see that when the speed of the wind is increased from 20 m/s to 30m/s the speed of the vehicle decreases at the initial stage, after the vehicle has crossed the force due to aerodynamic drag the vehicle speed is seen to be saturated since it is not facing any hindrance due to drag, this has been done for few different types of vehicles and the results are shown in the subsequent figures

Chevrolet Volt

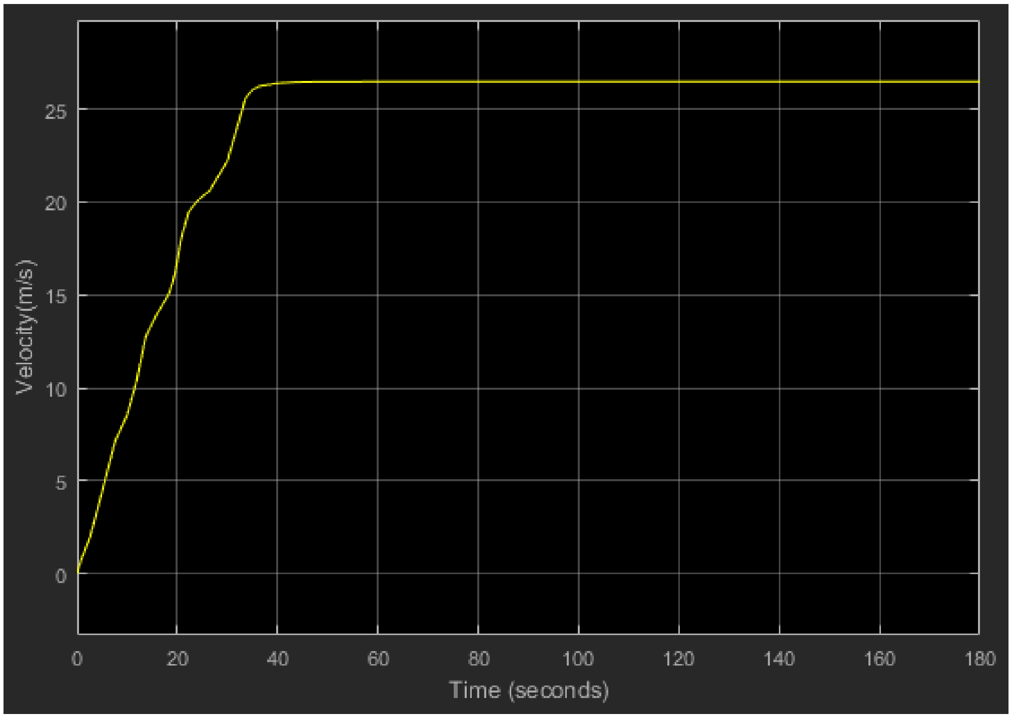


Fig. 5.9 Velocity graph of the vehicle at wind speed 20m/s

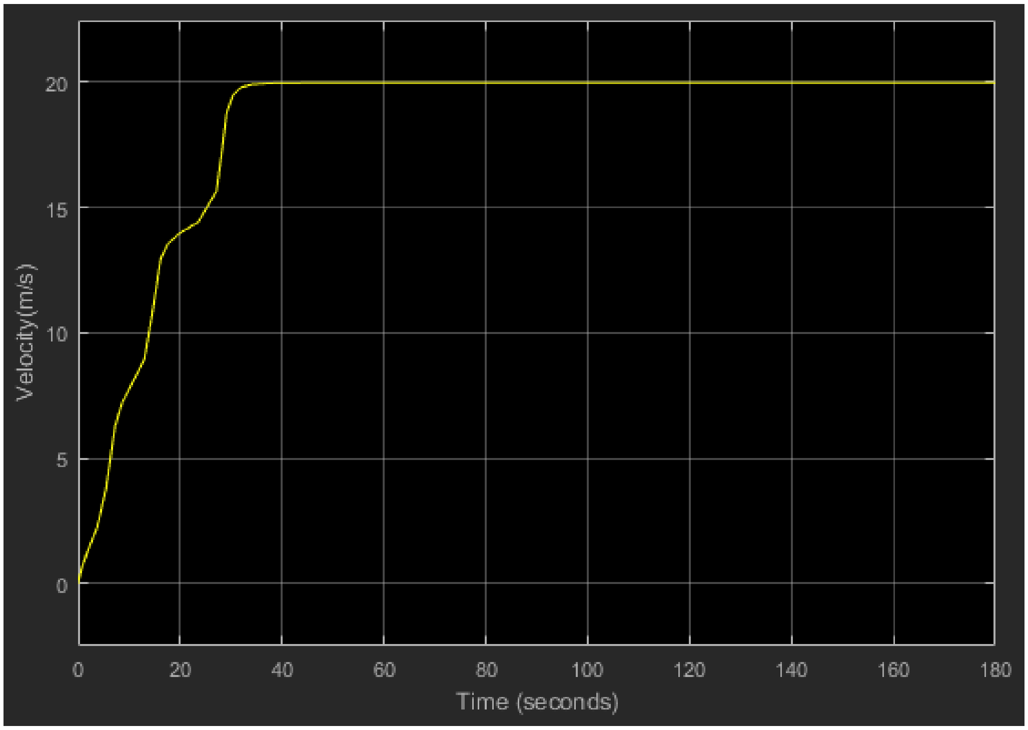


Fig. 5.10 Velocity graph of the vehicle at wind speed 30m/s

Nissan Leaf SL (2012)

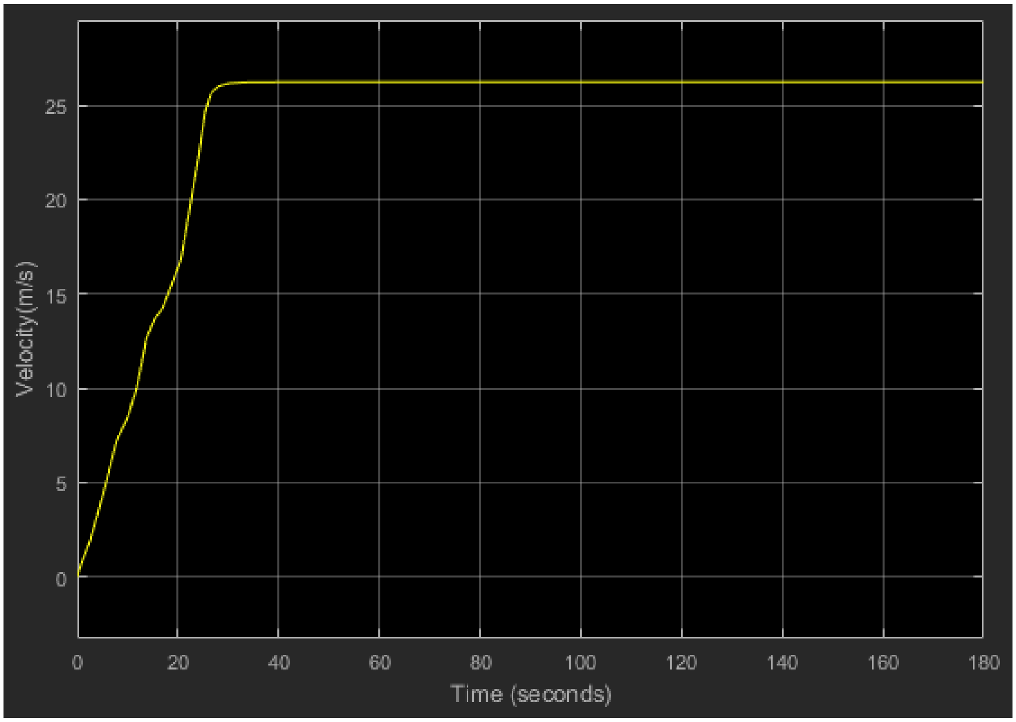


Fig. 5.11 Velocity graph of the vehicle at wind speed 20m/s

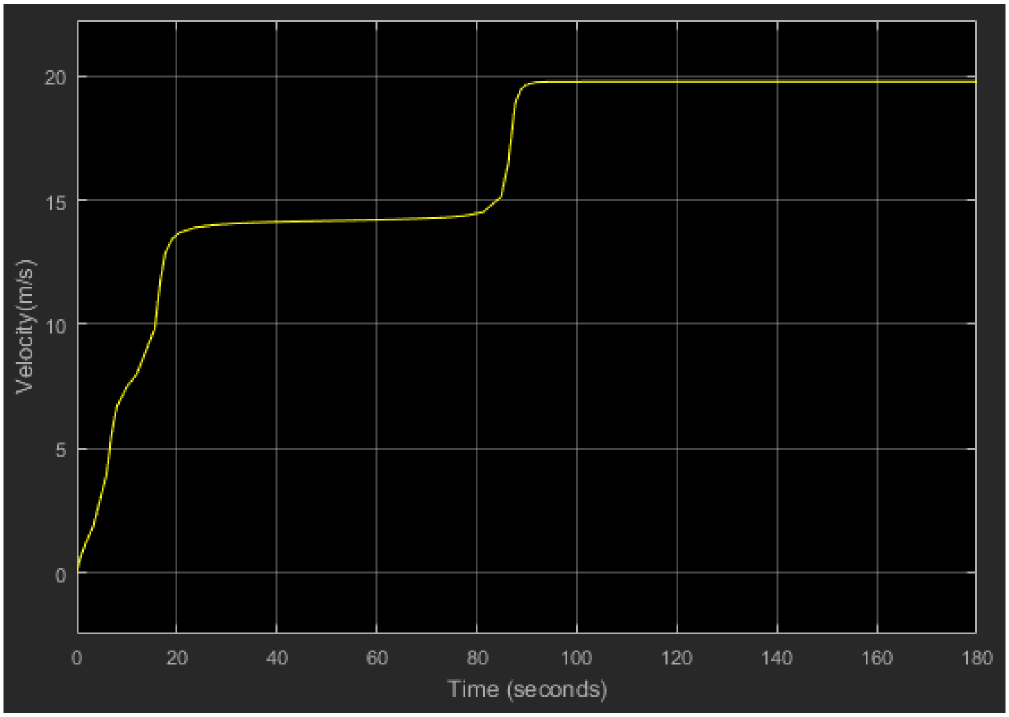


Fig. 5.12 Velocity graph of the vehicle at wind speed 30m/s

Tesla Model S (2012)

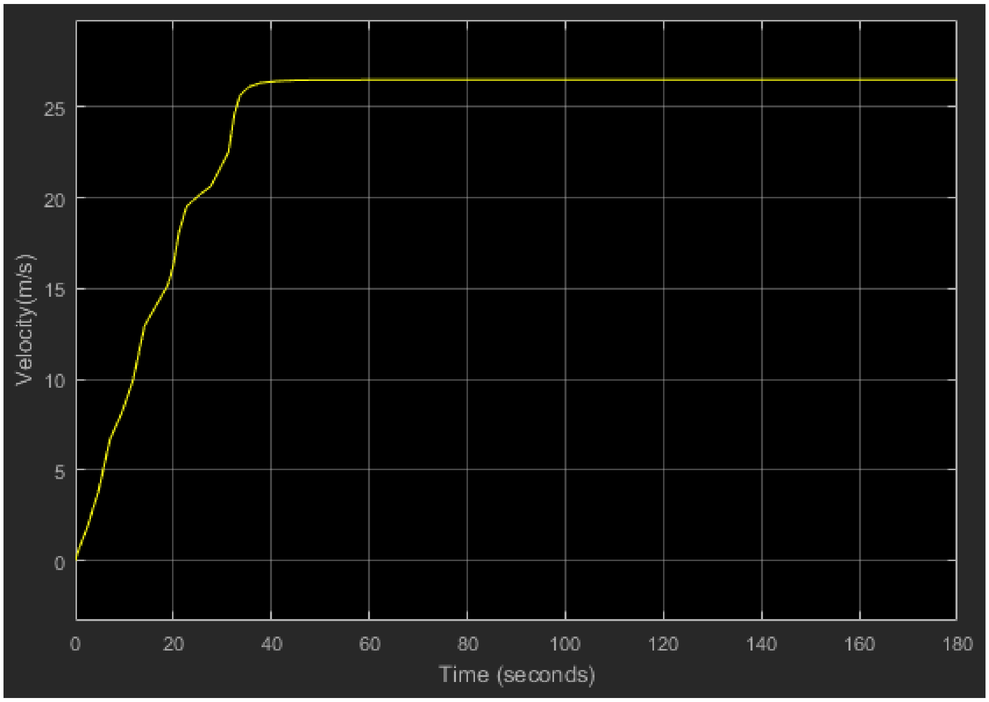


Fig. 5.13 Velocity graph of the vehicle at wind speed 20m/s

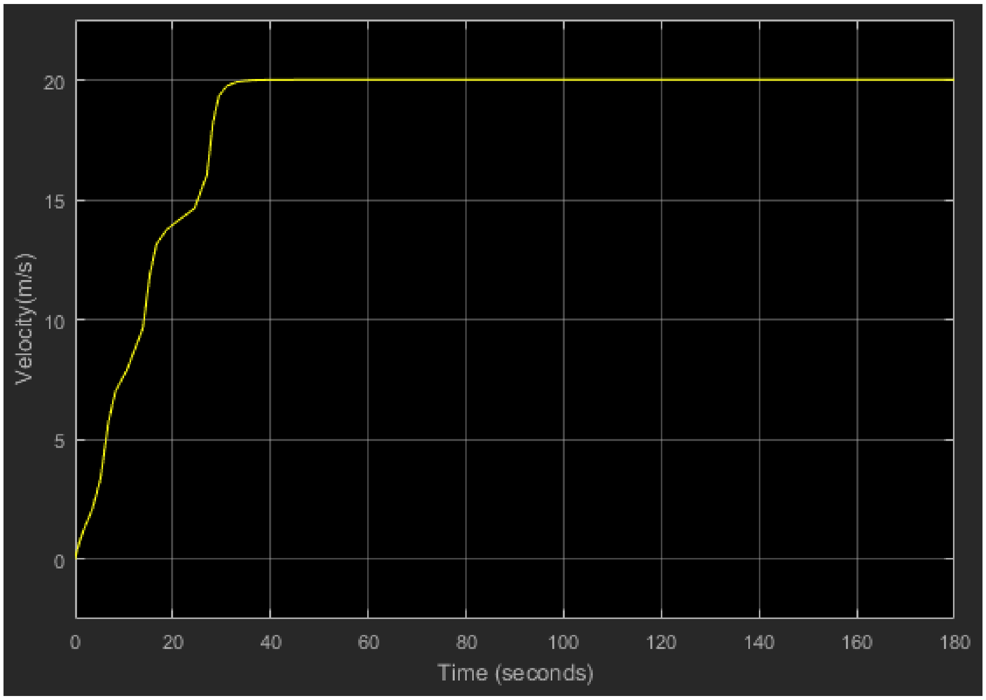


Fig. 5.14 Velocity graph of the vehicle at wind speed 30m/s

Toyota Prius

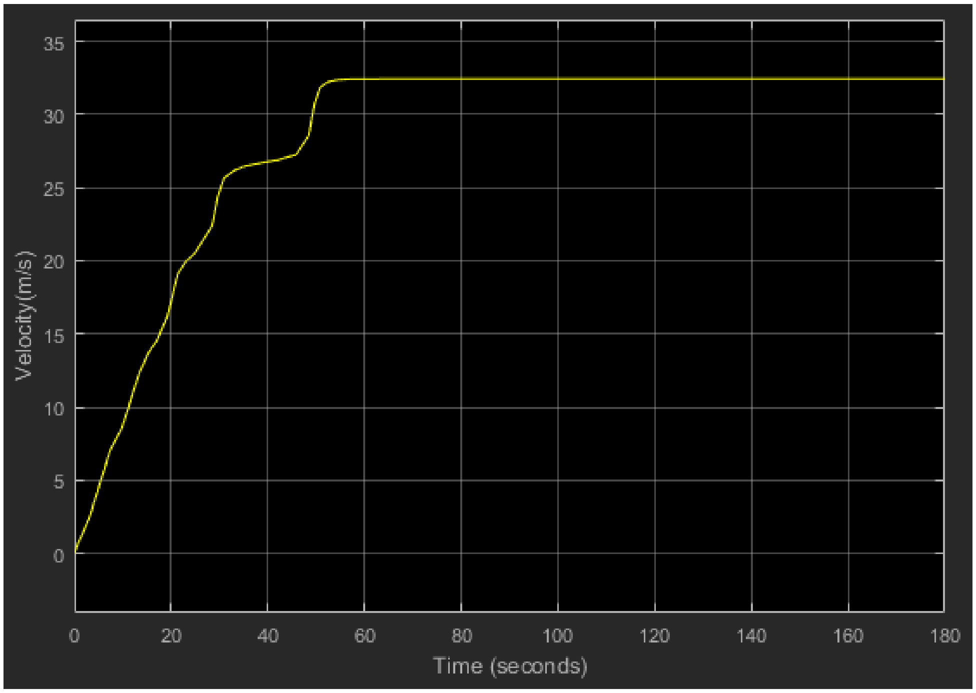


Fig. 5.15 Velocity graph of the vehicle at wind speed 20m/s

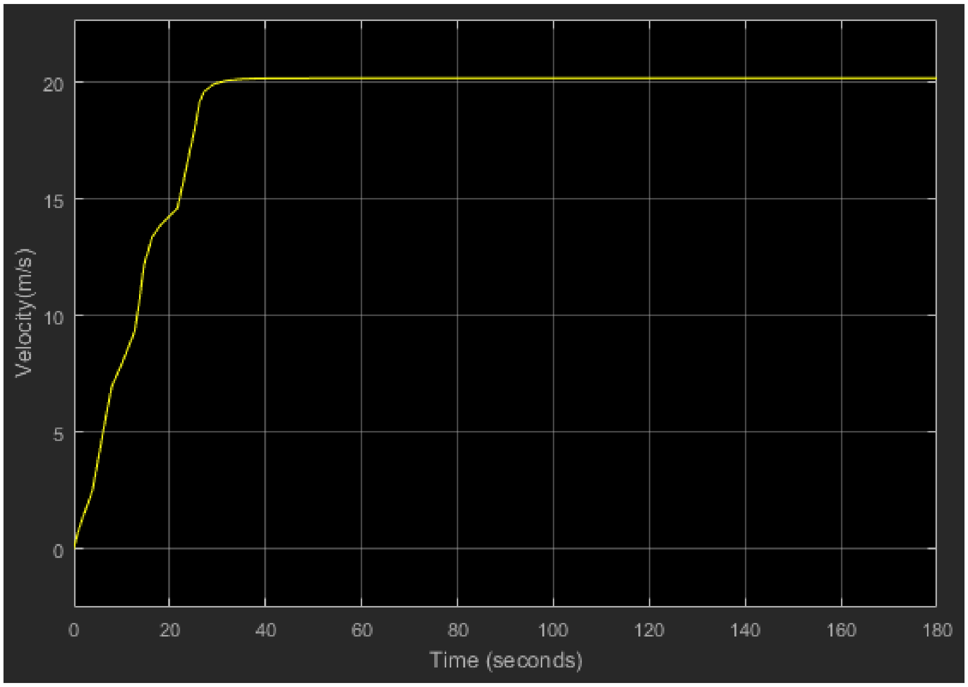


Fig. 5.16 Velocity graph of the vehicle at wind speed 30m/s

The changes in the velocity due to different drag coefficient, frontal area and mass of the vehicles are being shown in the above figures, for these differences in the values the velocity changes.

Chapter 6
Motor Control

6.1 Introduction

The main control system of an electric vehicle is the control of its motor. Its prime objective is to create a flawless control of the acceleration, speed and travelling distance with respect to charge. The control system should be designed in such way so that it is well adaptive to improve the performance of the system in both dynamic and steady state. The control of an EV is also very important because they need to be efficient in energy management of the system.

Controlling the torque of the motor is one of the major aims of the control system. A fast responsive and low-ripple control system is most appreciated. Electric machines having a wide range of speed regulation is required for an EV. Large torque output under low speed and high over-load capability is required to provide that. Certain power output at high speed operation is also required [57]. Different types of motors can be used to generate the torque needed for an electric vehicle. These motors are controlled with different control strategies to maintain the required torque needed for an EV. In this paper, four types of motors have been discussed with three control strategies.

6.2 Variety of Motors

Two types of DC motors

- Brushed DC Motor
- Brushless DC Motor (BLDC)

Two types of AC motors

- Permanent Magnet Synchronous Motor (PMSM)
- Induction Motor (IM)

6.2.1 Brushed DC motor

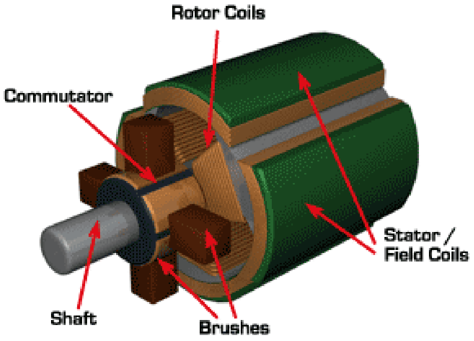


Fig. 6.1 A Brushed DC Motor [60]

Motor controlling of a DC motor is simple as the power supply from the battery is DC in nature. DC motors can be of three types a) series b) shunt c) separately excited windings. Controlling the shunt motor can be difficult at times. Because a small reduce in the supply voltage results a weakened magnetic field. This leads to a reduction in the back EMF and hence tending to increase the speed. A reduction in supply voltage may have very little effect on the speed. The separately excited motor allows having independent control of both the magnetic flux and the supply voltage. This allows great flexibility in setting the required torque at any required angular speed. Generating comparatively larger startup torque and its simplicity in operating, series wound DC motors are also selected for EVs [57]. Brushed DC motors have high maintenance cost as the brushes wear off and hence needs to be replaced often. The equation given below can be used to calculate the torque in a brushed DC motor.

$$T_e = \frac{1}{2\pi} k_b . I_a . \Phi$$

Where, T_e = electro mechanical Torque, k_b = counter emf equation constant, Φ = flux per stator pole, I_a = armature current.

6.2.2 Brushless DC Motor

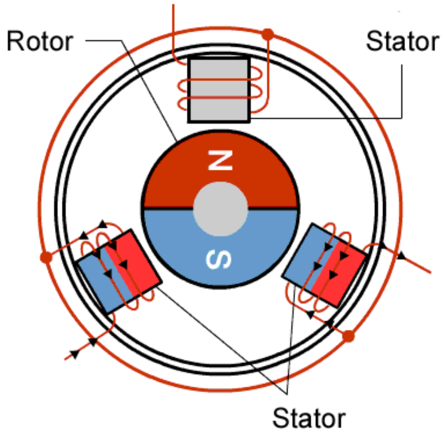


Fig. 6.2 A Brushless DC motor [61]

As their names implies, brushless DC motors do not have brushes. Their mechanism is even simpler than brushed dc motors. In a BLDC, the rotor itself is a permanent magnet and it rotates. The coils with electromagnets are attached to the stator and remains fixed. The rotation of the permanent magnets in this motor is obtained by changing the direction of the magnetic fields generated by the surrounding stator stationary coils. Hence, the rotation is controlled by adjusting the magnitude and direction of the current in these stator coils. The electromagnetic torque in a BLDC motor can be expressed as

$$T_e = (e_a i_a + e_a i_b + e_c i_c) / \omega$$

Where, I_r = rotor current, e_a ,e_b ,e_c = back emf in each phase, ω=angular velocity

6.2.3 Permanent magnet synchronous motor

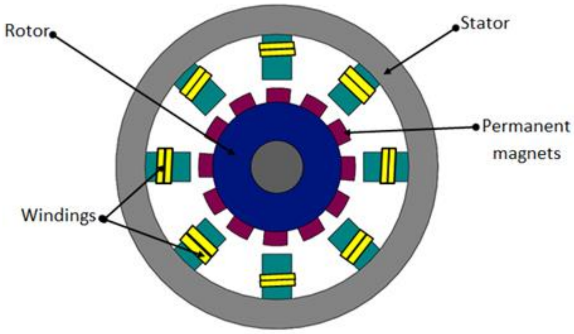


Fig. 6.3 A permanent magnet synchronous motor (PMSM) [62]

In a permanent magnet synchronous motor (PMSM), permanent magnets embedded in the rotor to create a constant magnetic field. The stator contains multiphase electromagnets, which creates rotating magnetic field in time with the oscillations of sinusoidal current. The two magnetic fields interacts with one another creating a force to move the rotor. The stator current is can be control in such way to so that it always creates a stator vector perpendicular to rotor magnets resulting a maximum force. The torque in a PMSM can be calculated using the formula:

$$T_m = 1.5p\ (\psi i_q + (L_q - L_d) i_d i_q)$$

Where, T_m = motor torque, ψ = total flux linkage, L_d ,L_q = self inductance of dq axis,

$i_{d,}i_q$ = currents in dq axis,p=no. of poles

6.2.4 Induction Motor (IM)

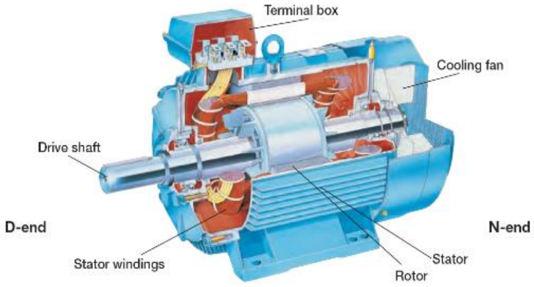


Fig. 6.4 An Induction Motor [63]

An induction motor is an AC electric motor in which the power supplied in the rotor to produce torque is done by electromagnetic induction from the magnetic field of the stator winding. When a three-phase supply is supplied to the stator windings, they create a rotating magnetic field, which induces current in the rotor conductors. This current then interacts with the rotating magnetic field created by stator and hence results a rotation movement of the rotor. An induction motor can be either an asynchronous motor or squirrel-cage motor.

$$T = k\ \Phi\ I_r \cos\theta$$

Where,θ = angle between rotor emf and rotor current, k = turn ratio between primary voltage and secondary voltage.

6.3 The control strategies

The control of an electric vehicle is essentially the control of its motor. Different control strategies are applied to different motors to control the torque. In this paper, three different control strategies have been applied for two different types of motors.

- Pulse Width Modulation (PWM) for DC Motors.
- Direct Torque Control (DTC) and Field-oriented control (FOC) for PMSM.

6.3.1 Pulse width modulation for DC motors

Pulse width modulation control is a very simple control technique to control a DC motor. The fact that either voltage or current can be varied to change the power (P=VI) makes the system more dynamic. PWM takes full advantage of this fact. Pulse-width modulation uses a square wave whose pulse width is modulated resulting in the variation of the average value of the waveform [65]. Example of a PWM signal is given below.

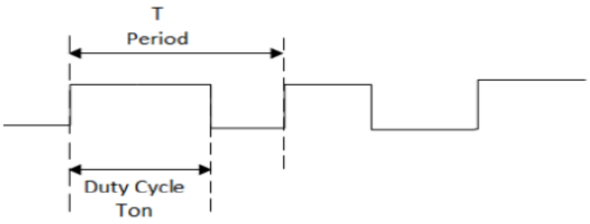


Fig. 6.5 A PWM signal [59]

The average voltage supplied to a DC motor can be expressed as:

$$V_{avg} = (T_p / T_{on})\ V_{in}$$

Where, V_{avg} = average voltage, T_p=time period, V_{in}=input voltage

Duty cycle is one of the parameters of any square wave. In is the ratio of on to off time. Different percentage of duty cycle can be attained by changing T_{on}. In PWM method, operating power to the motor is turned on and off to modulate the current to the motor. The duty cycle in a PWM signal is varied to control the speed of the motor. Thus, the desired speed of the motor can be obtained by changing the duty cycle. A controller is used to control the duty cycle of a DC motor drive. The frequency being constant, and the on-off time varied, the duty cycle is of PWM is obtained by the width of the pulse [59].

An H bridge is used to apply the voltage to the load in different direction. This determines the direction of the motor rotation (forward or backward). Different combination of switching can determine different modes of operation for the vehicle. Regenerative braking can also be obtained here. The diagram of an H bridge in given below and different switching states are shown to determine the mode of operation [59].

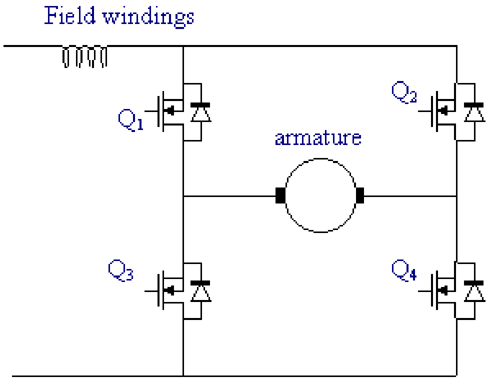


Fig. 6.6 A H-bridge diagram [59]

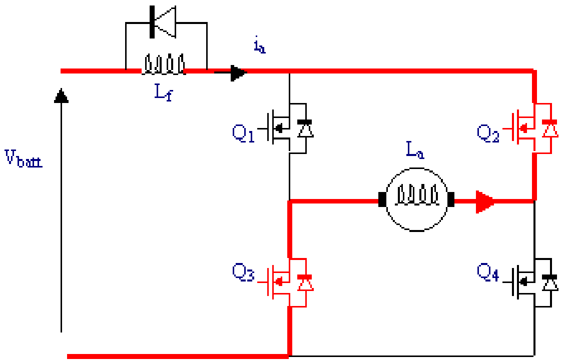


Fig. 6.7 Regenerative braking [59]

Table. 6.1 H Bridge switches configuration [59]

Q1	Q2	Q3	Q4	Operation Mode
1	0	0	1	Forward Drive
0	1	1	0	Reverse Drive
0	0	0	0	Free Running
1	0	1	0	Brakes
0	1	0	1	Brakes

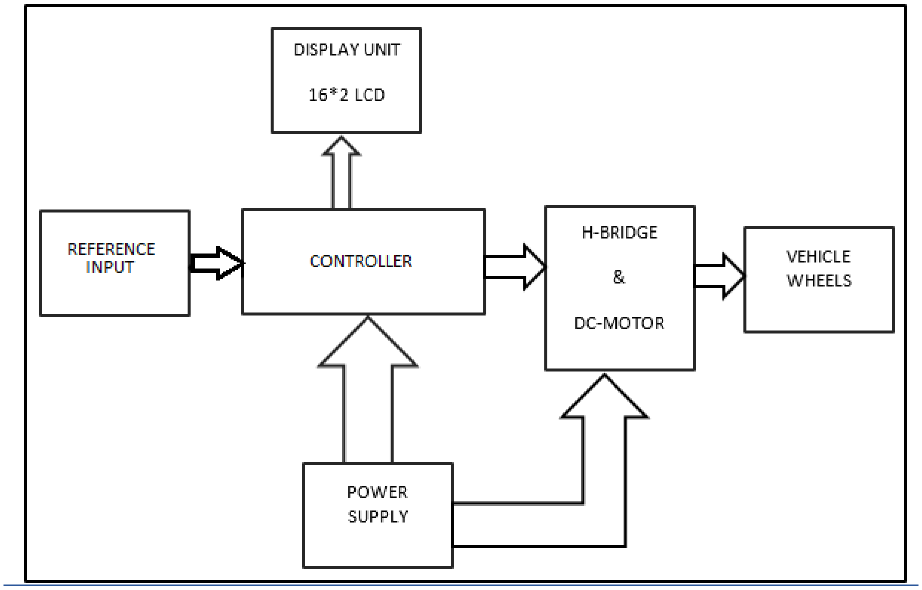


Fig. 6.8 Block Diagram for PWM control of DC Motor [59]

6.3.2 Direct Torque Control (DTC) and Field-oriented control (FOC) for PMSM

There are also two control strategies for designing a controller for Induction Motor.

1. Vector Control
2. Direct Torque Control

6.3.2.1 Vector Control

Vector control is used widely for the speed regulation of an induction motor. The basic principle of vector control is that the magnetic force and power are invariant under normal transform. When the number of poles are fixed, the torque of a PMSM is obtained by the stator current. Therefore, at first the stator phase currents i_a ,i_b,i_c are measured and converted to phase current projections i_α and i_β through Clarke Transformation (assuming $i_c = - i_a - i_b$).[57]

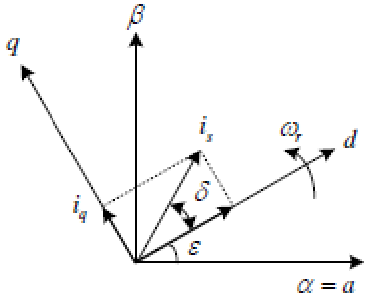


Fig. 6.9 Current vector decomposition [57]

$$i_\alpha = i_a$$

$$i_\beta = \frac{1}{\sqrt{3}} i_a + \frac{2}{\sqrt{3}} i_b$$

where, i_α, i_β are phase current projections.

i_d and i_q are then deduced from the i_α and i_β by using the rotation of the angle ε:

$$\begin{pmatrix} i_d \\ i_q \end{pmatrix} = \begin{pmatrix} \cos \varepsilon & \sin \varepsilon \\ \sin \varepsilon & \cos \varepsilon \end{pmatrix} \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix}$$

With proper coordinate transformation, the electric torque of a PMSM can be written as:

$$T_e = P. \Phi.i_q$$

Currently, vector control (or FOC) is an effective method in variable frequency speed regulation system in synchronous motors. It can obtain large instantaneous speed regulation range. The stator current is measured, then transformed to rotor coordinate with coordinate transformation, forming a current feedback, which can dynamically follow the variation of the current. The speed and rotor position are obtained by optical encoder, forming the speed loop, and finally implement the control of current and speed, greatly enhancing the stability, response speed and control accuracy of the system.[57]

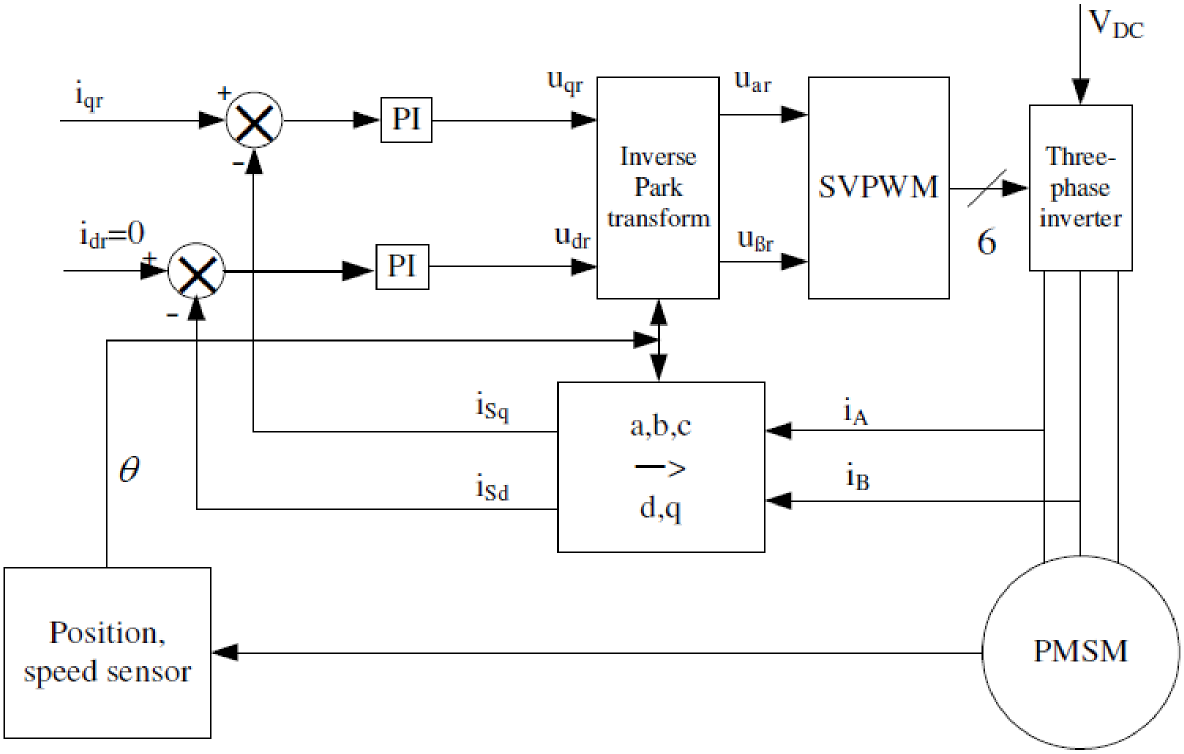


Fig. 6.10 Block Diagram for vector control of PMSM [57]

6.3.2.2 Direct Torque Control (DTC)

In direct torque control, the stator flux linkage is estimated by integrating the stator voltages. Cross product of stator flux linkage and motor current vector is used to estimate torque. The estimated torque and flux magnitude are then compared with the reference values. Any deviation, which is greater than the tolerance limit when compared with the reference value, is not accepted. As a result, the transistors of the variable frequency drive are turned on and off in such a way that the torque and flux values return to their tolerance limit [57]. So, the three parameters to control in DTC method are:

- Torque
- Amplitude of the stator flux linkage
- Angle between the rotor and stator flux vector

An estimator obtains the torque and flux signal. Two hysteresis controllers helps to regulate these signals. Output signal from the position estimator and the hysteresis controller are given to the switching table who in turn selects switching of the three-inverter legs, and applies a set of voltage vectors across the motor terminals [58].

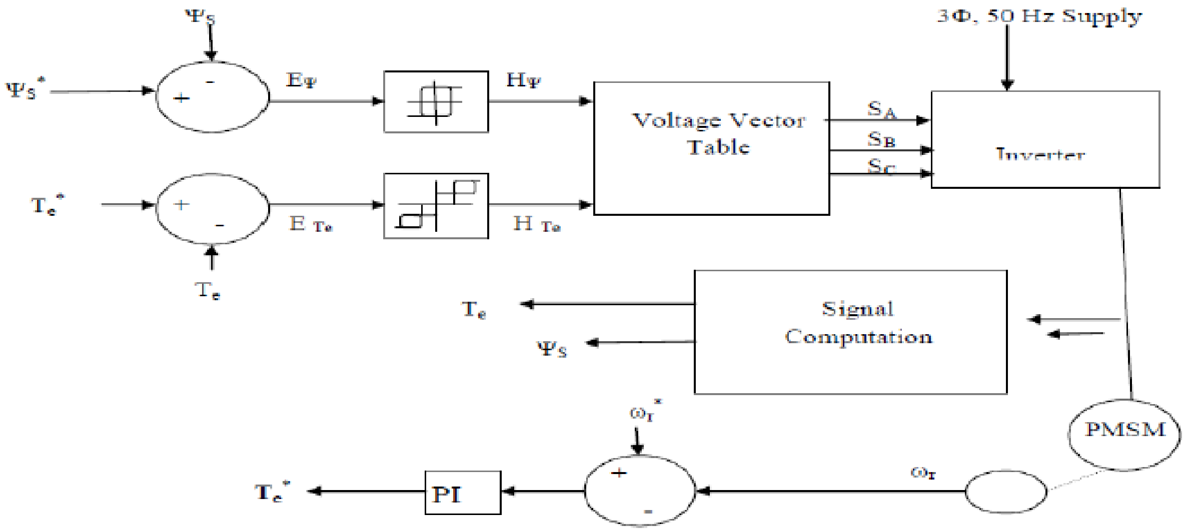


Fig. 6.11 Block Diagram of Direct Torque Control for PMSM [58]

The measured motor currents are calculated with the Clarke transform and then, perk transformation is done to obtain the currents in dq reference frame. The voltage, u_{set}, is estimated from the inverters switching state and the DC-link voltage, u_{dc}, in the reference frame by the voltage equation [58]:

$$u_{set}\,(S_{abc}) = \sqrt{\frac{2}{3}}\frac{u_{dc}}{2}\left(S_a e^{0i} + S_b e^{\frac{2\pi i}{3}} + S_c\, e^{\frac{4\pi i}{3}}\right) - \sqrt{\frac{2}{3}}\left(u_a e^{0i} + u_b e^{\frac{2\pi i}{3}} + u_c\, e^{\frac{4\pi i}{3}}\right)$$

Where, S_{abc} is the state of the switches and u_{abc} is the voltage loss in the switches.

The flux linkage through Clarke Transform can be written as:

$$\psi_{s\alpha} = \int (V_{s\alpha} - R_s i_{s\alpha})dt$$
$$\psi_{s\beta} = \int (V_{s\beta} - R_s i_{s\beta})dt$$

Hence, the torque is calculated using the equation:

$$T_e = \frac{3}{2}P(\psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha})$$

The angle between the rotor and stator flux can be calculated using the formula:

$$\theta_s = \tan^{-1} {}^{\psi_\beta}\!/_{\psi_\alpha}$$

Table. 6.2 Relation between flux linkage sector and its position. [58]

Sector	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
Angle	-π/2, -π/6	-π/6, π/6	π/6, π/2	π/2, 5π/6	5π/6, 7π/6	7π/6, 3π/2

For finding out the correct commands for control, flux and torque hysteresis comparators are used. The comparator calculates the error between the required and estimated values, and hence obtain if the torque and flux vectors should be [58]

- Increased: then output is 1
- Decreased: then output is -1
- Constant or Same: then the output is 0

Space Vector Calculation

For state (++-/110)

V_{a0} =V_{dc} , V_{b0} = V_{dc}, V_{c0}=0

V_s = V_{a0} + $V_{a0}e^{2\pi i/3}$ + $V_{c0}e^{-2\pi i/3}$
V_s = $V_{dc}(\frac{1}{2} + \frac{j\sqrt{3}}{2})$
V_s = $V_{dc} < 60°$

The switching vectors for rest of the inverter switching state are shown below.

Table. 6.3 Different switching states and corresponding space [58]

Switching State [a b c]	Space Vector V_s (In polar form, in degree)
V_0 [0 0 0]	$0<0$
V_1[1 0 0]	$V_s< 0°$
V_2[1 1 0]	$V_s< 60°$
V_3[0 1 0]	$V_s< 120°$
V_4[0 1 1]	$V_s< 180°$
V_5[0 0 1]	$V_s< 240°$

Finally, the input is given in terms of +1, 0, -1 for torque and 1, 0 for flux depending on the errors within or outside the hysteresis band.

Chapter 7
Simulation and Results

7.1 Introduction

This simulation is focused on a general electric vehicle drive-system that can be used to analyze the power flow during both motoring and regeneration. Throughout the simulation certain assumptions were made according to the requirements. The complete model includes a permanent magnet synchronous motor (PMSM), an ideal motor controller joined together with a proportional-integral (PI) controller and the electric vehicle battery which works as the power source for the EV. The complete motor drive model is developed in MATLAB Simulink. Generally, in gasoline powered vehicle the fuel source is excluded from the design of the drive train model. However, for EVs the battery is also a vital part of the drive train model as the drive train charges the battery through regeneration process while the motor operates as a generator. When the vehicle's brakes are applied the motor operates in regeneration mode thus reversing both the current direction and torque direction. The vehicle braking torque is achieved from the reversed torque direction and then it contributes in charging the battery.

7.2 Simulation process

This simulation works with a given set of torque and speed values which are taken from an ideal drive cycle generated by ADVISOR software. These values were then entered into the 1-D lookup tables as input to the drive system model. The values are as follows,

Speed: Sg = [0 2000 3000 1000 1000];
St = [0 5 50 85 100]

Torque: Tg = [0 330 330 160 160 -220 -220 0 0];
Tt = [0 5 10 15 50 55 80 85 100]

The lookup tables however requires a clock input which defines the simulation run time and uses the following parameters: start time=0s, step=0.01s, end time=120s which was given

As for the output, there are multiple scopes connected to each of the block to show the performance of the motor, battery error, the PI controller gain etc. The complete model is shown in fig. 7.1

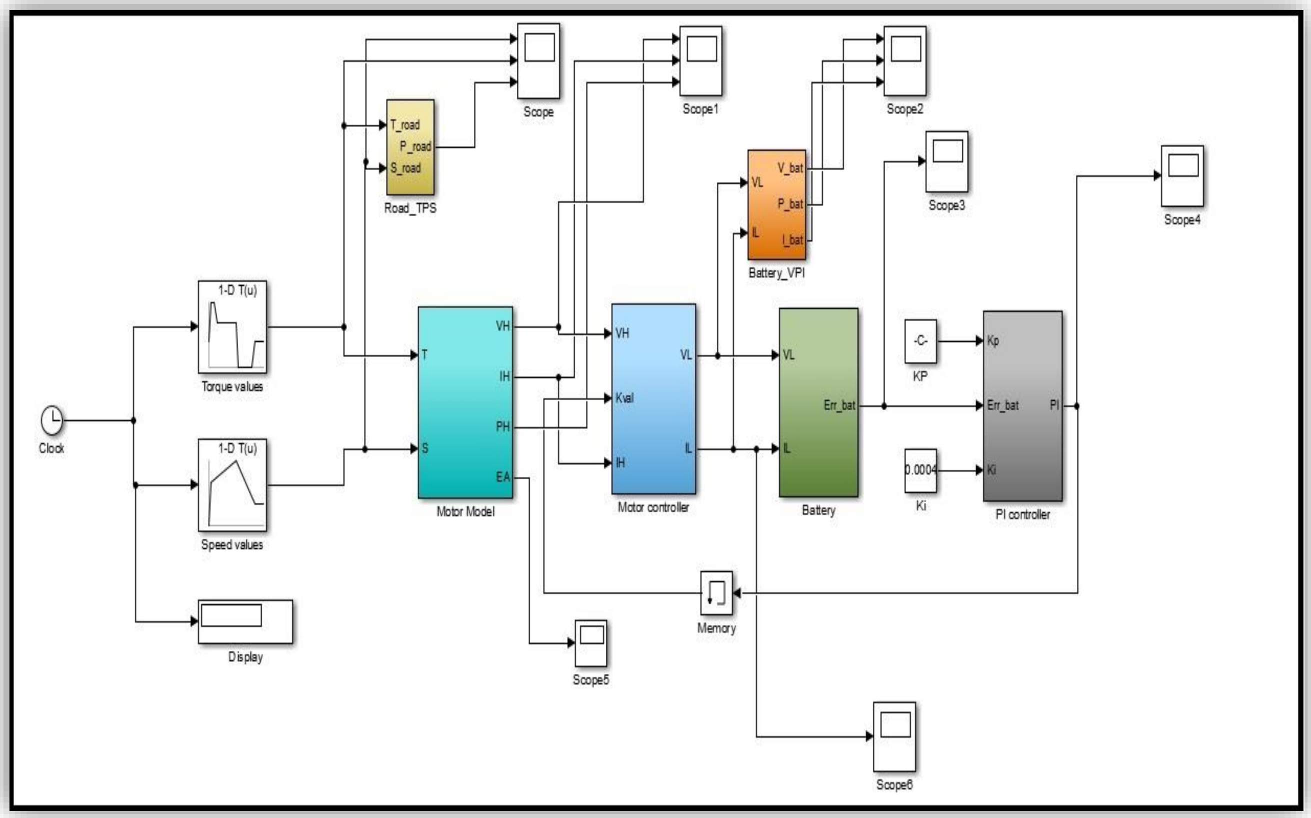


Fig. 7.1 Complete drive system model

7.3 Simulink blocks

7.3.1 Motor Model

In this simulation process a DC permanent magnet motor has been used. In the block, the power losses due to winding resistance and inductance has been incorporated. However, the eddy current loss, hysteresis loss and the time lags due to rotor inertia and inductance has been ignored for the simplicity of the simulation. The equations used for this block and the model are given below:

Developed torque: T_{dev} (Nm) = Km*Ia(A)

Developed voltage: V_{dev} (V) = ω (rad/sec)/Km

Motor voltage: V_H (V) = I_H (A)*R_A(Ω)+L(H)*di/dt+V_{dev}(V)

Where Ia= armature current, ω= armature speed, Km= physical constant, I_H = high side current, L=inductance, R_A= armature resistance

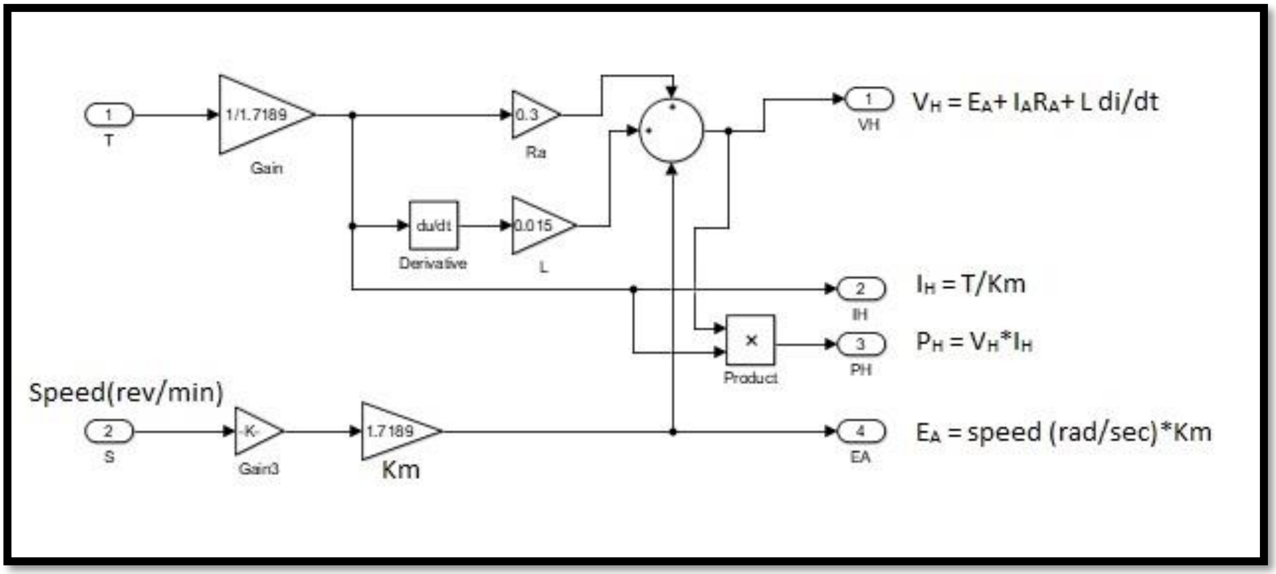


Fig. 7.2 Motor model

7.3.2 Motor controller model

The motor controller is basically modeled as an ideal controller for which the power loss and the time lags were not taken into consideration. The controller is connected with the battery block to set the battery voltage according to the requirement of the motor. The dimensionless constant gain or the K ratio of the input and output voltages is determined to meet the motor requirements and this same K ratio is used to adjust the current so that input and output powers are equal [66]. This model is based on the equations given below:

Controller high side voltage: $V_H = K_C*V_L$

Controller high side current: $I_H = (1/K_C)*V_L$

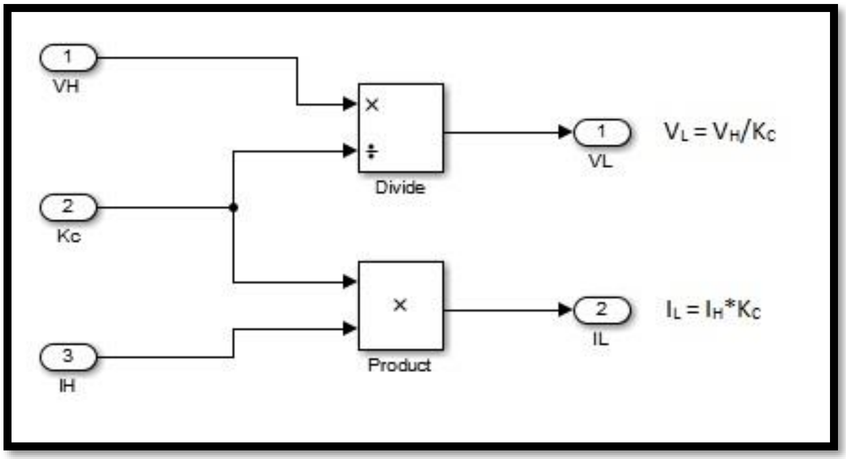


Fig. 7.3 Motor controller model

7.3.3 Battery model block

The battery block is modeled with an internal resistance (R_bat) of 0.01Ω and it is assumed to have a constant internal voltage (E_bat) of 375votls. The battery encounters internal power loss due to the resistance but there is no time lag. The motor controller provides the current and voltage data for the battery model to calculate the required battery's internal voltage. A battery voltage error, Err_bat is generated by the battery block when the calculated internal voltage is compared with the actual one. The PI controller model takes this error as an input to adjust the loop gain.

Battery terminal voltage: V_L (V) = I_L (A)*R_{bat}(Ω)+E_{bat}(V)

Battery voltage error: Err_{bat} = E_{bat} (actual)-E_{bat}(calculated)

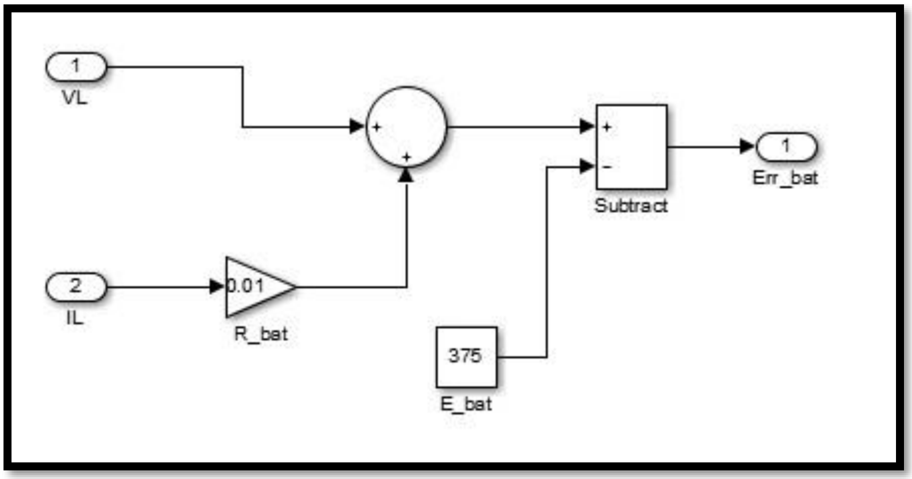


Fig. 7.4 Battery model

7.3.4 PI controller model

The PI controller gets the error signal (Err_bat) from the battery model as an input and then by using the proportional (Kp) and integral (Ki) it calculates the loop gain which is used by the motor controller. In order to avoid the Simulink simulation error due to an algebraic loop, an initial starting value of 0.1 was preset in the controller's integration block. In a Simulink model, an algebraic loop occurs when a signal loop exists with only direct feed through blocks within the loop. Direct feed through means that the block output depends on the value of an input port; the value of the input directly controls the value of the output [67]. The operation of PI controller in this simulation is to make the battery error voltage zero. However, a gain limiting block is also used to get rid of unwanted feedback signals. The saturation limit is from +5 to -5.

PI controller gain: K_PI = (Kp+s*Ki)*Err_bat

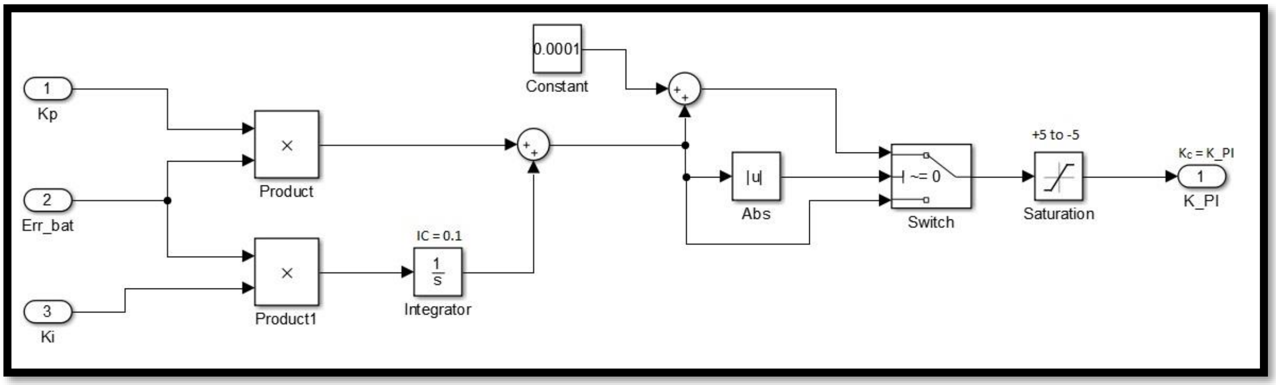


Fig. 7.5 PI controller

7.4 Results

7.4.1 Road Torque, speed and power

As said earlier, specific road torque and speed data were provided for the simulation which was taken from an ideal drive cycle. The road power however is calculated from these torque and speed values as the power is nothing but the multiplication of torque and speed. The normal motoring operation occurs when both the torque and speed are positive values. During this operation, the motor provides torque in the direction of rotation and the transaction of power is from motor to the load. On the other hand, regeneration process occurs when the motor torque becomes negative and has the opposite direction to the speed. The motor works as a generator at this stage and supplies voltage to the battery. It can be explained from the 4 quadrant speed torque map which shows +/- torque at the x-axis and +/- speed at the y-axis. The motoring mode is basically the 1st quadrant operation while the speed and torque have the same polarity. The motor operates in the 4th quadrant when the torque is negative and the motor is being pushed by external source.

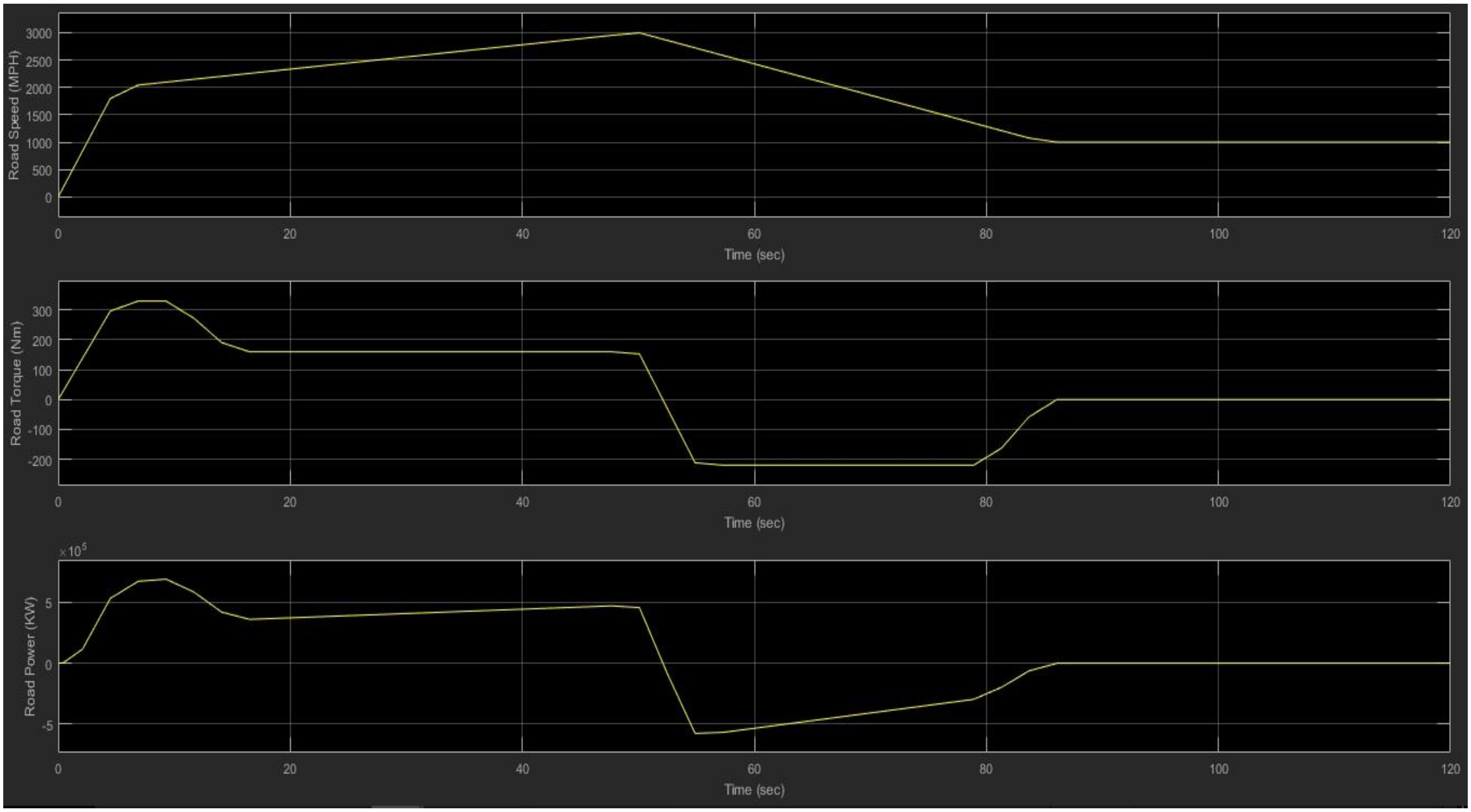


Fig. 7.6 Road speed, torque and power (Motoring and regeneration)

7.4.2 Motor outputs

The motor gets it's required power from the battery as shown in fig. 7.7. From the comparison of fig. 7.6 and fig. 7.7 it can be seen that the voltage and speed curves and the torque and current curves generally follow each other [66]. Both motoring and regeneration are shown by the power plot. The motoring operation occurs when the voltage and current have positive values. During this stage, the motor provides torque in the direction of rotation and transfers powers to the load. Whereas, in the regeneration mode the voltage and current have opposite direction which converts the motor into a generator and the power is being supplied by the generator to the battery.

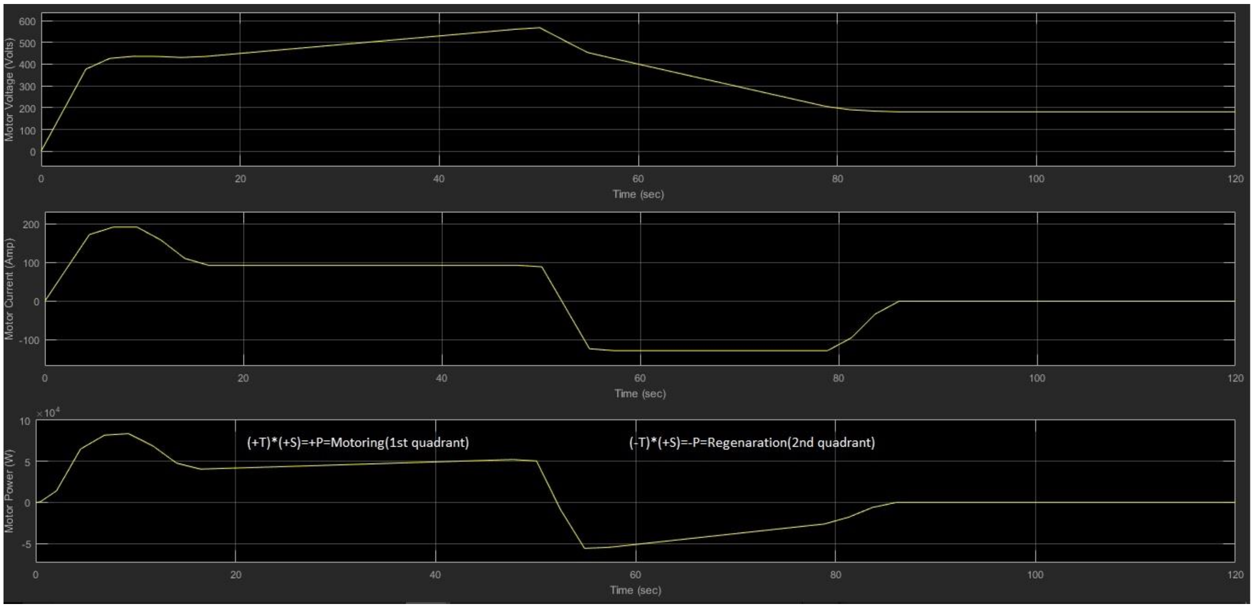


Fig. 7.7 Motor outputs

7.4.3 Battery outputs

The battery block outputs are basically the required voltage, current and power by the motor. As torque is proportional to current, it can be seen from the comparison of fig. 7.6, fig. 7.7, fig. 7.8 that the motor torque, current and battery current are almost similar. The current drawn from the battery increases over time along with the increasing torque of the motor. The energy consumption during motoring and the generation of energy through regenerative braking can be obtained by integrating the power curve. This is done using the trapezoidal rule function in MATLAB editor panel. This shows the resulting energy consumption in Watt-seconds which is afterwards divided by 3600 to get the energy consumption in terms of Watt-hours. Through this process, the calculated energy consumption during the motoring and the energy formation during regeneration is 715.2Watt-hours and -432.25Watt-hours.

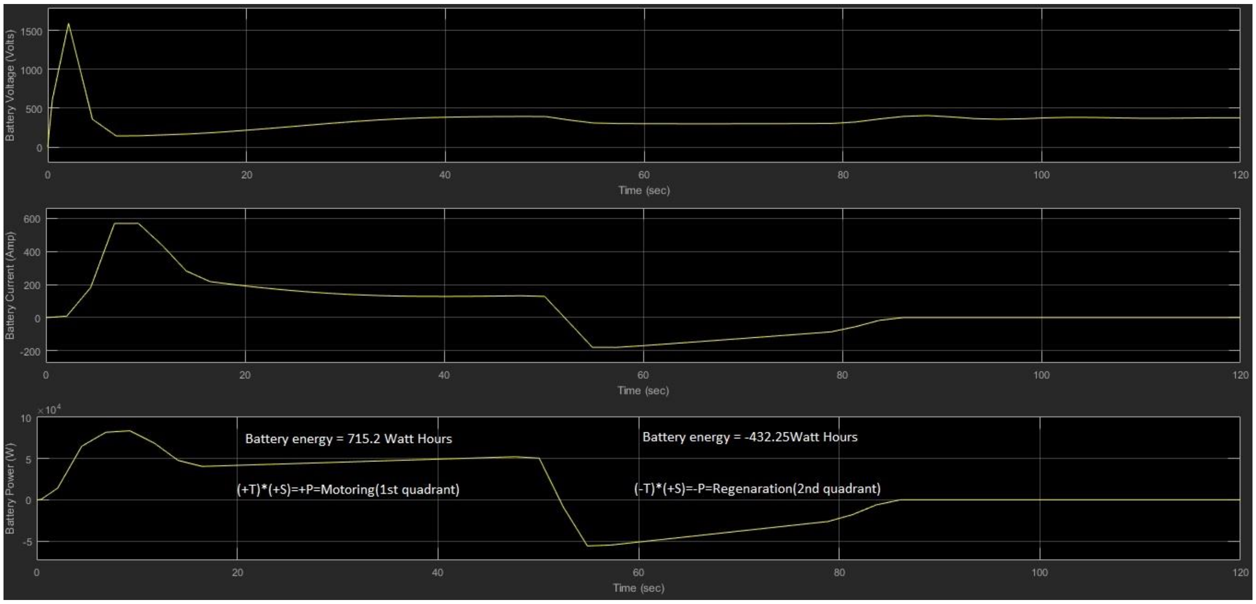


Fig. 7.8 Battery outputs

7.4.4 Battery voltage error (Err_bat)

The battery voltage error is generated as the output of the battery block. The battery voltage error comes from the comparison of the actual internal battery voltage (E_bat_{actual}=375V) with the calculated one. The calculated battery voltage depends on the motor voltage and current values.

The error varies in a large scale from negative to positive values and within a moment it drops down to zero as the controller starts sending the feedback signals to neutralize the error. As it can be seen from the fig. 7.9 that an error of almost -390 occurs initially due to the natural response of the simulation and a maximum positive error of around 1200 occurs when the motor starts operating. This high error achieved by the motor is because of the very high current when it starts. The negative error achieved afterwards represents the regeneration process. The change in current polarity reverses the I_L*R_{bat} term in battery terminal voltage equation which reduces the actual internal voltage. Thus the difference between the actual and calculated battery voltage comes out negative resulting in a negative battery error signal. Even though the errors are pretty high in the initial stage but they drop down to a very low value within a few seconds and throughout the simulation process it remains close to zero.

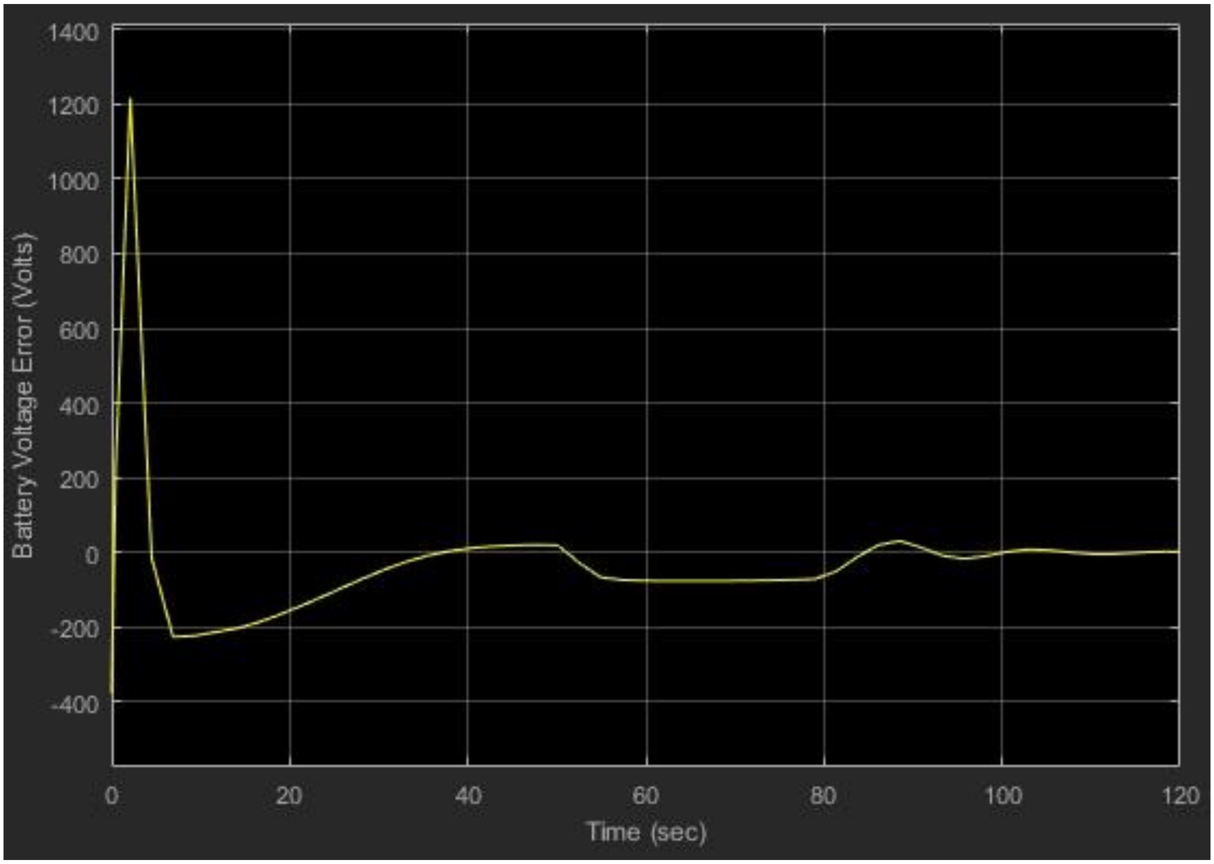


Fig. 7.9 Battery voltage error

7.4.5 PI controller output

The output of the PI controller model provides the motor controller gain (K_C). The controller gain varies according to the motor speed. The minimum value of the PI controller gain is 0.1 and the maximum is 2.9 as shown in fig. 7.10. The controller keeps the system stable with a proper response to the changes in the system by the proportional signal while the integral signal works to reduce the constant errors by integrating that signal over time. This is done by the Kp and Ki constants of the controller which was obtained by trial and error and from the tuning process in MATLAB Simulink platform.

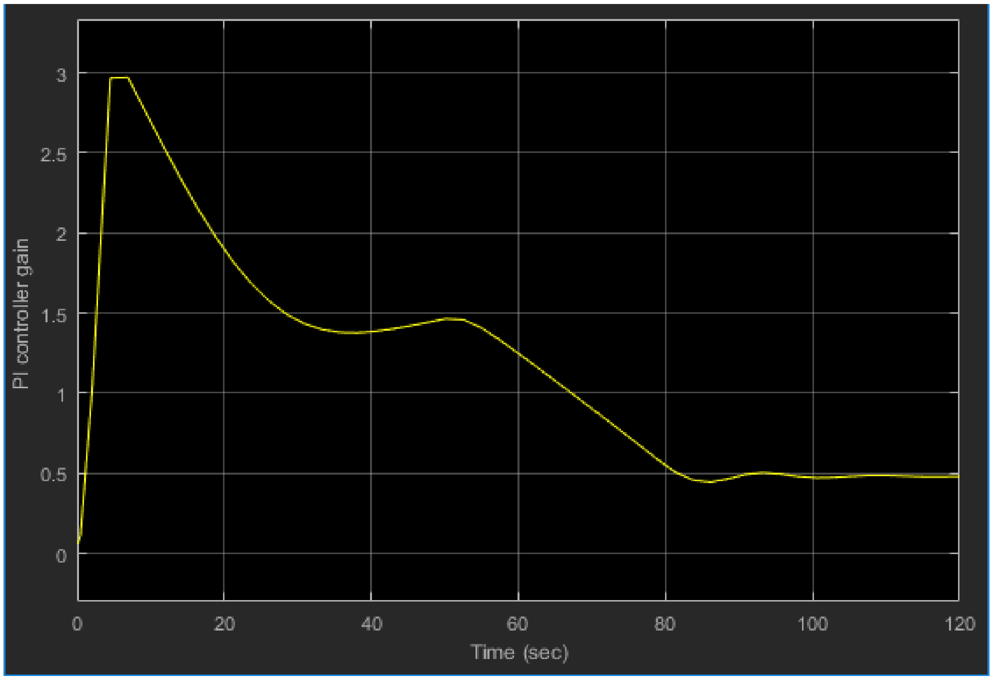


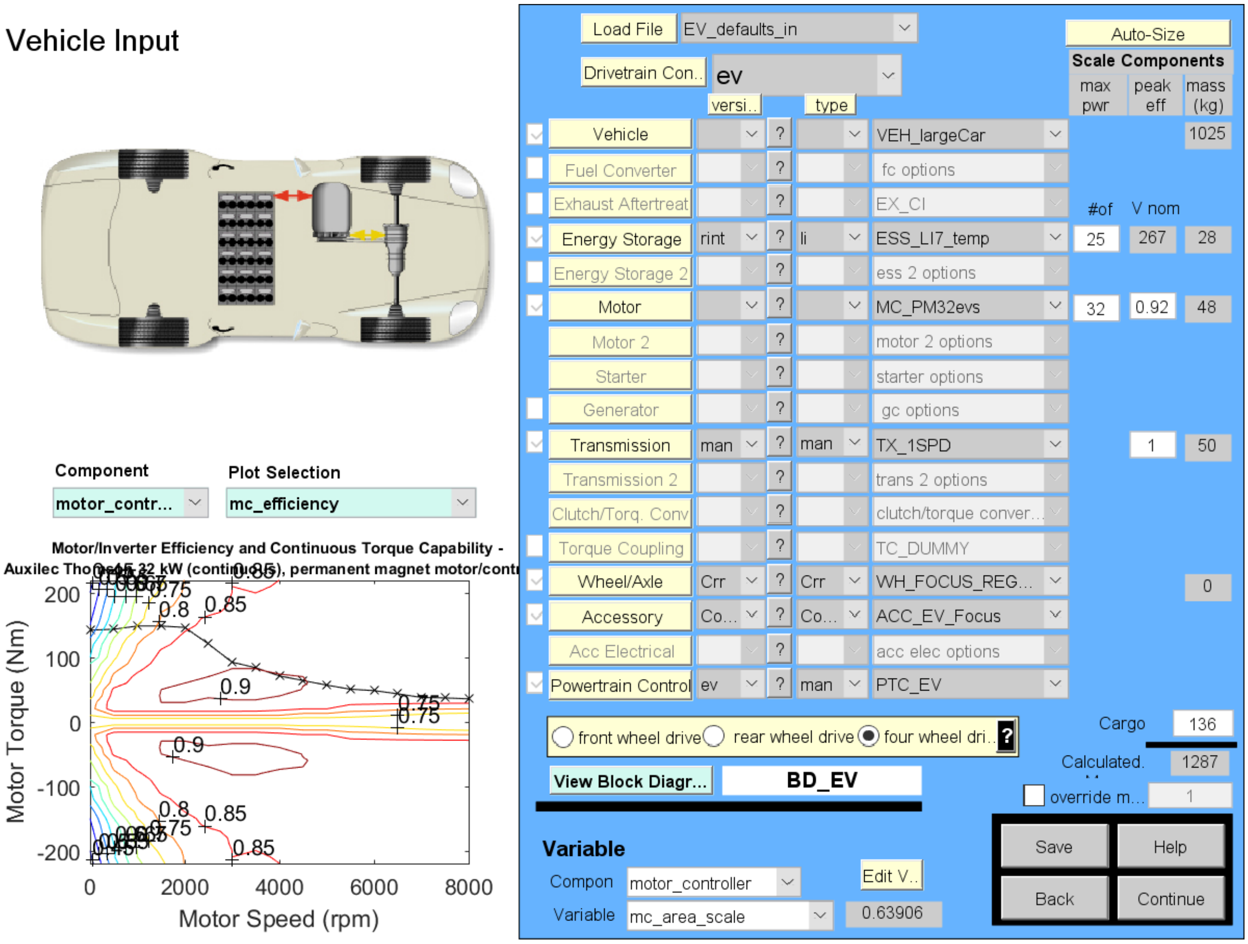
Fig. 7.10 PI controller gain

7.5 Advisor Simulation

For the simulation of the Electric Vehicle, we have selected the Advisor software which is a toolbox in MATLAB. It is highly flexible and versatile in designing vehicles and takes several parameters into account including ambient temperature and the cooling down of the motor controller amongst several others.

7.5.1 Electric Vehicle Input and Block Diagram

The input we have selected for the simulation of our Electric Vehicle can be seen by the figure below:



Component: motor_contr...
Plot Selection: mc_efficiency

Load File: EV_defaults_in
Drivetrain Con..: ev

☑ Vehicle — VEH_largeCar — 1025
☐ Fuel Converter — fc options
☐ Exhaust Aftertreat — EX_CI
☑ Energy Storage — rint — li — ESS_LI7_temp — 25 — 267 — 28
☐ Energy Storage 2 — ess 2 options
☑ Motor — MC_PM32evs — 32 — 0.92 — 48
Motor 2 — motor 2 options
Starter — starter options
☐ Generator — gc options
☑ Transmission — man — man — TX_1SPD — 1 — 50
Transmission 2 — trans 2 options
Clutch/Torq. Conv — clutch/torque conver...
☐ Torque Coupling — TC_DUMMY
☑ Wheel/Axle — Crr — Crr — WH_FOCUS_REG... — 0
☑ Accessory — Co... — Co... — ACC_EV_Focus
Acc Electrical — acc elec options
☑ Powertrain Control — ev — man — PTC_EV

○ front wheel drive ○ rear wheel drive ● four wheel dri..

Cargo: 136
Calculated: 1287
☐ override m...: 1

BD_EV

Compon: motor_controller
Variable: mc_area_scale — 0.63906

Fig. 7.11 Input Parameters of Electric Vehicles

For the input we have selected to load the EV_defaults.in with the EV drivetrain. We simulated a large car using the lithium ion battery as the energy storage system with Rint (internal resistance). The motor controller uses PM32evs which is the motor controller using a permanent magnet of 32kWs as the maximum power. The transmission selected was manual and TX_1SPD. This means that the vehicle simulated will have only one gear so it does not really matter if it is manual or auto. We have selected manual in this case because the auto configuration was not compatible with one or more settings of this input window. As for the wheels/axles a type with focus regenerative power was selected as is the case with most Electric Vehicles. Crr stands for constant co-efficient of rolling resistance. For the accesory setting the Co wass selected, also with a focus on EV. Co stands for constant power accessory load models. Using these settings the overall mass of the Electric vehicle comes out to be 1287kg.

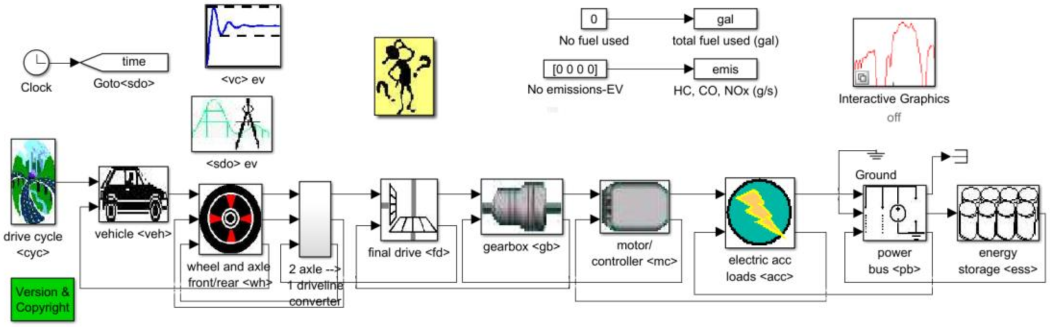


Fig. 7.12 Block Diagram of the designed Electric Vehicle

The block diagram of the simulated Electric vehicle can be seen above. Here, the drive cycle (which will be shown in later segments of this chapter) is put in as the input and the other input comes through the wheel and axle; either the front wheel, rear wheel or both into to the electric vehicle. From here, the output produced by the vehicle is transferred to the wheel and axle along with another input coming in from the 2 axles and 1 driveline converter. This driveline converter is being controlled by the final drive produced and the output of the wheels and axles. The ouputs produced by the wheel is then input to the driveline converter as a feedback loop. In every step, there is a strong feedback system associated with the previous block in the block diagram of the vehicle; which is to be expected. Next, the driveline converter's output goes to the final drive of the electric vehicle which is controlled by the differential in the gearbox. This allows for different wheels to rotate at different torques, independent of each other. The gearbox is controlled by the motor/controller and the output produced by the final drive and in turn the motor/controller is dependent on the rpm output of the gearbox. The last 3 blocks comprise of the electric accessory loads, power bus and the energy storage. Looking above at the upper right corner it can also be seen that no kinds of emissions are produced and no fuel in gallons are used which is otherwise present for fuel cell cars.

7.5.2 Individual Component Analytics

Next we will look into each of the components separately and their analytics in a graphical format.

Motor/Controller

First comes the motor/controller, which is in this case the inverter using the setting of PM_32evs (Permanent magnet 32 kW for evs) and this is given by the following figure:

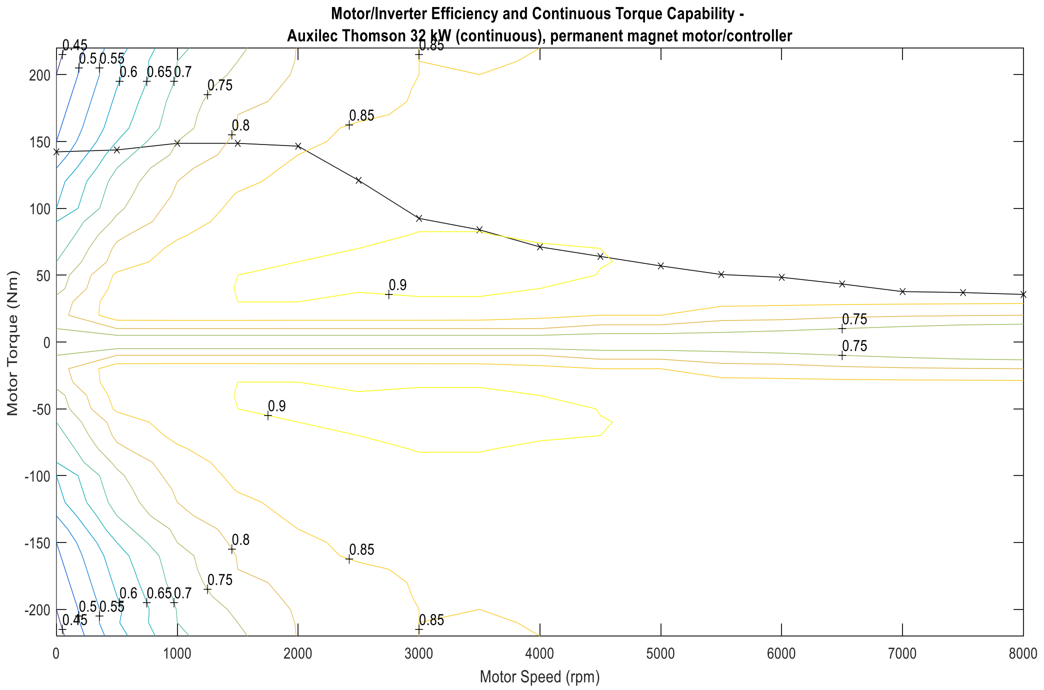


Fig. 7.13 Motor/Inverter Efficiency and Continuous Torque Capability for 32kW, Auxilec Thomson, permanenent magnet motor/contoller

Here, we can see that for the 32kW Auxilec Thomson, permanent magnet motor/controller, the motor's torque increases silightly from approximately 142 to 150 and then as the motor's speed increases from roughly 2000, the motor's torque shows decline. As the motor's speed goes up further, the motor's torque, in Nm, starts to decrease over the whole range of 2000-8000 and the motor's torque falls to 40 Nm. The other points which can be seen on the countours of the input map correspond to the efficiencies of the controller unit. The negative portions on the map corresponds to the motor acting as a generator and their efficiencies can also be seen.

With a PM_16evs (permanent magnet 16kWs) setting selected, the following graph is shown as the output:

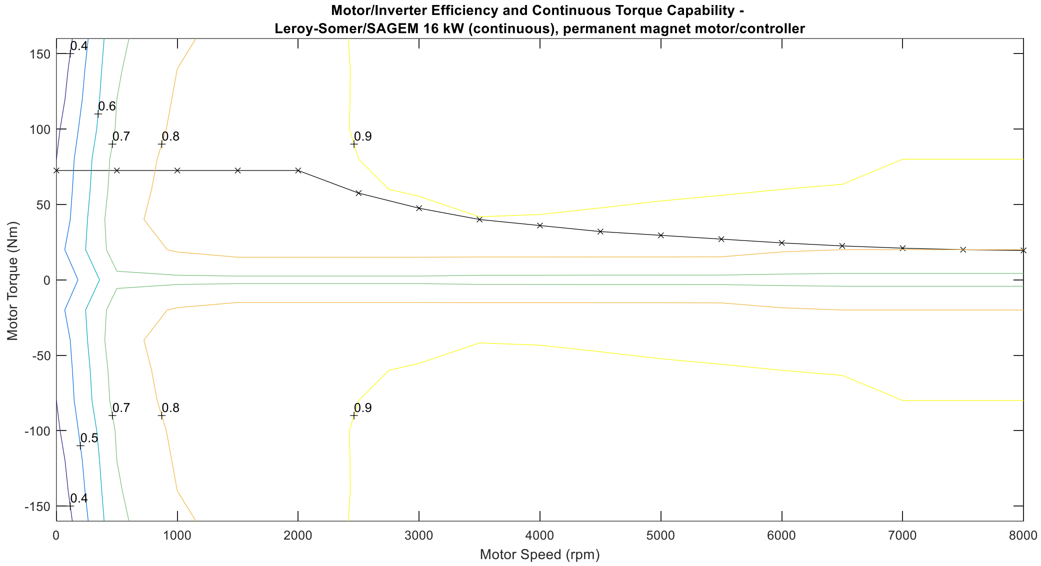


Fig. 7.14 Motor/Inverter Efficiency and Continuous Torque Capability for 16kW, Leroy-Somer, permanenent magnet motor/contoller

Here, we can see that for the 16kW Leroy-Somer, permanent magnet motor/controller, the motor's torque is quite constant from 75 Nm from the motor speed (in rpm) of 0 to 2000, and then as the motor's speed goes up further, the motor's torque, in Nm, starts to decrease over the whole range of approximately 2000-8000 and the motor's torque falls to about 25 Nm. The other points which can be seen on the countours of the input map correspond to the efficiencies of the controller unit. The negative portions on the map corresponds to the motor acting as a generator and their efficiencies can also be seen.

7.5.3 Energy Storage Systems

Next the plots for the energy storage systems (ESS settings) and their output graphs are displayed.

Ess_rint (Internal Resistance)

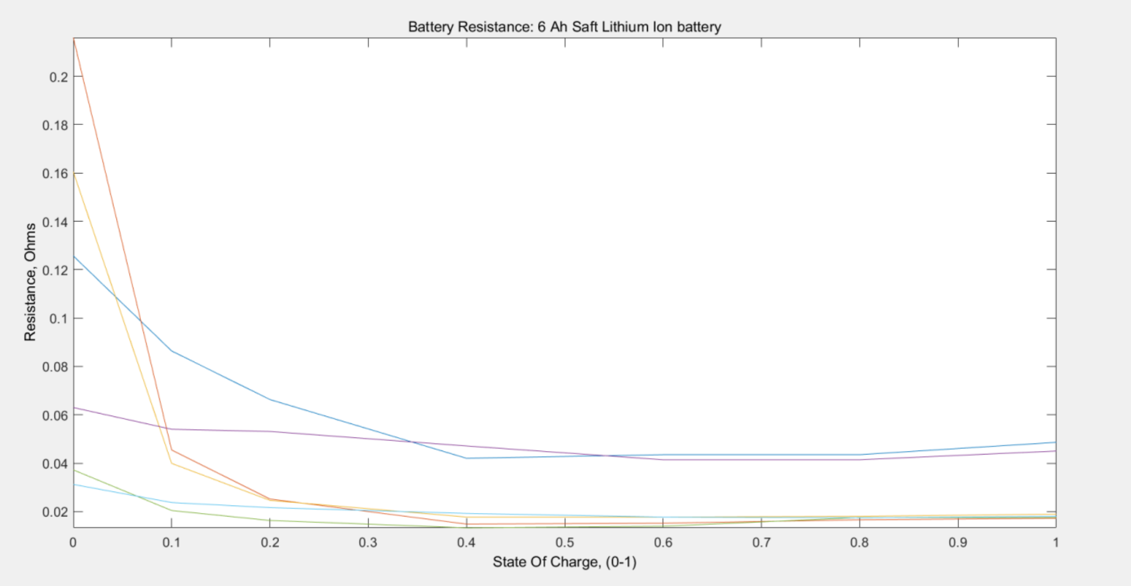


Fig. 7.15 Change in internal resistance with the increase of state of charge

Here several graphs are displayed for the Lithium Ion battery, with a 6Ah rating at different temperatures. These batteries simulated were manufactured by Saft, a well renowned battery manufacturer. These data have been provided by Saft themselves, and we can see how state of charge (SOC) through the range of 0 to 1 varies with internal resistance. As the state of charge of the battery increases, the internal resistance of the battery to being charged drops. The highest internal resistance of the battery is there when the battery is empty for every case.

Ess_Voc (Open circuit voltage)

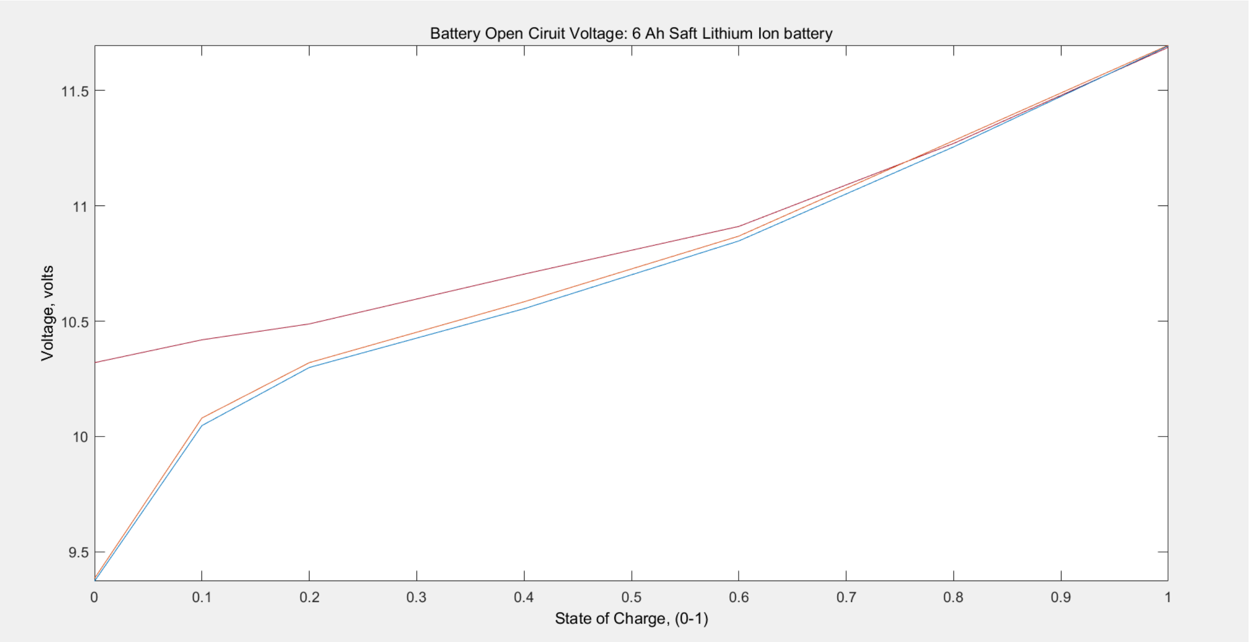


Fig. 7.16 Change in open circuit voltage with the increase of state of charge

These plots shows how the open circuit voltage of the batteries vary over the state of charge of the battery from 0 to 1 at different temperatures. When the battery is empty and no charge is present, the voltage of the open circuit is 0. As the battery is charged up, the voltage across it increases reaching a value of approximately 11.75V.

Ess_pwer (Instantaneous power)

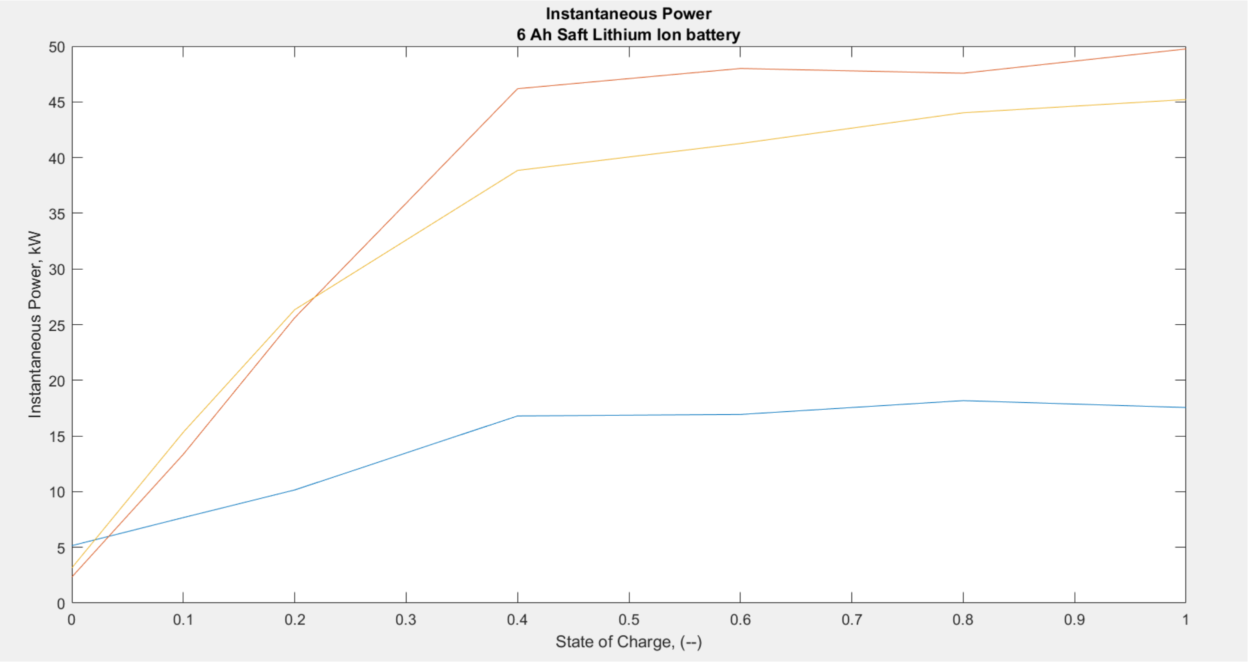


Fig. 7.17 Instantaneous Power delivered in kW, with different SOCs

These plots show the instantaneous power, in kW, delivered by the 6Ah Lithium ion batteries over different temperatures. As the batteries' state of charge increases, the instantaneous power, in kWs which can be delivered by the battery module increases.

Roundtrip efficiency

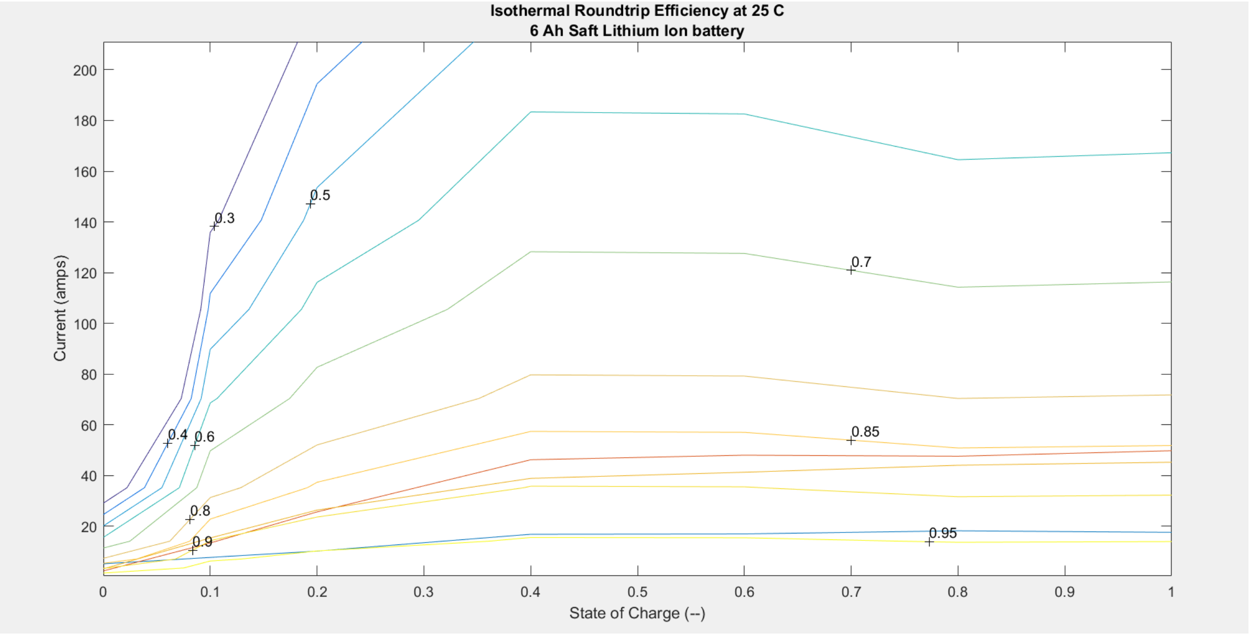
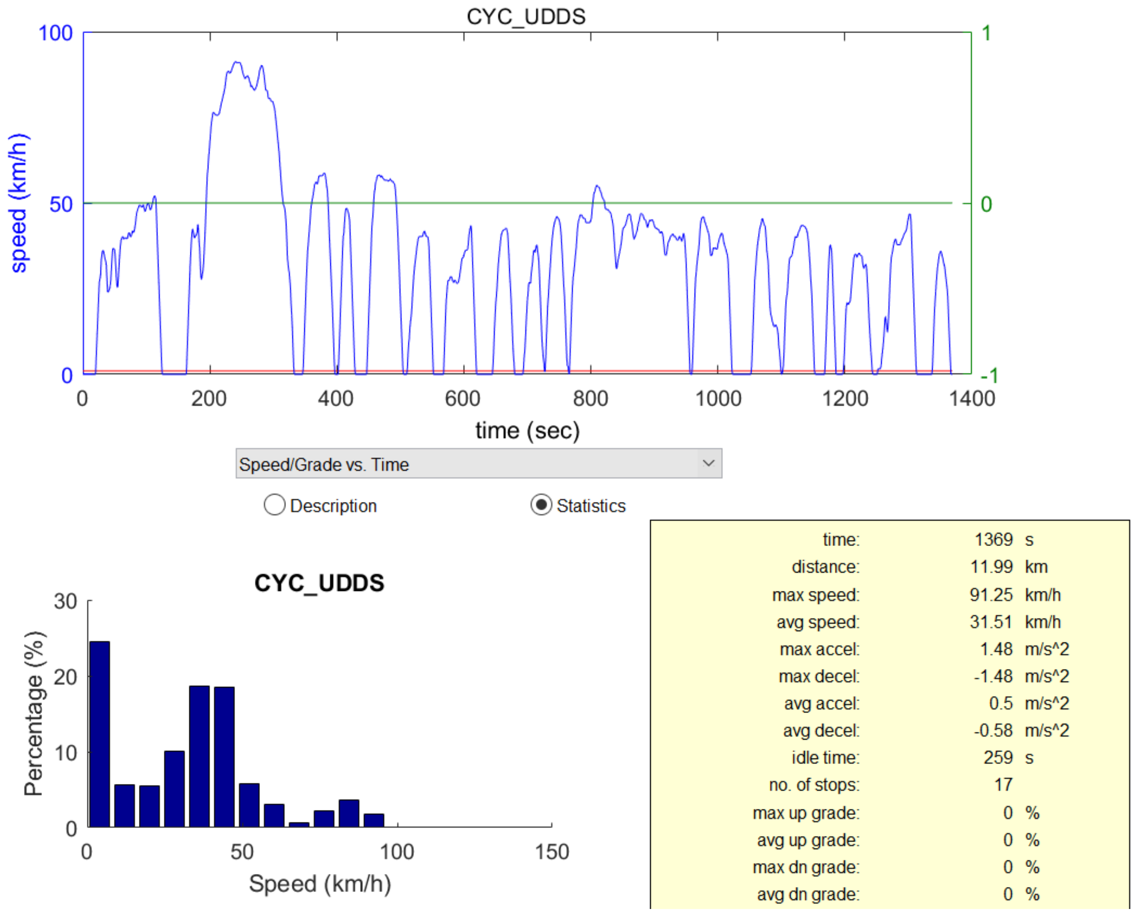


Fig 7.18 Roundtrip Efficiencies at 25 degrees Celsius

Finally comes the round-trip efficiency offered by the 6Ah Saft Li-ion battery over the entire SOC range from 0 to 1 for different currents, keeping the temperature constant at 25 degrees Celsius. The round-trip efficiency is the fraction of energy which is put into the battery and is possible to be recovered. These efficiencies are plotted as contours on the map. It can be seen that higher efficiencies result with lower amperes of current.

7.5.4 Input Drive Cycle and Outputs

Previously, we have investigated the individual components' analyses, block diagram and the inputs subjected to the EV. Now, we shall apply a drive cycle to the input of the electric vehicle. A drive cycle is a predefined set of values of points which is typically speed vs. time. They are used to compare between vehicles, such as the efficiency or emmissions produced. Here, we are applying the UDDS drive cycle to our simulated Electric Vehicle. UDDS stands for Urban Dynamometer Driving Schedule, as it is a very common and universal one.

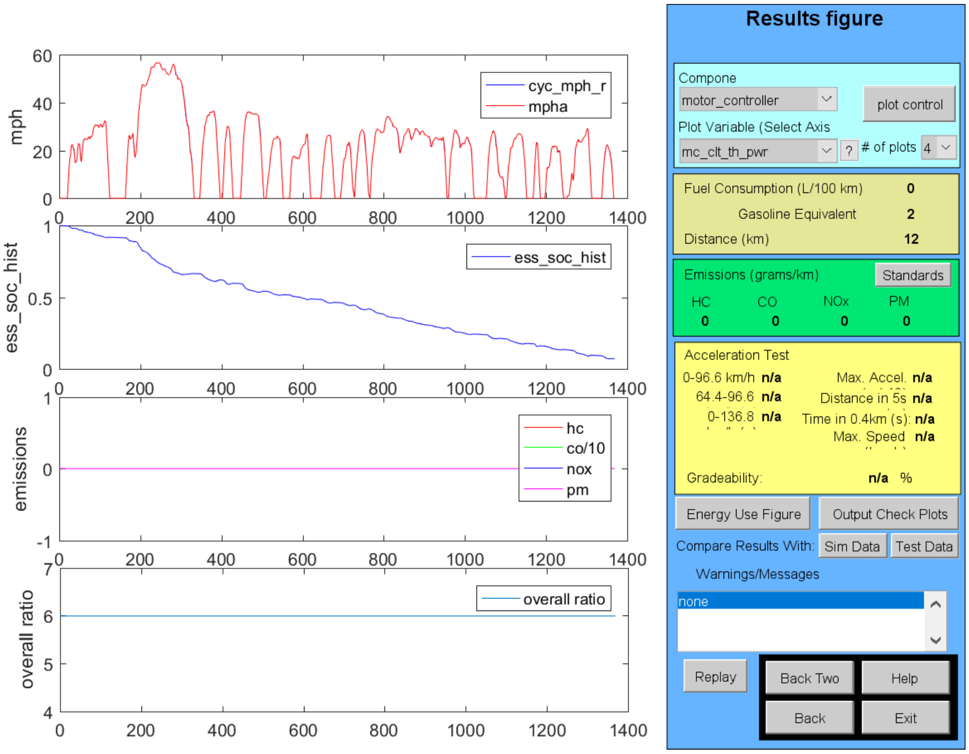


time:	1369	s
distance:	11.99	km
max speed:	91.25	km/h
avg speed:	31.51	km/h
max accel:	1.48	m/s^2
max decel:	-1.48	m/s^2
avg accel:	0.5	m/s^2
avg decel:	-0.58	m/s^2
idle time:	259	s
no. of stops:	17	
max up grade:	0	%
avg up grade:	0	%
max dn grade:	0	%
avg dn grade:	0	%

Fig. 7.19 UDDS Drive Cycle

The parameters defined by the UDDS cycle is defined by the table on the lower right hand and the bar chart shows the different speeds and percent of each speed represented by the UDDS drive cycle.

Using this drive cycle as input, for normal vehicles we can observe emissions to be present as seen in the diagram below:



Results figure

Compone
motor_controller

Plot Variable (Select Axis
mc_clt_th_pwr
# of plots 4

Fuel Consumption (L/100 km) 0
Gasoline Equivalent 2
Distance (km) 12

Emissions (grams/km)

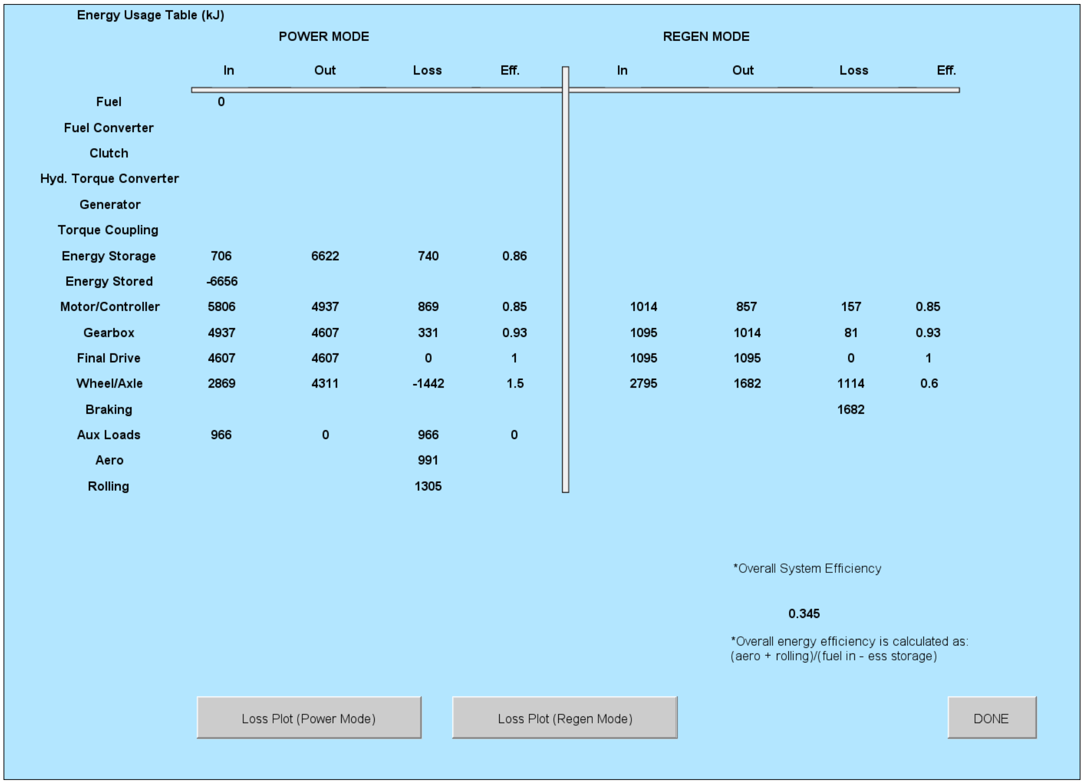
HC	CO	NOx	PM
0	0	0	0

Acceleration Test
0-96.6 km/h n/a
64.4-96.6 n/a
0-136.8 n/a
Max. Accel. n/a
Distance in 5s n/a
Time in 0.4km (s): n/a
Max. Speed n/a
Gradeability: n/a %

Warnings/Messages
none

Fig. 7.20 Emissions and Change of SOCs for Pure Electric Vehicles

However, when we are selecting Electric Vehicles as the input to the drive cycle; we get the following figure which shows that there are no emissions, which is to be expected. The State of charge history over the time in seconds is also shown.



Energy Usage Table (kJ)

	POWER MODE				REGEN MODE			
	In	Out	Loss	Eff.	In	Out	Loss	Eff.
Fuel	0							
Fuel Converter								
Clutch								
Hyd. Torque Converter								
Generator								
Torque Coupling								
Energy Storage	706	6622	740	0.86				
Energy Stored	-6656							
Motor/Controller	5806	4937	869	0.85	1014	857	157	0.85
Gearbox	4937	4607	331	0.93	1095	1014	81	0.93
Final Drive	4607	4607	0	1	1095	1095	0	1
Wheel/Axle	2869	4311	-1442	1.5	2795	1682	1114	0.6
Braking							1682	
Aux Loads	966	0	966	0				
Aero			991					
Rolling			1305					

*Overall System Efficiency

0.345

*Overall energy efficiency is calculated as:
(aero + rolling)/(fuel in - ess storage)

Fig. 7.21 Energy Usage Table in KJs for Power Mode and Regeneration Mode

The above table results shows a 34.5% Efficiency for the simulated car under the UDDS drive cycle.

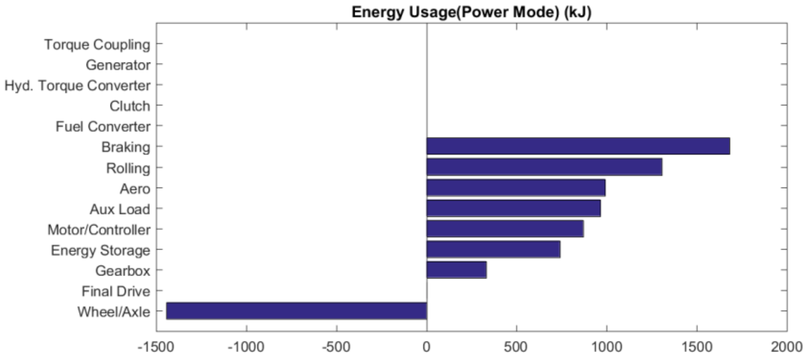


Fig. 7.22 Loss Plot for Power Mode

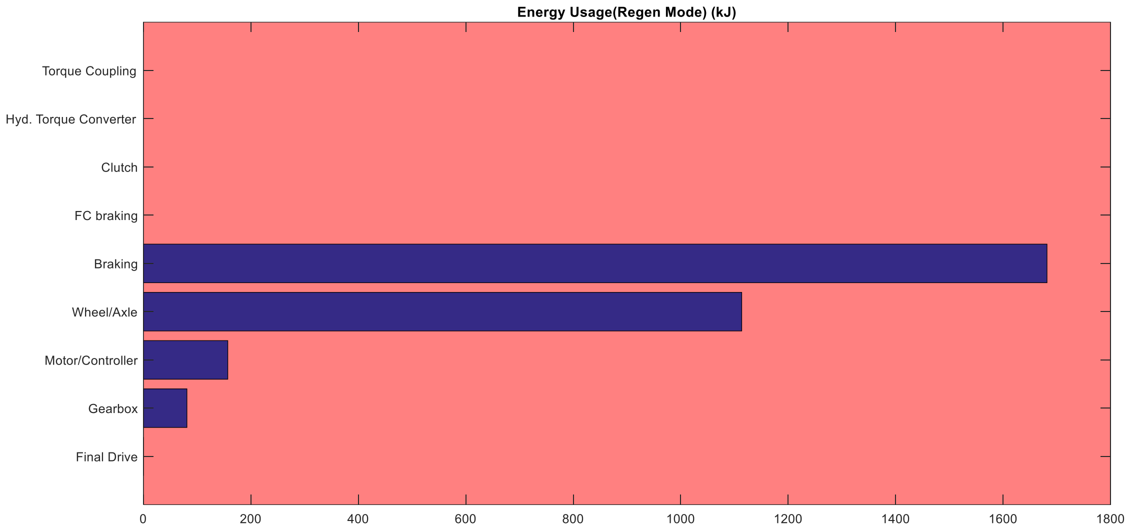


Fig. 7.23 Loss Plot for Regeneration Mode

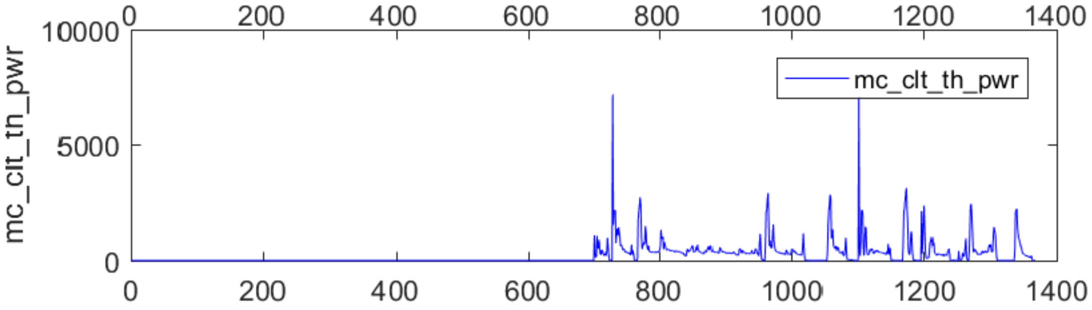


Fig 7.24 Heat Removed by Coolant from the motor/controller in Watts

For the simulated vehicle, the heat removed by coolant (mc_clt_th_pwr) from the motor/controller is shown above. The units are in Watts and the x-axis represents the time in seconds. We can see that initially no cooling was required for cooling down the motor, however, as time went by it was eventually necessary over the drive cycle.

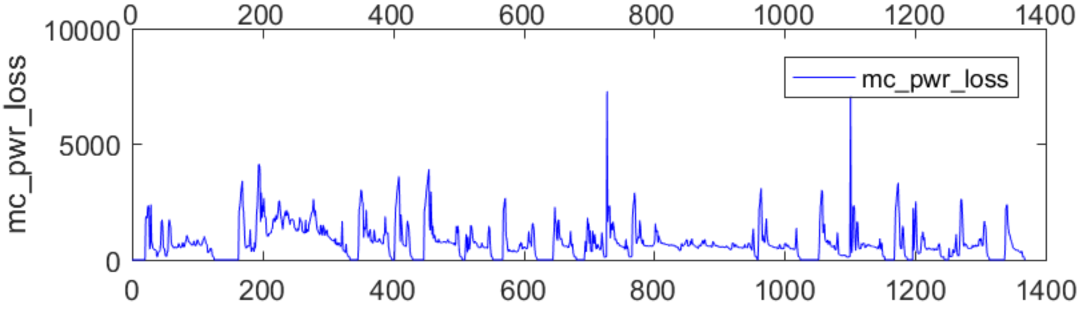


Fig. 7.25 The power lost over the drive cycle for the motor/controller

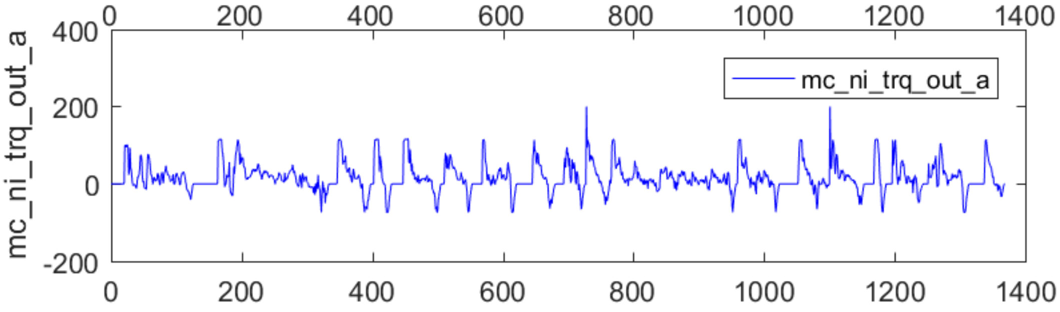


Fig. 7.26 Rotor drive torque in Nm

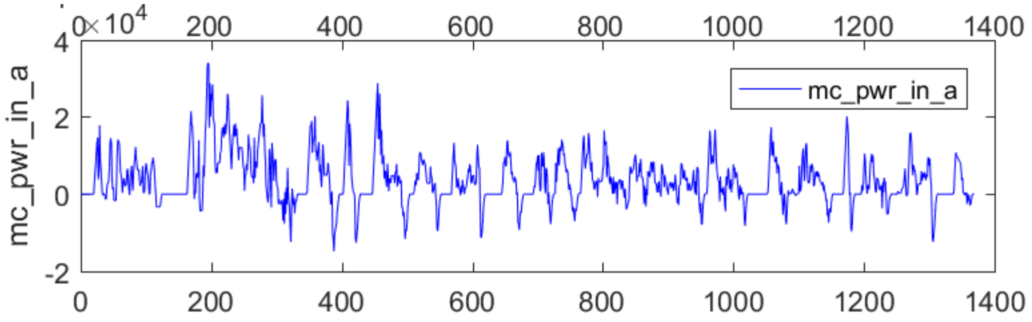


Fig. 7.27 Power available to the motor/controller in Watts

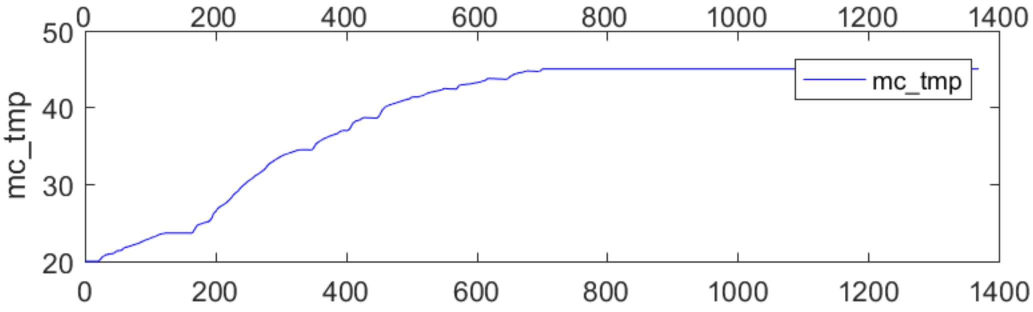


Fig. 7.28 The average temperature of the motor/controller

The temperature is represented in degrees. Over time the temperature gradually increases before coming to a constant value of approximately 47 degrees Celsius over the drive cycle.

:

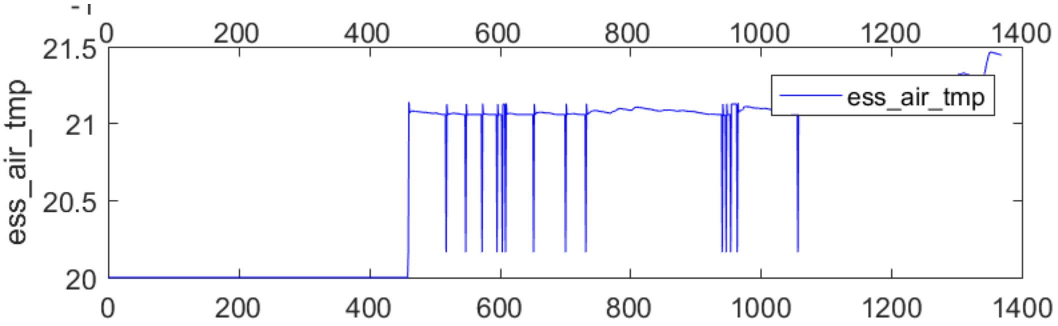


Fig. 7.29 the outputs for the Energy storage system

The average temperature here is measured in degrees Celsius. Here, initially cooling air was not required, however, over time it was necessary to be applied as the battery heats up.

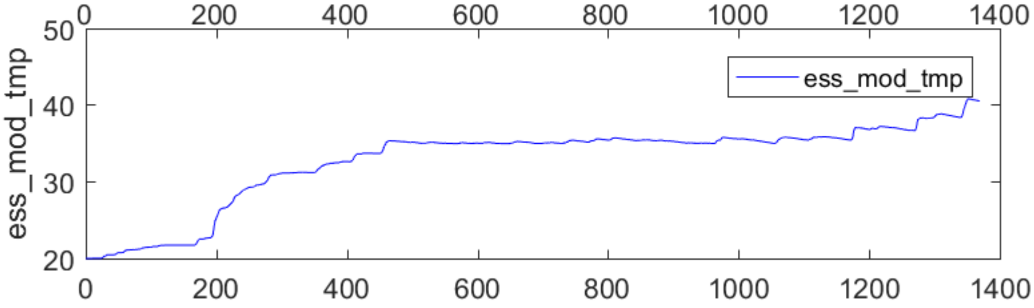
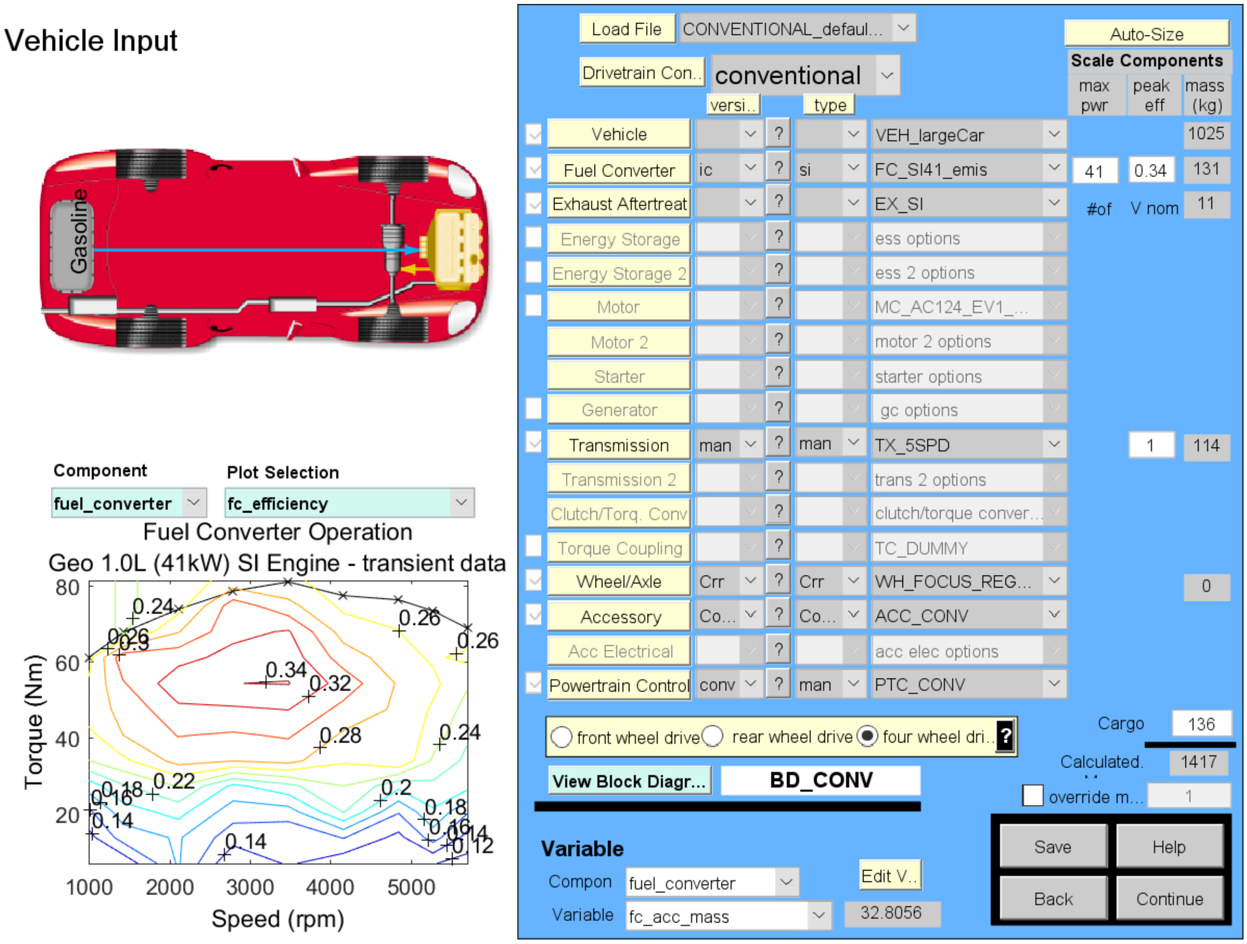


Fig. 7.30 The average temperature of the battery module overtime

The temperature measured is in degrees Celsius.

The above examples for the select parameters were carried out under the UDDS drive cycle applied as the input. By using different kinds of drive cycles one can find similar plots for Electric Vehicles and their respective efficiencies under those conditions. Several kinds of drive cycles and their descriptions have been given below at the end of this chapter.

7.5.5 IC Vehicle Inputs and Block Diagram



Component: fuel_converter
Plot Selection: fc_efficiency

Load File: CONVENTIONAL_defaul...
Drivetrain Con..: conventional

☑ Vehicle: VEH_largeCar — 1025
☑ Fuel Converter: ic, si, FC_SI41_emis — 41, 0.34, 131
☑ Exhaust Aftertreat: EX_SI — 11
☐ Energy Storage: ess options
☐ Energy Storage 2: ess 2 options
☐ Motor: MC_AC124_EV1_...
Motor 2: motor 2 options
Starter: starter options
☐ Generator: gc options
☑ Transmission: man, man, TX_5SPD — 1, 114
Transmission 2: trans 2 options
Clutch/Torq. Conv: clutch/torque conver...
☐ Torque Coupling: TC_DUMMY
☑ Wheel/Axle: Crr, Crr, WH_FOCUS_REG... — 0
☑ Accessory: Co..., Co..., ACC_CONV
Acc Electrical: acc elec options
☑ Powertrain Control: conv, man, PTC_CONV

○ front wheel drive ○ rear wheel drive ● four wheel dri..

Cargo: 136
Calculated: 1417
☐ override m...: 1

View Block Diagr...: BD_CONV

Variable

Compon: fuel_converter
Variable: fc_acc_mass — 32.8056

Fig. 7.31 Input Parameters of traditional IC Vehicles

For the traditional conventional vehicle, the internal combustion fuel converter is chosen with the spark ignition option. The wheels were chosen with a focus on regeneration of power. The accessory and powertrain controls were selected as conventional and the four wheel drive option was selected. A manual transmission with 5 speed gears was selected as the input option for the transmission.

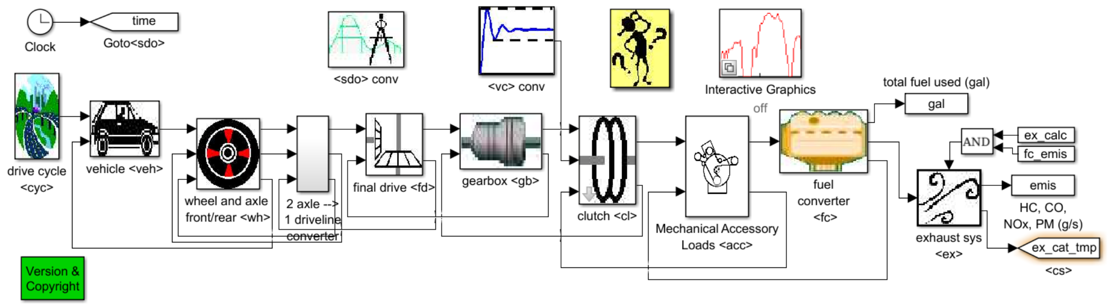
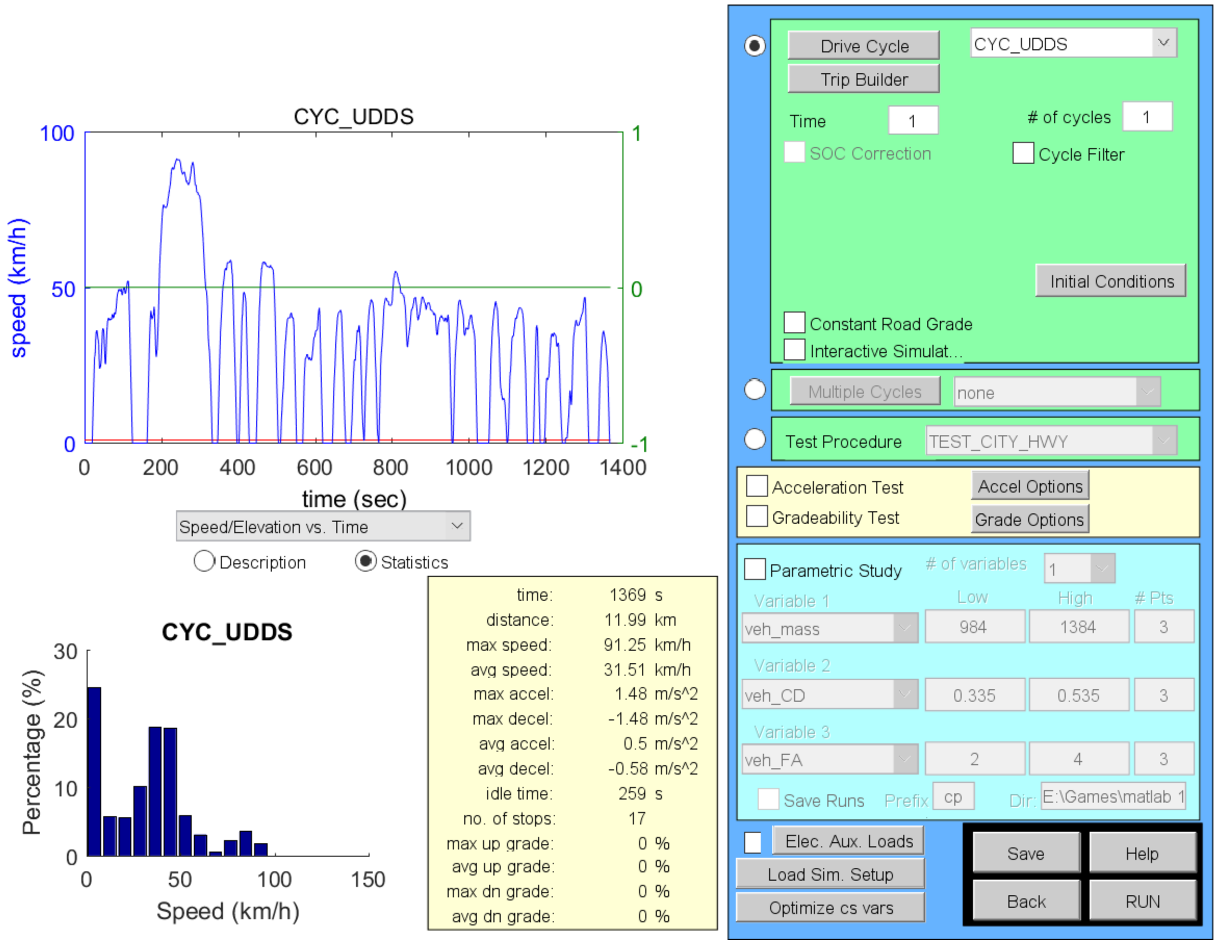


Fig. 7.32 Block Diagram of the designed IC Vehicle

The block diagram for the internal combustion model is shown as above. Up to the gearbox section, the IC conventional vehicle works in the same manner as the Electric Vehicle had operated. Here, instead of the motor/controller unit, electrical accessories, power bus and energy storage unit which was present on the Electric Vehicle's block diagram; it is instead replaced with the clutch, mechanical accessory loads, and the fuel converter. The clutch here ensures a smooth transition from one transmission gear to another for optimal driving smoothness. In the Electric Vehicle's block diagram, this is not necessary as it uses one speed transmission and not five speeds. The inputs taken by the clutch here is from the gearbox and <vc> conv which stands for the vehicle control variables such as the engine. The mechanical accessory loads (the steering system as one example) also provide an input to the clutch. The clutch then; as it is being controlled, in turn, produces an output which controls the mechanical accessories of the vehicle. The last three blocks here, analogous to the Electric Vehicle, comprises of the mechanical accessory loads, fuel converter, exhausts and their outputs. In this case, however, there are emissions produced by the exhausts and fuel (in gallons) is also used up.

7.5.6 Input Drive Cycle and Outputs



time: 1369 s
distance: 11.99 km
max speed: 91.25 km/h
avg speed: 31.51 km/h
max accel: 1.48 m/s^2
max decel: -1.48 m/s^2
avg accel: 0.5 m/s^2
avg decel: -0.58 m/s^2
idle time: 259 s
no. of stops: 17
max up grade: 0 %
avg up grade: 0 %
max dn grade: 0 %
avg dn grade: 0 %

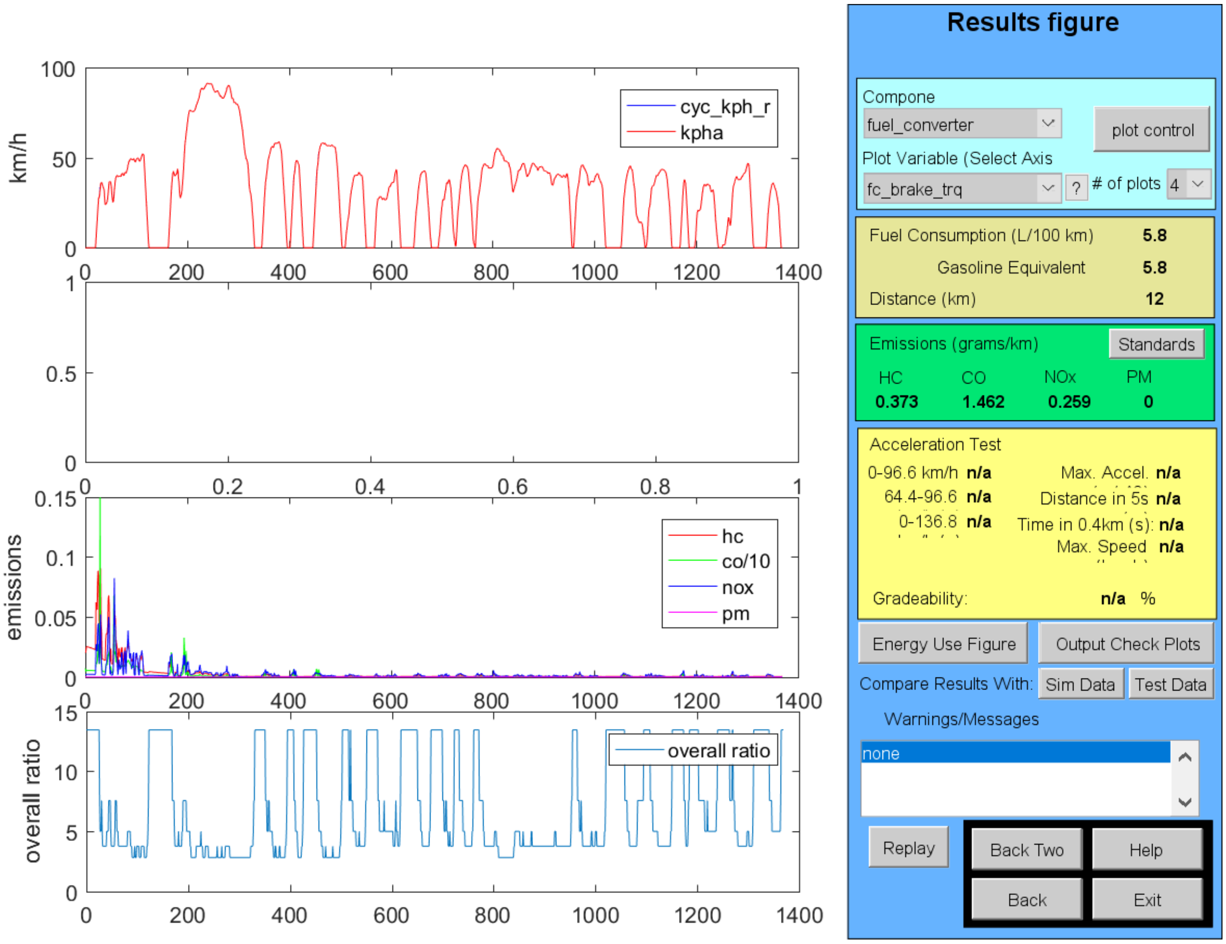
● Drive Cycle: CYC_UDDS
Time: 1
# of cycles: 1
☐ SOC Correction
☐ Cycle Filter
☐ Constant Road Grade
☐ Interactive Simulat...
○ Multiple Cycles: none
○ Test Procedure: TEST_CITY_HWY
☐ Acceleration Test
☐ Gradeability Test
☐ Parametric Study — # of variables: 1

	Low	High	# Pts
Variable 1: veh_mass	984	1384	3
Variable 2: veh_CD	0.335	0.535	3
Variable 3: veh_FA	2	4	3

☐ Save Runs Prefix: cp Dir: E:\Games\matlab 1
☐ Elec. Aux. Loads

Fig. 7.33 UDDS Drive Cycle

Here the UDDS driving cycle is shown which is applied as the input to the conventional vehicle. Details on this cycle have been outlined in the previous section.



Compone: fuel_converter

Plot Variable (Select Axis: fc_brake_trq

\# of plots: 4

Fuel Consumption (L/100 km)	5.8
Gasoline Equivalent	5.8
Distance (km)	12

Emissions (grams/km)

HC	CO	NOx	PM
0.373	1.462	0.259	0

Acceleration Test

0-96.6 km/h **n/a**

64.4-96.6 **n/a**

0-136.8 **n/a**

Max. Accel. **n/a**

Distance in 5s **n/a**

Time in 0.4km (s): **n/a**

Max. Speed **n/a**

Gradeability: **n/a** %

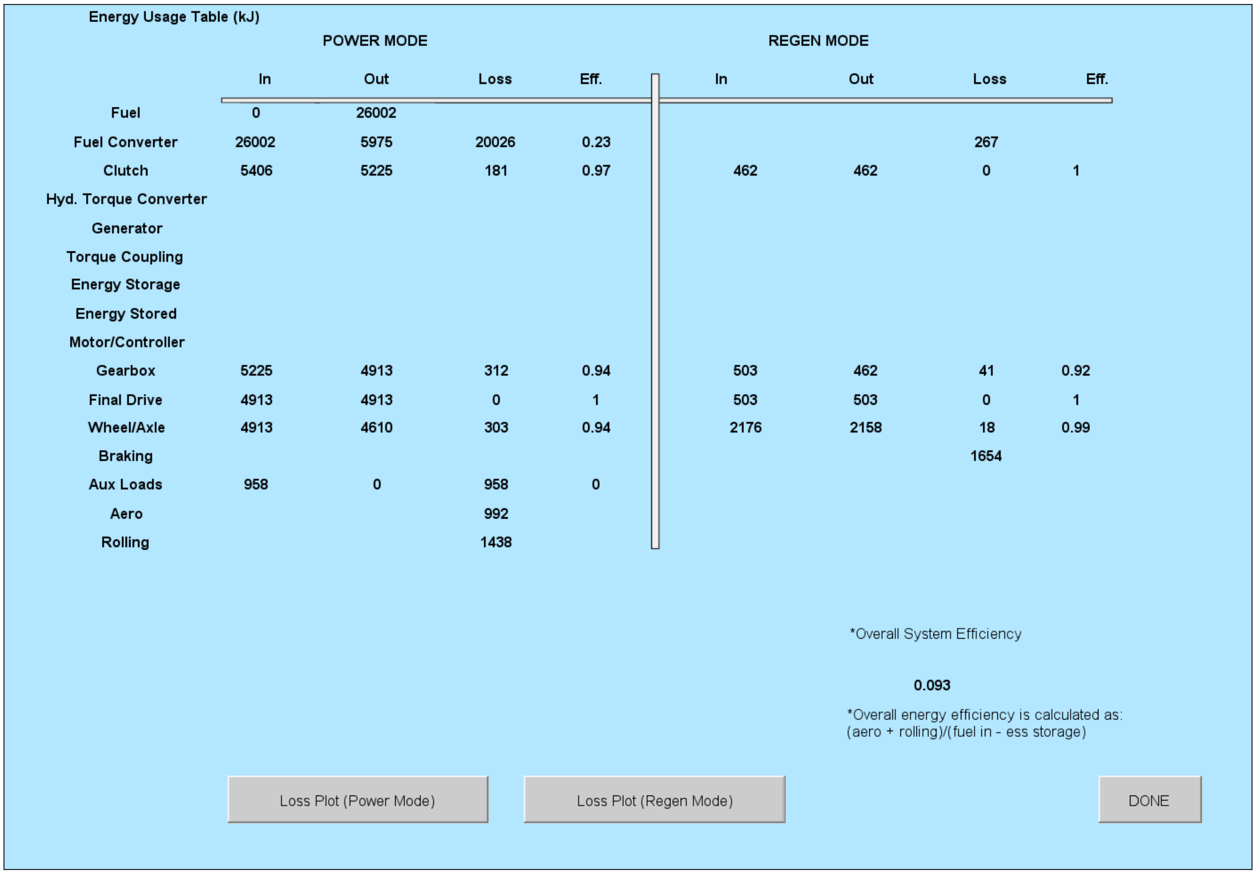
Compare Results With:

Warnings/Messages

none

Fig. 7.34 Emissions of IC Vehicles

Here, the output to the inputs described above can be seen. We can see that the emissions being produced initially is the highest as the vehicle is powered on. In Electric Vehicles these emissions are not present, and so, they are much cleaner for the environment. In the second figure, as compared to the Electric Vehicle's second figure, the SOC history is not present as the conventional vehicles do not possess an energy storage system.



Energy Usage Table (kJ)

	POWER MODE				REGEN MODE			
	In	Out	Loss	Eff.	In	Out	Loss	Eff.
Fuel	0	26002						
Fuel Converter	26002	5975	20026	0.23			267	
Clutch	5406	5225	181	0.97	462	462	0	1
Hyd. Torque Converter								
Generator								
Torque Coupling								
Energy Storage								
Energy Stored								
Motor/Controller								
Gearbox	5225	4913	312	0.94	503	462	41	0.92
Final Drive	4913	4913	0	1	503	503	0	1
Wheel/Axle	4913	4610	303	0.94	2176	2158	18	0.99
Braking							1654	
Aux Loads	958	0	958	0				
Aero			992					
Rolling			1438					

*Overall System Efficiency

0.093

*Overall energy efficiency is calculated as:
(aero + rolling)/(fuel in - ess storage)

Fig. 7.35a Energy Usage Table in KJs for Power Mode and Regeneration Mode

The overall efficiency of the system can be seen to be 9.3% over the UDDS cycle, which is the lowest, as compared to the simulated Electric Vehicle and the hybrid Toyota Prius (which shall be seen in the section to be followed). The data here shown is that of energy usage and the numbers are in kJ. The plots shown below show the loss plots for both the power mode and the regenerative mode.

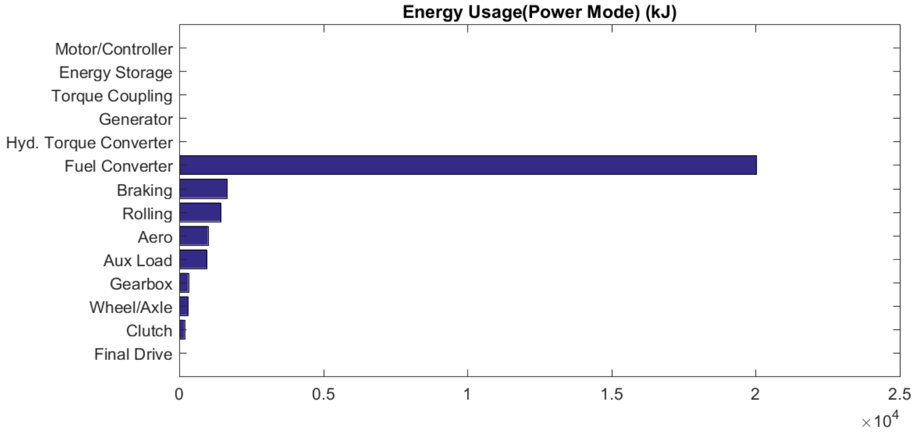


Fig. 7.35b Loss Plot for Power Mode

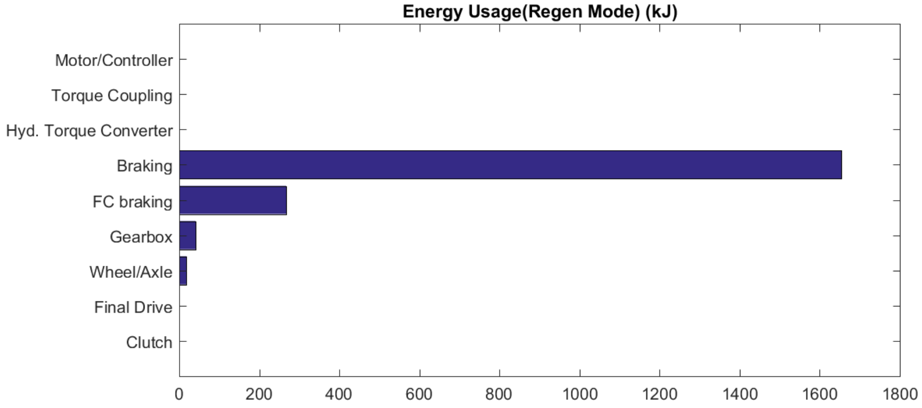


Fig. 7.35c Loss Plot for Regeneration Mode

Some select parameters' output for the gasoline vehicle are given below.

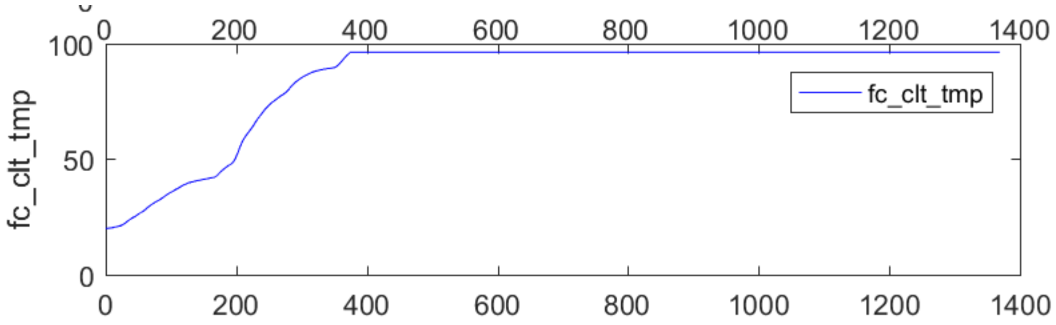


Fig. 7.36 Fuel converter's coolant Temperature

This figure shows the Fuel converter's coolant temperature over the UDDS cycle over time. Initially it starts at approximately 20 degrees Celsius and then at around 380 seconds or 6 minutes and 20 seconds, the coolant's temperature reaches its highest just below 100 degrees Celsius and maintains that over the rest of the cycle's duration.

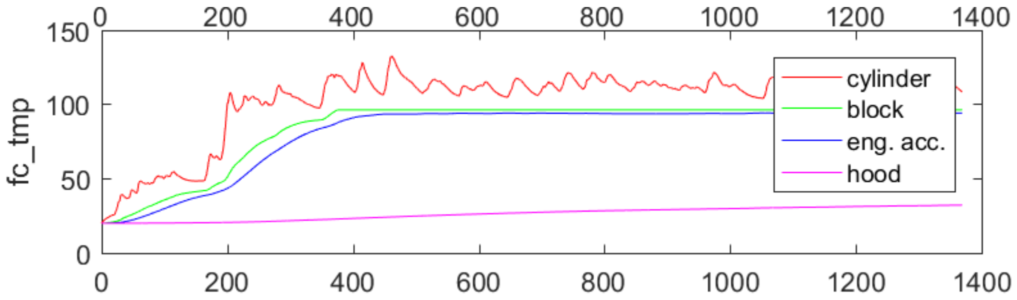


Fig. 7.37 Fuel Converter's Temperature in Degrees Celsius

The Fuel converter's temperatures are shown in this figure along the UDDS cycle. The highest temperature reached by the cylinder is approximately 140 degrees Celsius for the simulated vehicle subjected to the UDDS drive cycle.

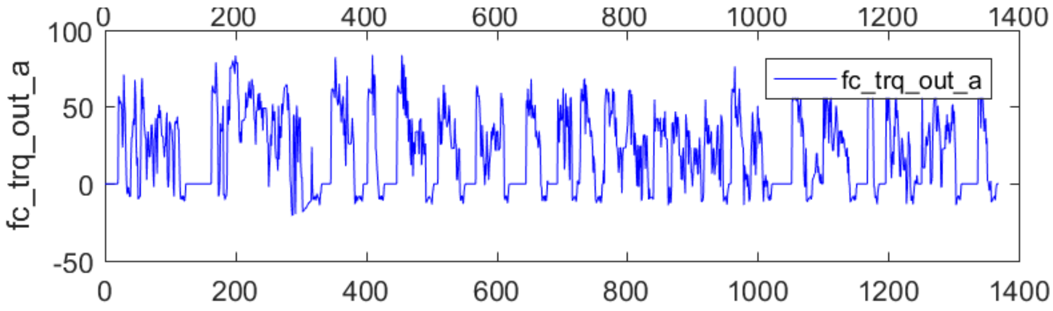


Fig. 7.38 The output torque achieved by the engine or fuel converter over the UDDS cycle

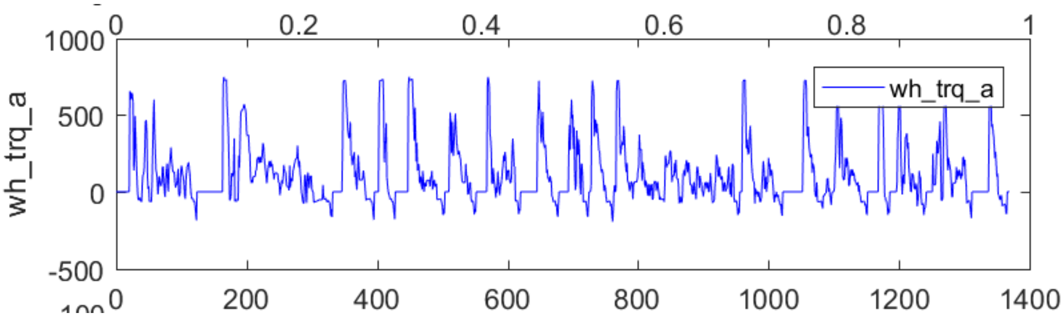
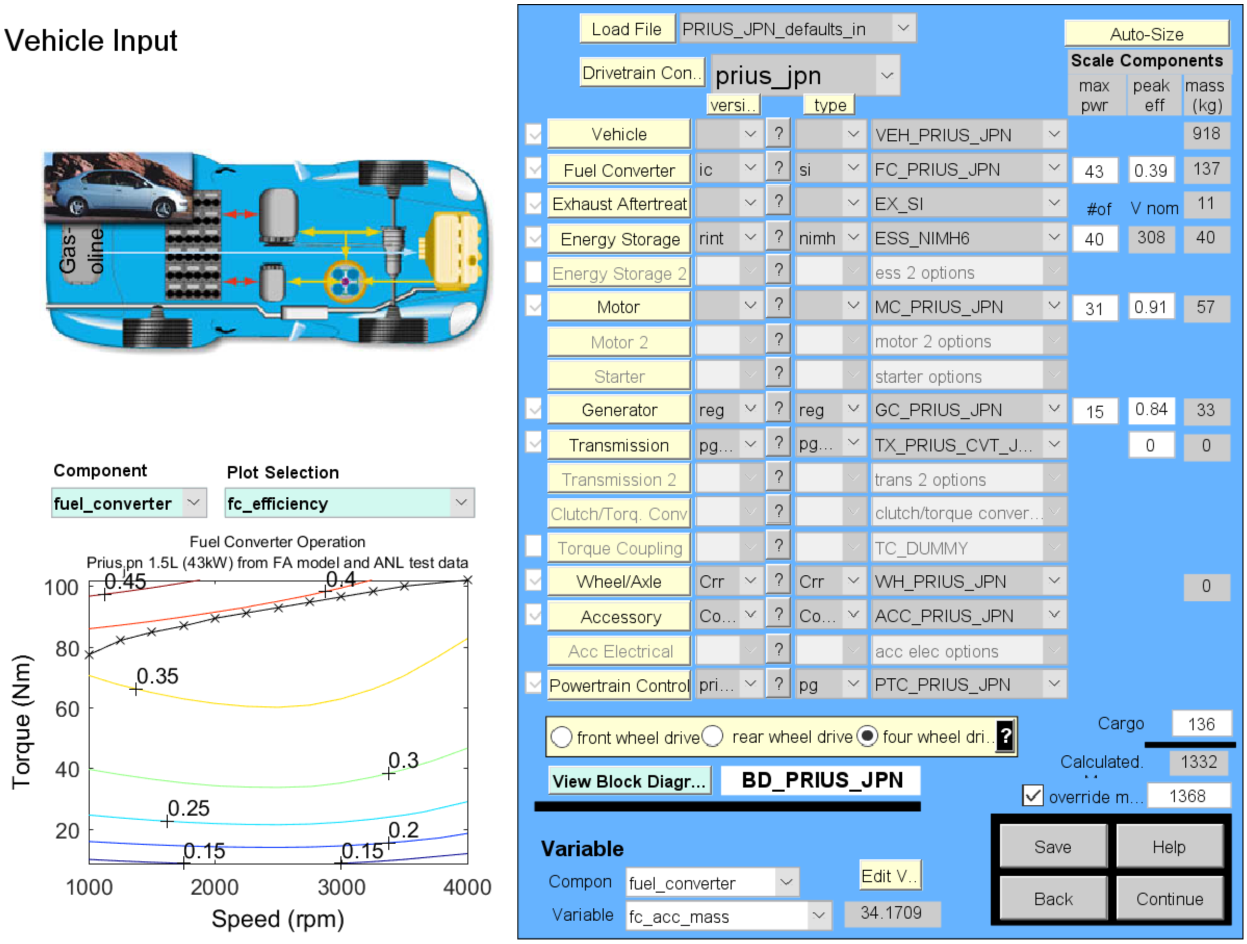


Fig. 7.39 The wheel torque achieved due to the output torque achieved by the fuel converter

7.5.7 Hybrid Vehicle Inputs and Block Diagram



Component: fuel_converter

Plot Selection: fc_efficiency

Load File: PRIUS_JPN_defaults_in

Drivetrain Con..: prius_jpn

Component	versi..	type		max pwr	peak eff	mass (kg)
Vehicle			VEH_PRIUS_JPN			918
Fuel Converter	ic	si	FC_PRIUS_JPN	43	0.39	137
Exhaust Aftertreat			EX_SI			11
				#of	V nom	
Energy Storage	rint	nimh	ESS_NIMH6	40	308	40
Energy Storage 2			ess 2 options			
Motor			MC_PRIUS_JPN	31	0.91	57
Motor 2			motor 2 options			
Starter			starter options			
Generator	reg	reg	GC_PRIUS_JPN	15	0.84	33
Transmission	pg...	pg...	TX_PRIUS_CVT_J...		0	0
Transmission 2			trans 2 options			
Clutch/Torq. Conv			clutch/torque conver...			
Torque Coupling			TC_DUMMY			
Wheel/Axle	Crr	Crr	WH_PRIUS_JPN			0
Accessory	Co...	Co...	ACC_PRIUS_JPN			
Acc Electrical			acc elec options			
Powertrain Control	pri...	pg	PTC_PRIUS_JPN			

○ front wheel drive ○ rear wheel drive ● four wheel dri..

View Block Diagr...: BD_PRIUS_JPN

Cargo: 136

Calculated: 1332

☑ override m...: 1368

Variable

Compon: fuel_converter

Variable: fc_acc_mass

34.1709

Fig. 7.40 Input Parameters of Hybrid Electric Vehicles

For the Toyota Prius Japan Hybrid Electric Vehicle, the inputs in the Advisor software had been given as shown above. The data was provided by the car manufacturers themselves at the time of release of this software. The Toyota Prius here in the input is using the internal combustion engine, which is of the spark ignition kind alongside an energy storage unit made using Nickel Metal Hydride.

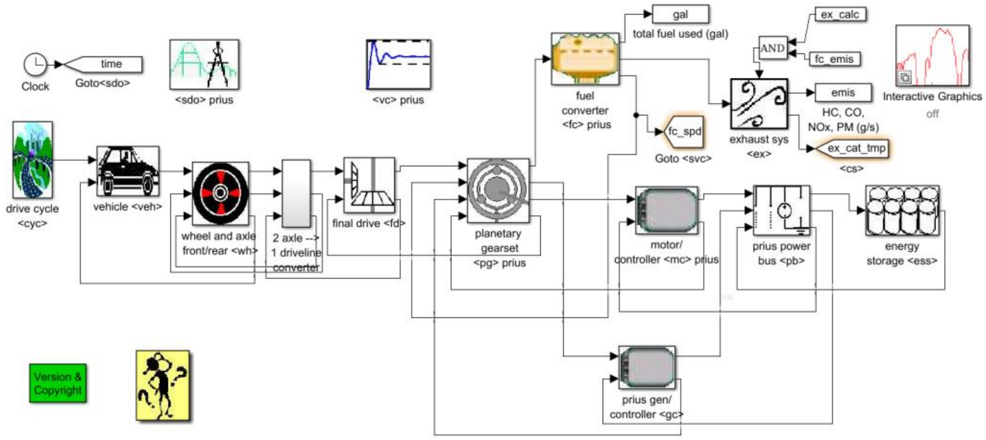


Fig. 7.41 Block Diagram of the Hybrid Electric Vehicle

The block diagram for the Toyota Prius up until the planetary gearbox was comprised just as the previous two vehicles, the Electric Vehicle and the Conventional vehicle was made. The added parts here incorporates both of the sections of the conventional vehicle and the electric vehicle. The planetary gear set here takes inputs from the final drive, fuel converter, power bus and the motor/controller and then gives feedback to the motor/controller depending on how much energy the energy storage unit would need to supply for smooth operation.

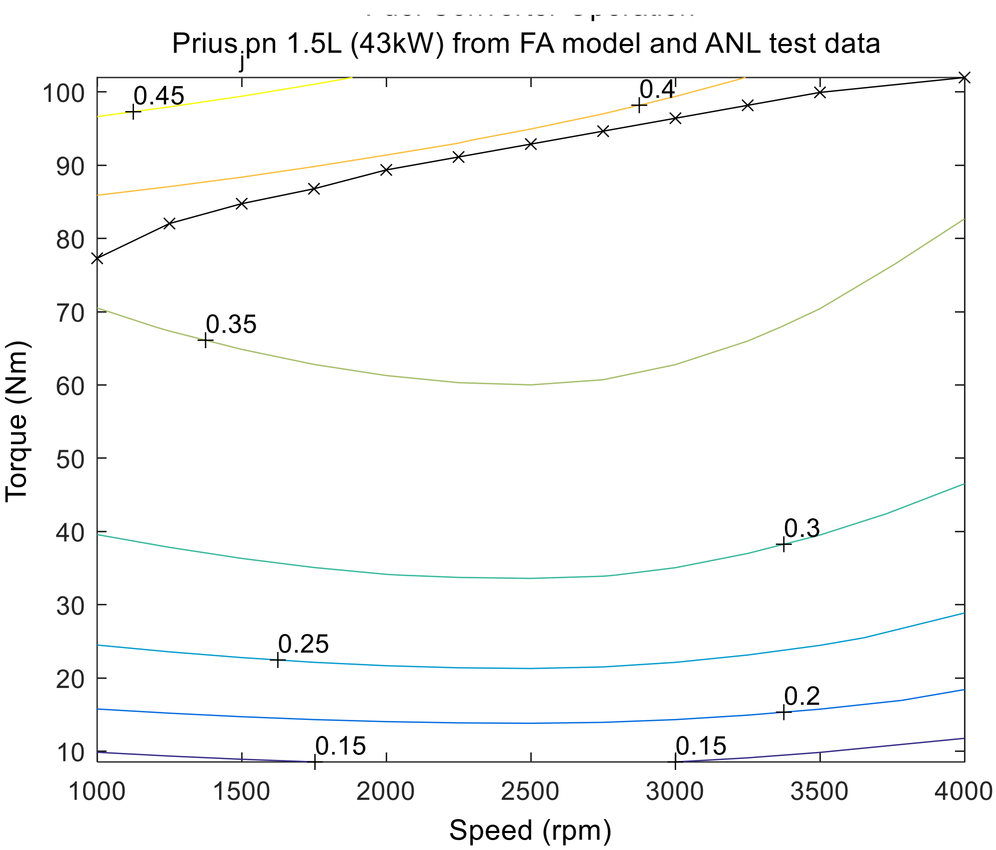


Fig. 7.42 Torque Speed Characteristics and efficiency of the Fuel Converter

Next, as part of the individual components' analysis, the Torque speed characteristics and efficiency of the fuel converter is shown above. This pertains only to the internal combustion engine's fuel converter and not the energy storage system or the motor/controller. Here we can see that as the speed is increasing over the range of 1000 to 4000 (in rpm) the torque produced in the Prius jpn 1.5L (43kW) increases. Points of efficiencies are also shown as contours based on the data of the input map.

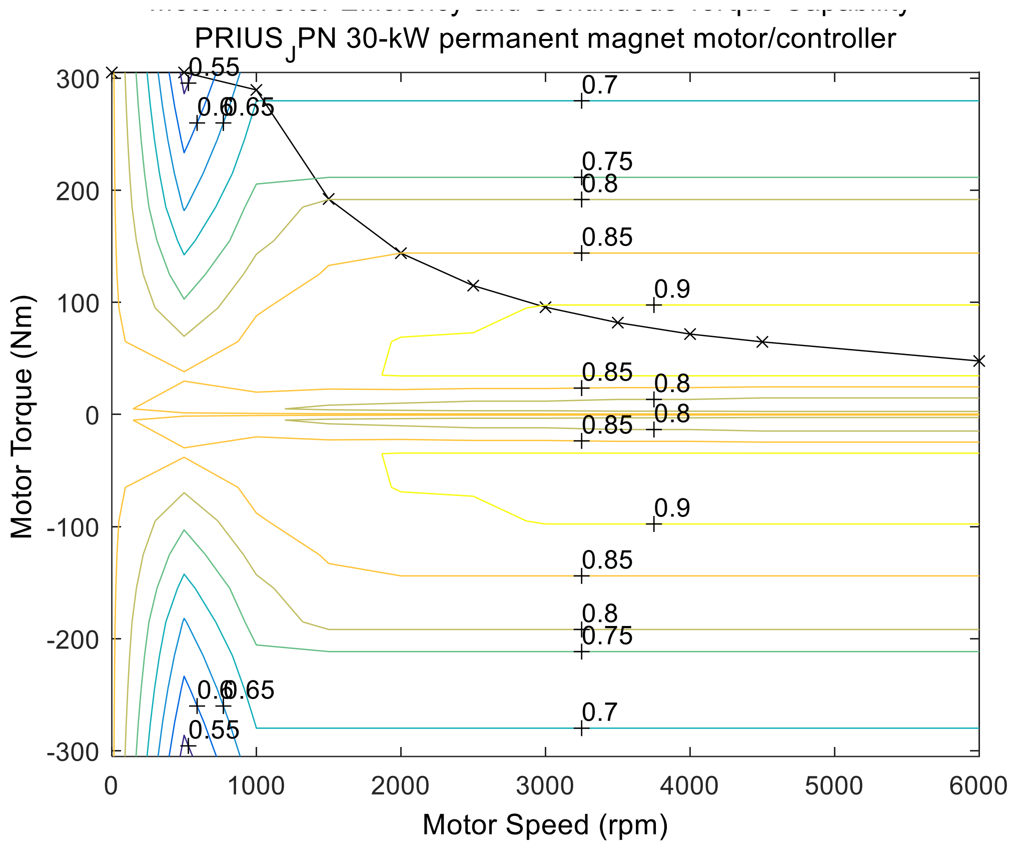


Fig. 7.43 Motor/controller efficiency and torque speed characteristics

This graph shows the efficiency and torque speed characteristics of only the motor. We can see here that as the motor's speed in rpm increases, the motor's torque decreases. Several points of efficiencies are also shown and the positive y-axis corresponds to the motor region and the negative portion, the generator region.

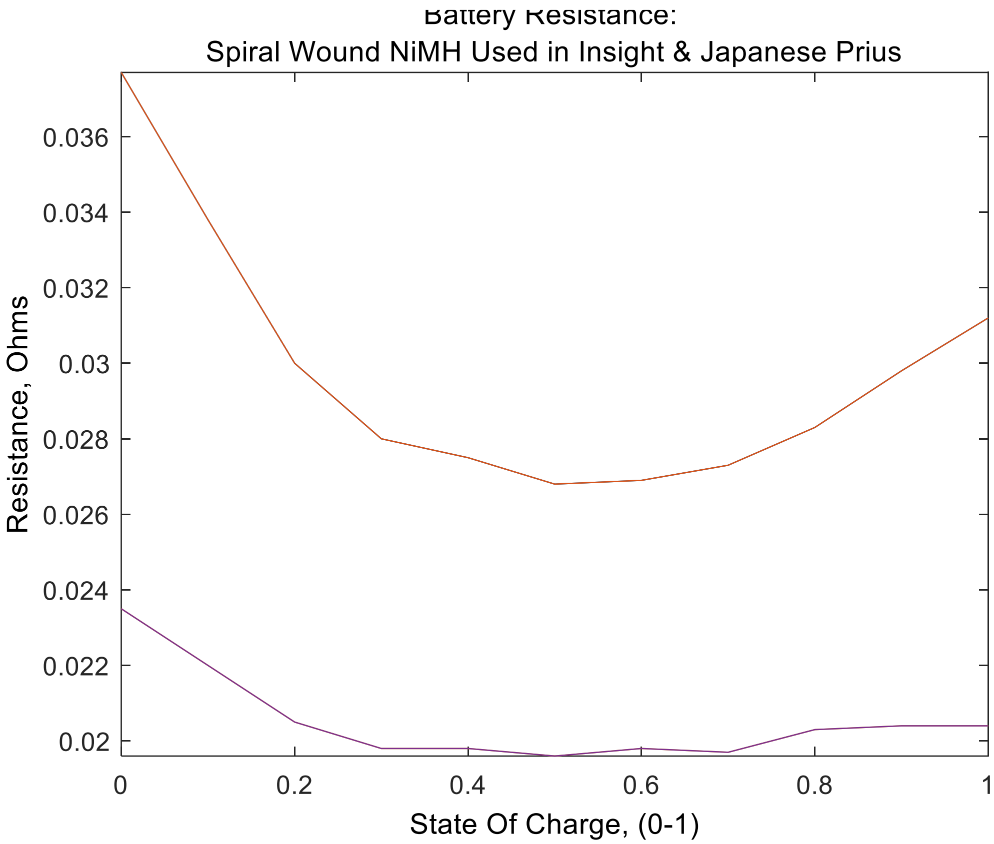


Fig. 7.44 Change of internal resistance with state of charge

As for the NiMH used as the energy storage system in the Toyota Prius, as the state of charge of the cell increases, there is a drop in the internal resistance of the fuel cell only to increase later on at higher SOCs.

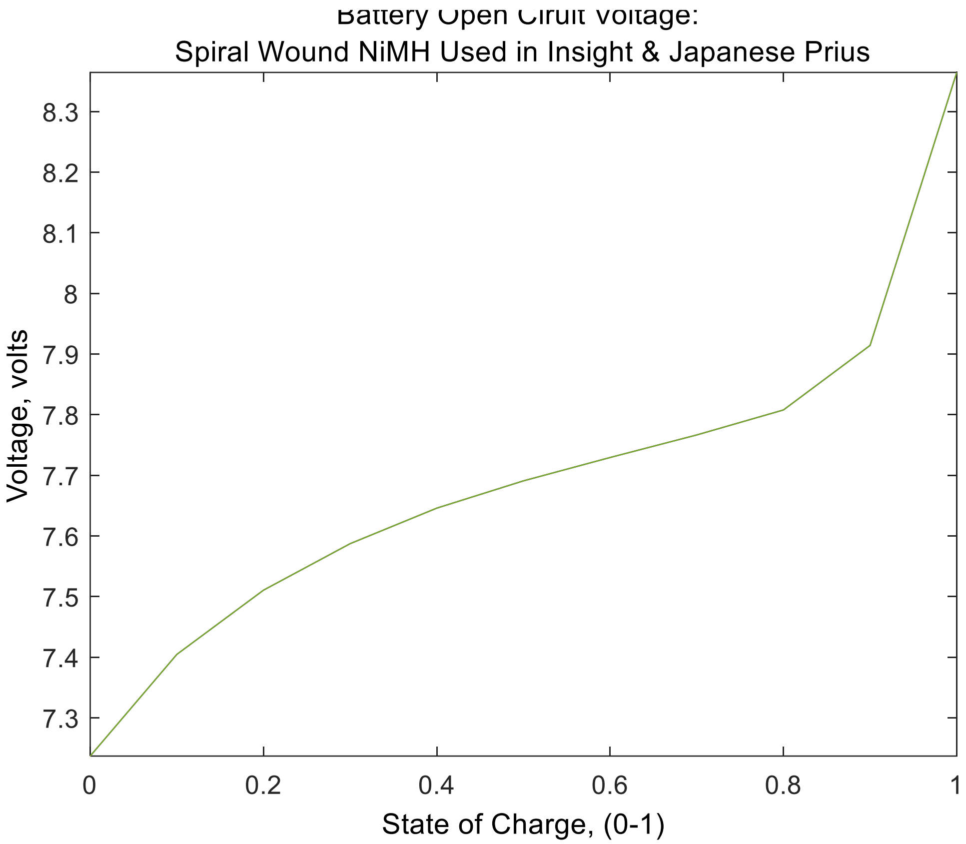


Fig. 7.45 Open circuit voltage of battery change with the state of charge

Another way that the SOC of the energy storage unit, NiMH cell, can be determined is through measuring the open circuit voltage. More the open circuit voltage is, more is the cell likely to have a higher SOC. This is most pronounced at approximately 0.9 SOC and an open circuit voltage of 7.9V.

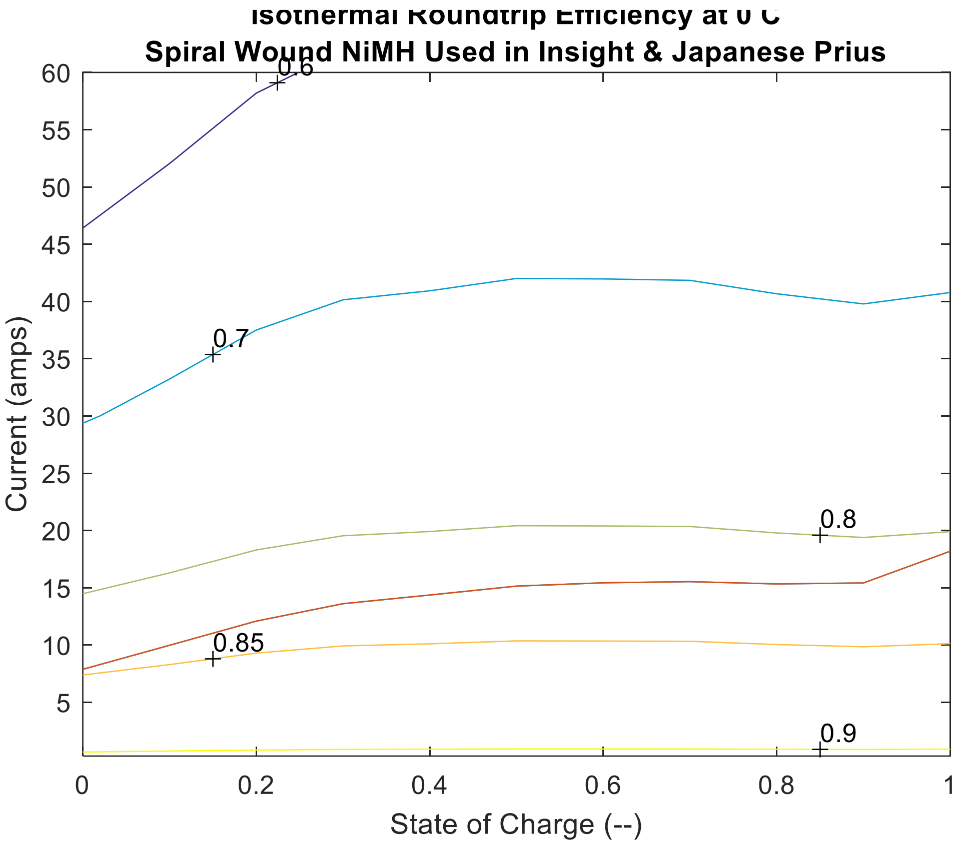
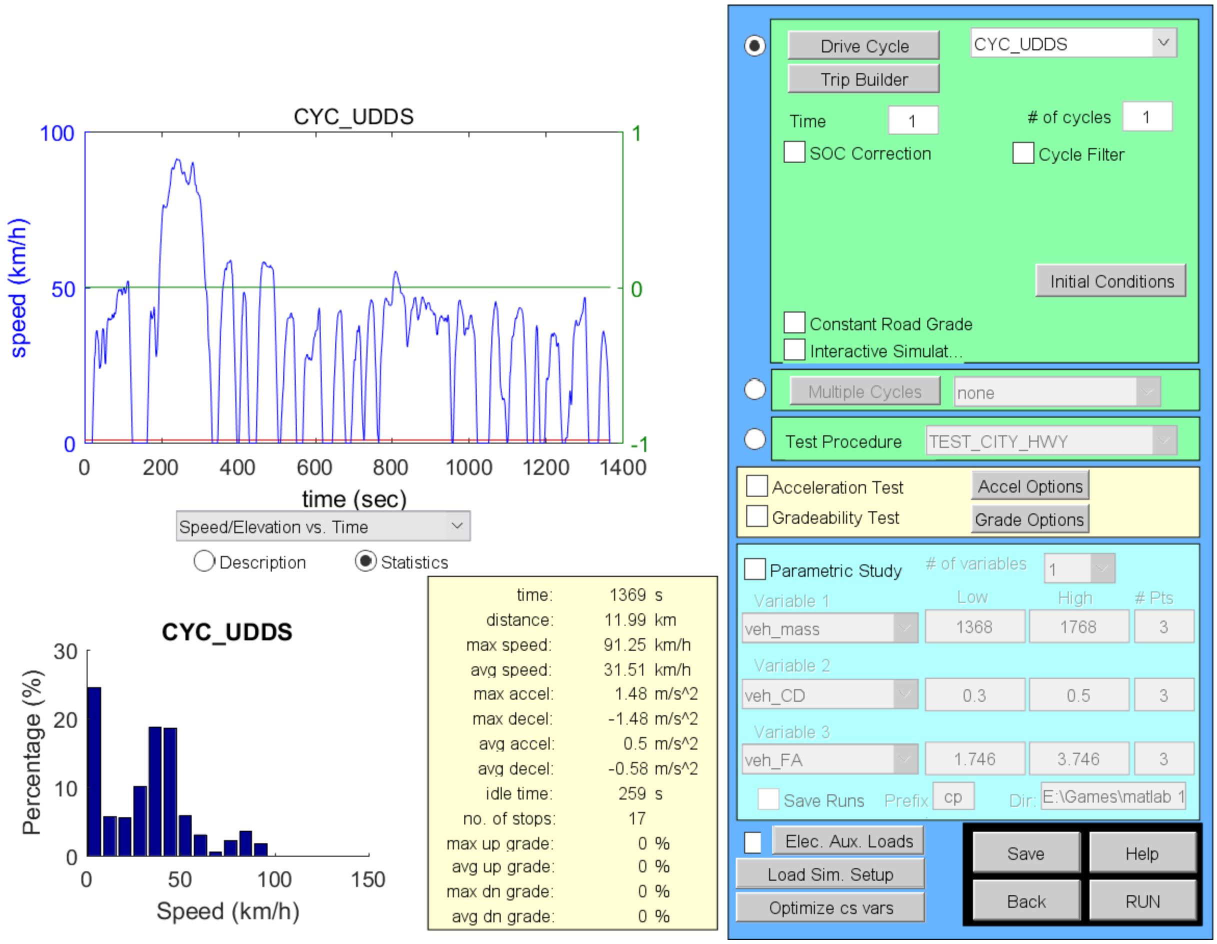


Fig. 7.46 Roundtrip efficiency

As for the roundtrip efficiency, which is the fraction of energy put into the battery, and the amount of energy possible to be retrieved from it, it can be seen that with increasing amperes of current the efficiency of the NiMH cell which is used as the energy storage system in the Hybrid Toyota Prius, the efficiency decreases. Stable points of efficiencies are shown as contours on the input map in the diagram above.

7.5.8 Input Drive Cycle and Outputs



time: 1369 s
distance: 11.99 km
max speed: 91.25 km/h
avg speed: 31.51 km/h
max accel: 1.48 m/s^2
max decel: -1.48 m/s^2
avg accel: 0.5 m/s^2
avg decel: -0.58 m/s^2
idle time: 259 s
no. of stops: 17
max up grade: 0 %
avg up grade: 0 %
max dn grade: 0 %
avg dn grade: 0 %

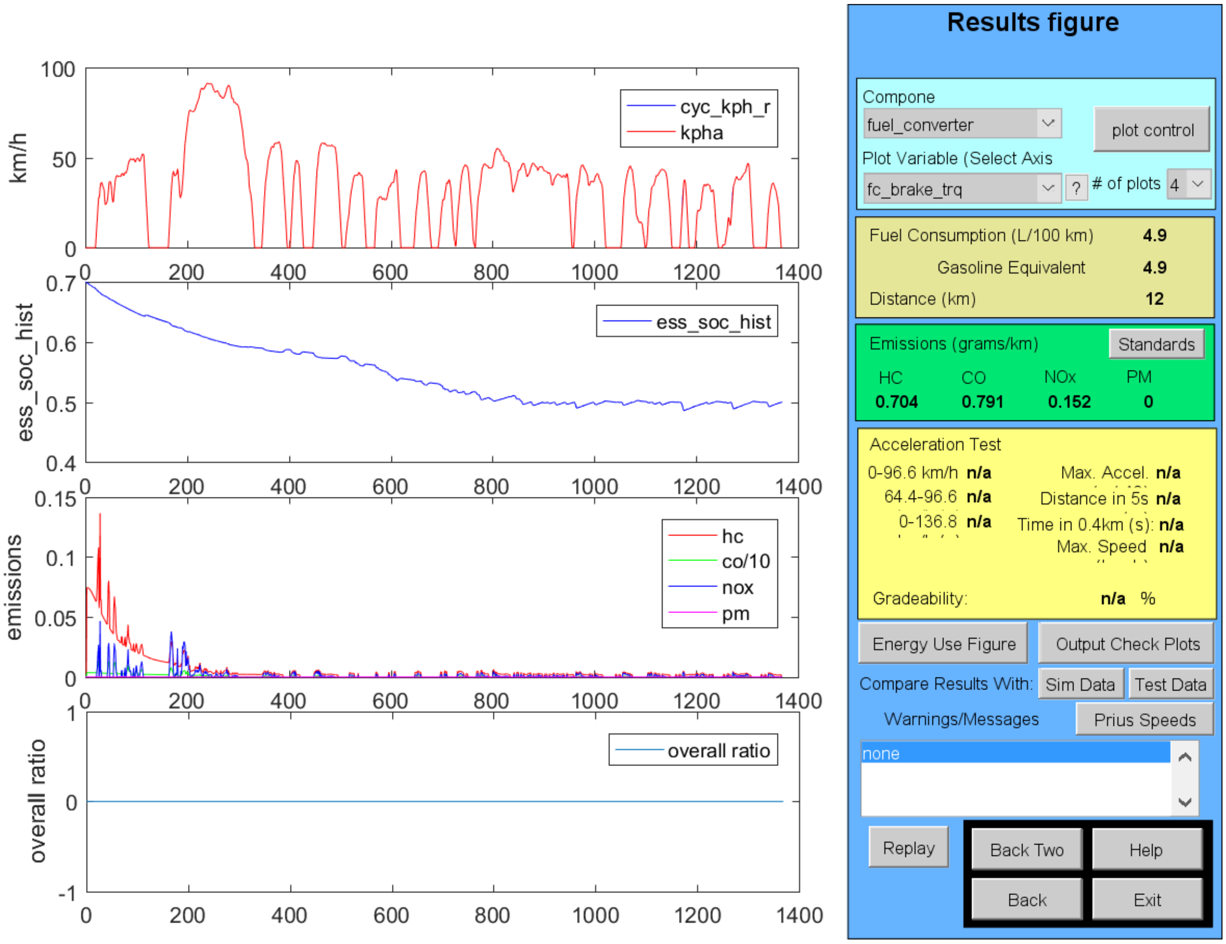
● Drive Cycle: CYC_UDDS
Time: 1
# of cycles: 1
☐ SOC Correction
☐ Cycle Filter
☐ Constant Road Grade
☐ Interactive Simulat...
○ Multiple Cycles: none
○ Test Procedure: TEST_CITY_HWY
☐ Acceleration Test
☐ Gradeability Test
☐ Parametric Study
# of variables: 1

	Low	High	# Pts
Variable 1: veh_mass	1368	1768	3
Variable 2: veh_CD	0.3	0.5	3
Variable 3: veh_FA	1.746	3.746	3

☐ Save Runs
Prefix: cp
Dir: E:\Games\matlab 1
☐ Elec. Aux. Loads

Fig. 7.47 UDDS Drive Cycle

Similar to the simulated Electric Vehicle and the conventional vehicle, here we apply the UDDS cycle as the input driving cycle for fair comparisons between the three kinds of vehicles. The parameters of the UDDS cycle can be seen as above.



Results figure

Compone: fuel_converter

Plot Variable (Select Axis: fc_brake_trq

# of plots: 4

Fuel Consumption (L/100 km)	**4.9**
Gasoline Equivalent	**4.9**
Distance (km)	**12**

Emissions (grams/km)

HC	CO	NOx	PM
0.704	**0.791**	**0.152**	**0**

Acceleration Test

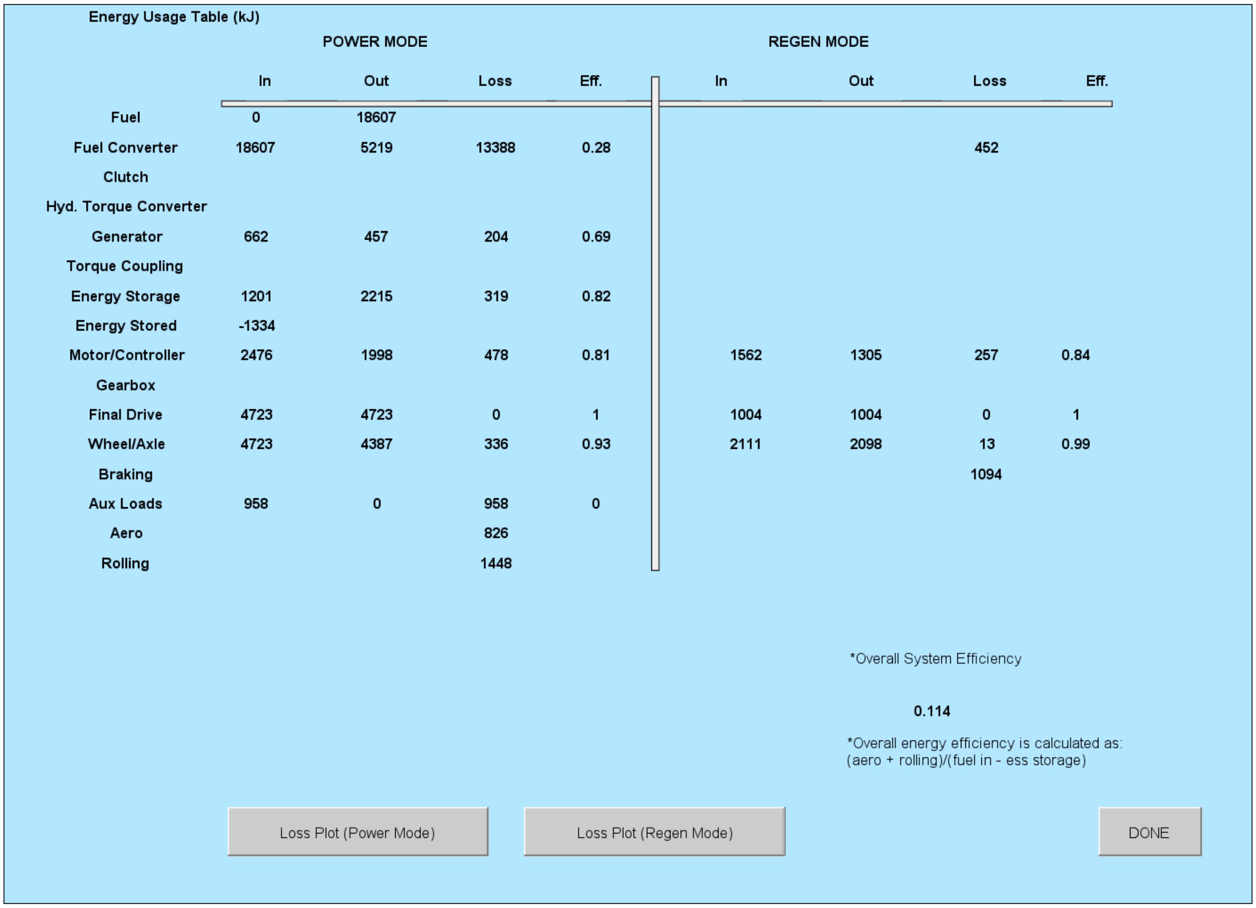
0-96.6 km/h	**n/a**	Max. Accel.	**n/a**
64.4-96.6	**n/a**	Distance in 5s	**n/a**
0-136.8	**n/a**	Time in 0.4km (s):	**n/a**
		Max. Speed	**n/a**

Gradeability: **n/a** %

Warnings/Messages: none

Fig. 7.48 Emissions and Change of SOCs for Hybrid Electric Vehicles

The output of the UDDS cycle is shown as above. It can be seen that there are emissions present initially over the drive cycle but with the increase of time over the cycle, these emissions are reduced significantly. There is also a change in the trend of the SOC history of the hybrid vehicle in comparison to the pure Electric Vehicle. This is because both gasoline and power from the energy storage system (NiMH) is used as means of fuel. Both together functioning simultaneously is the reason for the trend of the SOC history.


Energy Usage Table (kJ)

	POWER MODE				REGEN MODE			
	In	Out	Loss	Eff.	In	Out	Loss	Eff.
Fuel	0	18607						
Fuel Converter	18607	5219	13388	0.28			452	
Clutch								
Hyd. Torque Converter								
Generator	662	457	204	0.69				
Torque Coupling								
Energy Storage	1201	2215	319	0.82				
Energy Stored	-1334							
Motor/Controller	2476	1998	478	0.81	1562	1305	257	0.84
Gearbox								
Final Drive	4723	4723	0	1	1004	1004	0	1
Wheel/Axle	4723	4387	336	0.93	2111	2098	13	0.99
Braking							1094	
Aux Loads	958	0	958	0				
Aero			826					
Rolling			1448					

*Overall System Efficiency

0.114

*Overall energy efficiency is calculated as:
(aero + rolling)/(fuel in - ess storage)

Fig. 7.49 Energy Usage Table in KJs for Power Mode and Regeneration Mode

The Energy Usage by the Toyota Prius can be seen as above. All of these numbers are represented in kJ, and for the hybrid vehicle, over the UDDS cycle; the efficiency can be seen to be an overall 11.4%. Energies for both the Power mode and the regenerative mode are shown above.

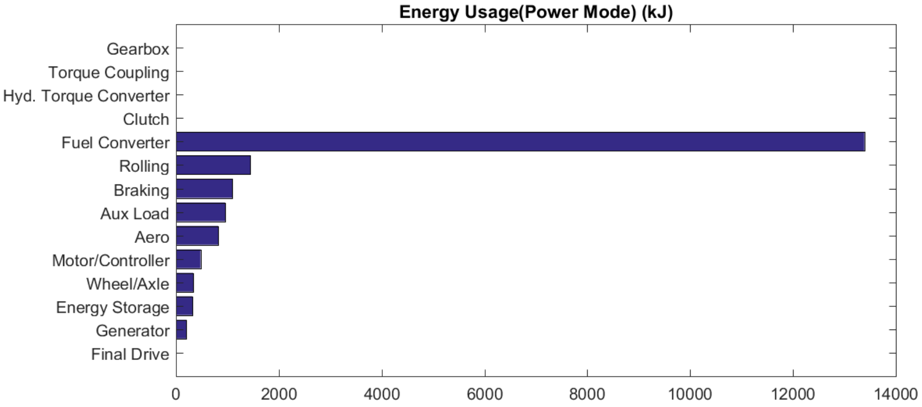


Fig. 7.50 Loss Plot for Power Mode

Shown above is an energy usage plot for the power mode and for a graphical representation the diagram above has been presented.

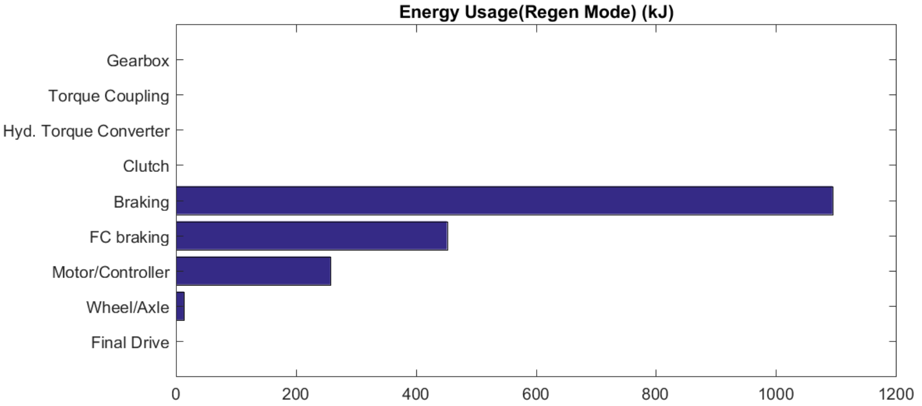
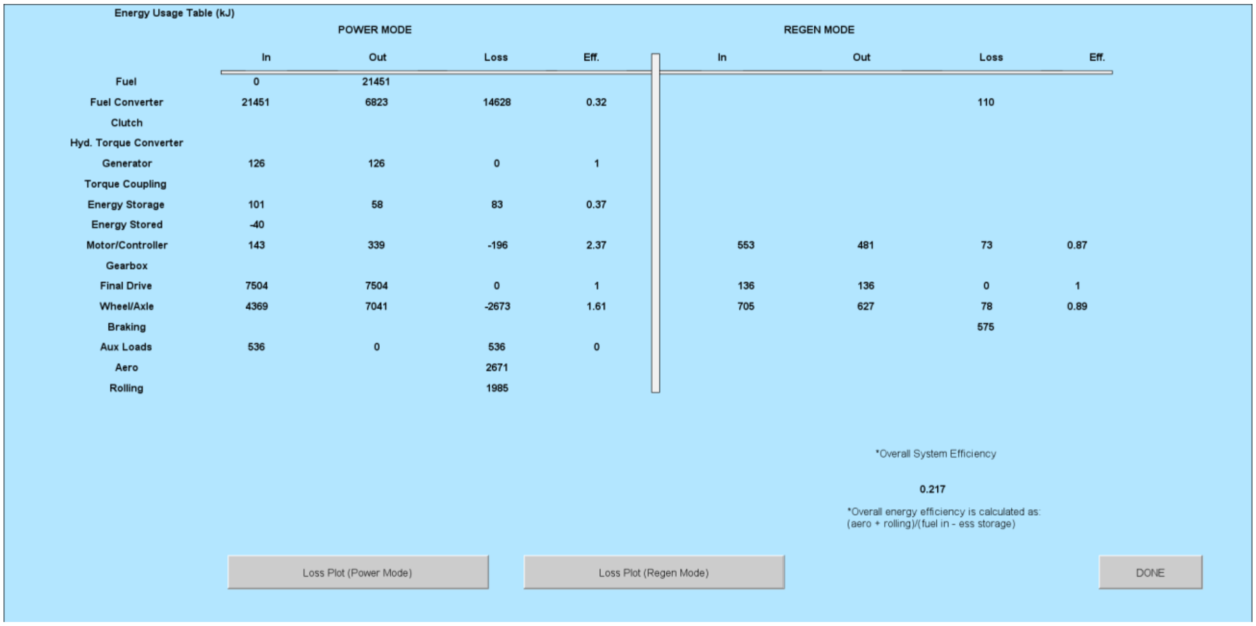


Fig. 7.51 Loss Plot for Regeneration Mode



Energy Usage Table (kJ)

	POWER MODE				REGEN MODE			
	In	Out	Loss	Eff.	In	Out	Loss	Eff.
Fuel	0	21451						
Fuel Converter	21451	6823	14628	0.32			110	
Clutch								
Hyd. Torque Converter								
Generator	126	126	0	1				
Torque Coupling								
Energy Storage	101	58	83	0.37				
Energy Stored	-40							
Motor/Controller	143	339	-196	2.37	553	481	73	0.87
Gearbox								
Final Drive	7504	7504	0	1	136	136	0	1
Wheel/Axle	4369	7041	-2673	1.61	705	627	78	0.89
Braking							575	
Aux Loads	536	0	536	0				
Aero			2671					
Rolling			1985					

*Overall System Efficiency

0.217

*Overall energy efficiency is calculated as:
(aero + rolling)/(fuel in - ess storage)

Fig. 7.52 Energy Usage Table in KJs for Power Mode and Regeneration Mode

Using a different drive cycle, the HWFET, the Toyota Prius presents a higher overall efficiency, a value of 21.7% and similarly, for different driving cycles, different values of efficiencies will be reached in every type of vehicle.

Next, in the diagrams presented below, we can see some chosen output parameters of the hybrid Toyota Prius' functioning to get an understanding graphically, on how each of them work.

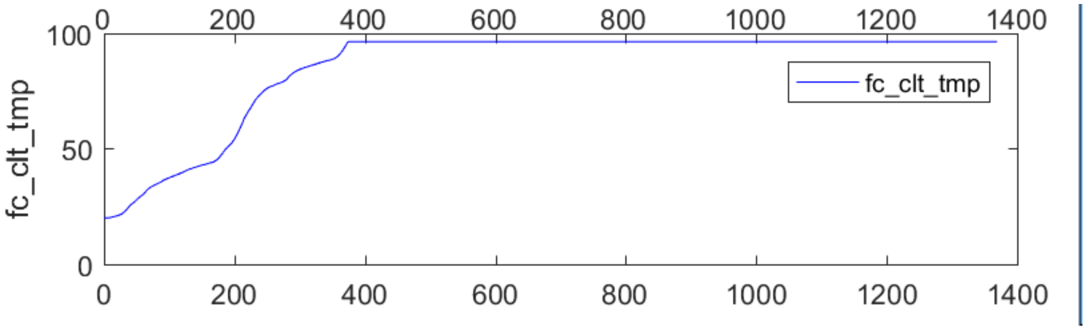


Fig. 7.53 The Fuel converter's coolant temperature's change over time

The fuel converter's coolant temperature goes from approximately 20 degrees up to 98 degrees.

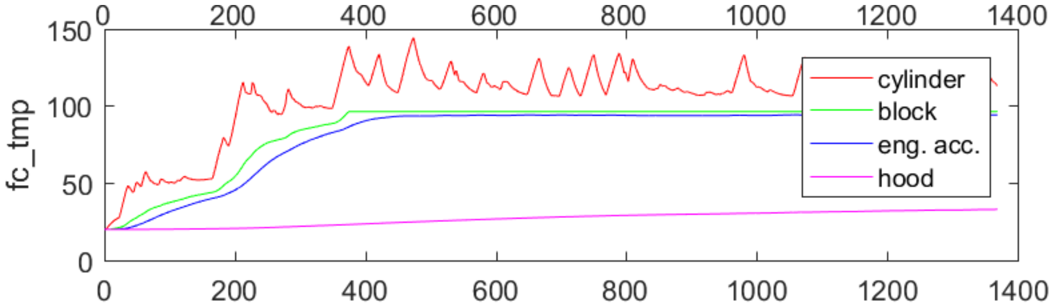


Fig. 7.54 The Fuel converter's temperature change with time

Temperature change of different components, such as the cylinder, block, the engine accessories and the hood's temperature is shown above. We can see how the cylinder's temperature spikes over the time of the UDDS cycle.

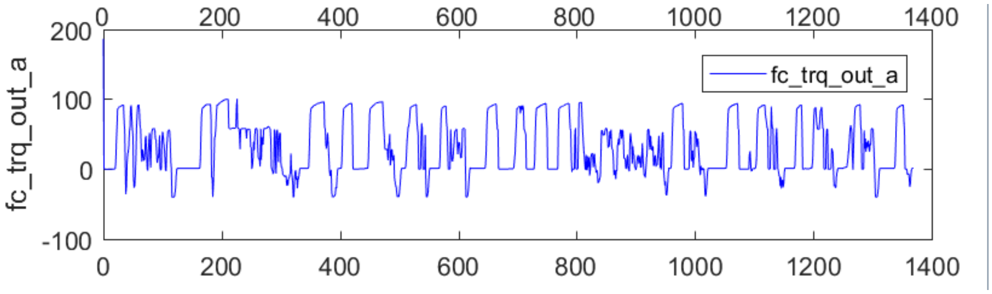


Fig. 7.55 The output torque that is reached or achieved by the Fuel Converter, in Nm

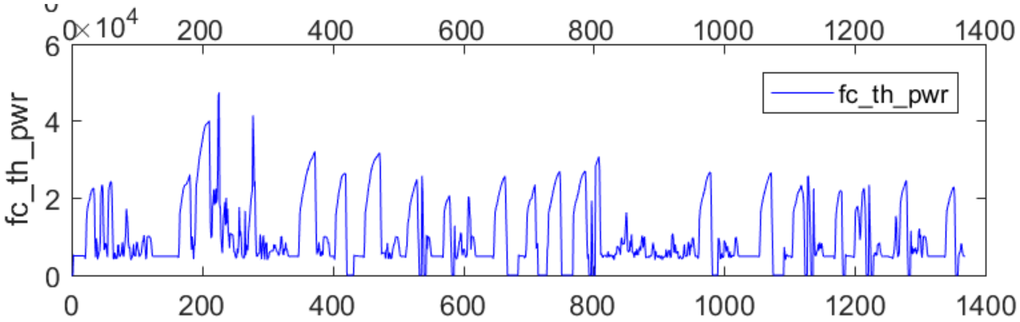


Fig. 7.56 Power wasted by the Fuel converter

This graph shows the thermal power wasted and that which is converted into heat over time. The y-axis values are in watts x10^4.

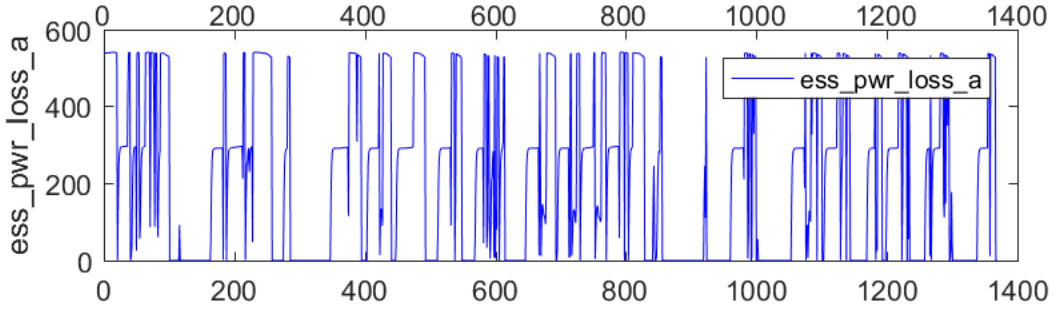
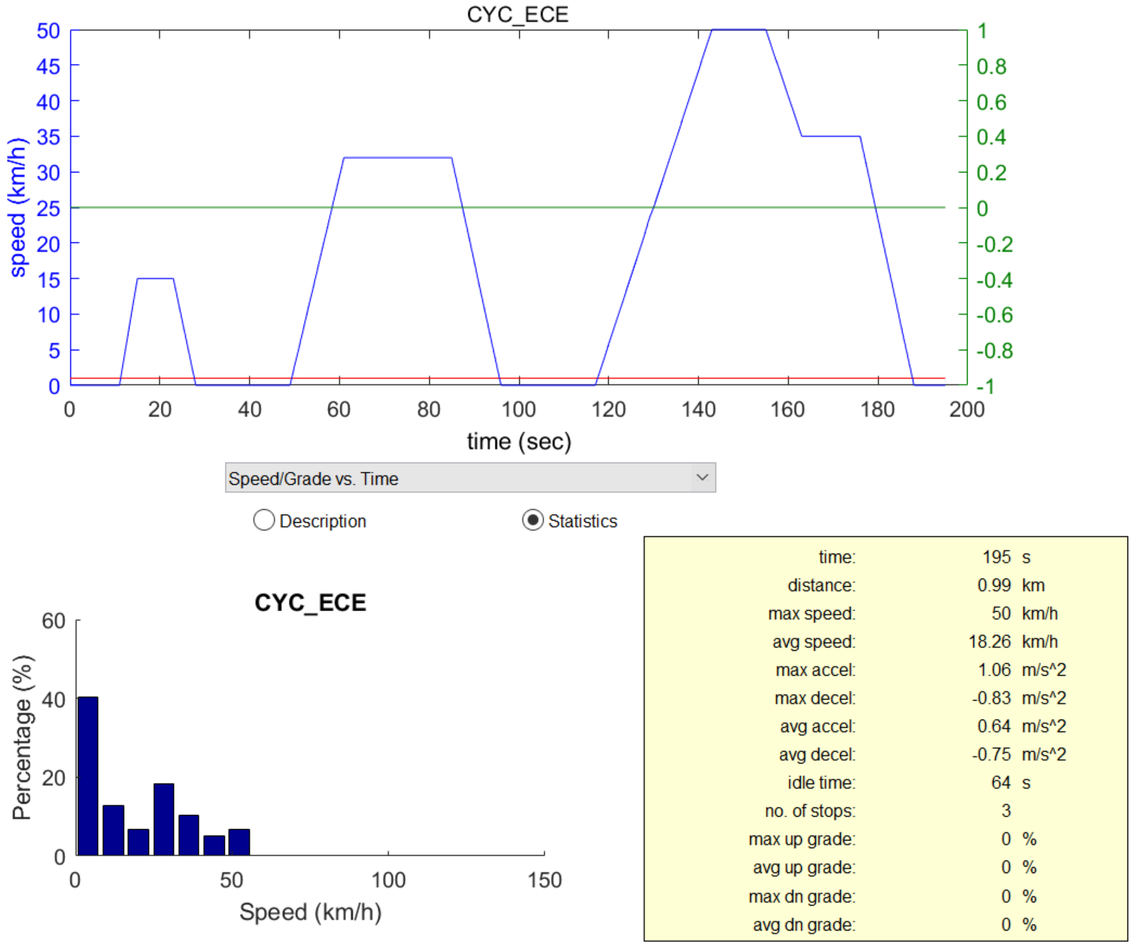


Fig.7.57 The Actual Power Loss from the energy storage system in Watts

7.6 Driving Cycles



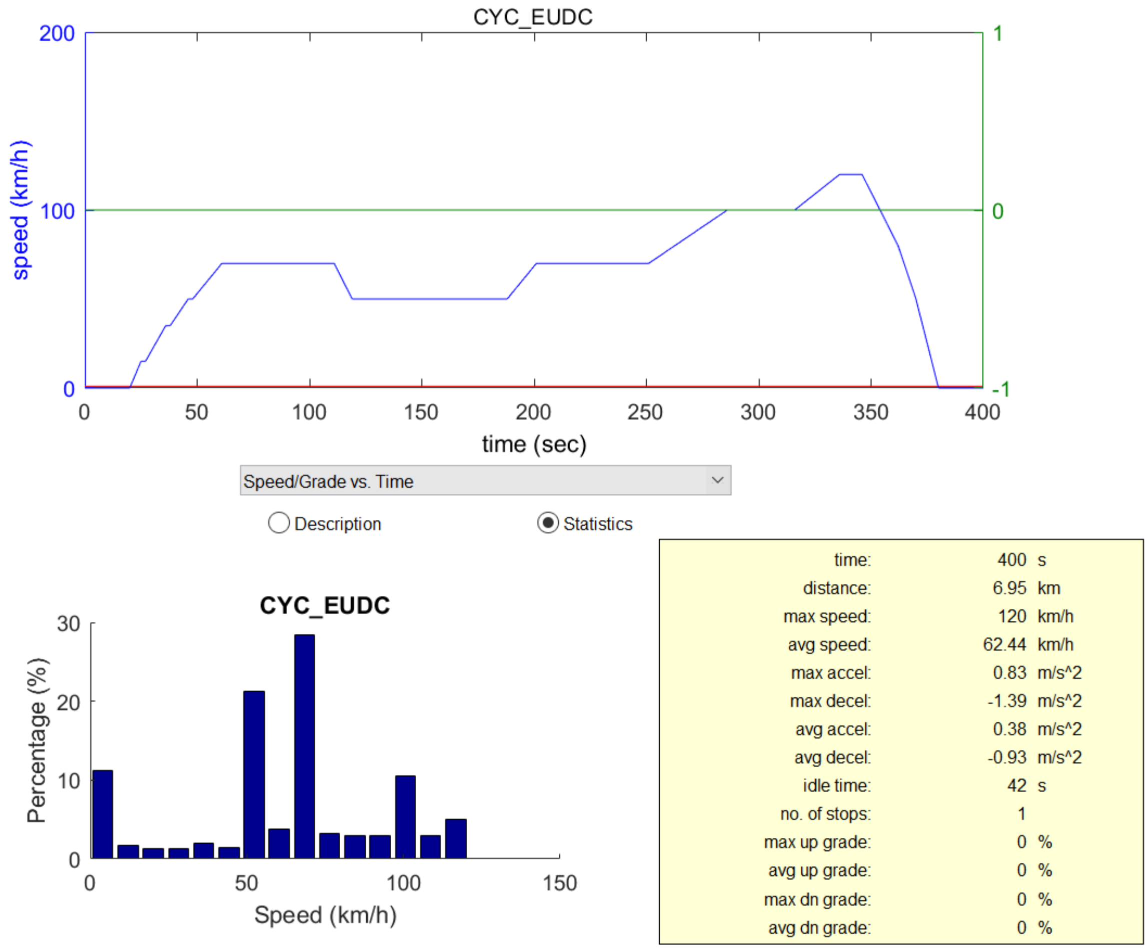
Speed/Grade vs. Time

○ Description ● Statistics

time:	195	s
distance:	0.99	km
max speed:	50	km/h
avg speed:	18.26	km/h
max accel:	1.06	m/s^2
max decel:	-0.83	m/s^2
avg accel:	0.64	m/s^2
avg decel:	-0.75	m/s^2
idle time:	64	s
no. of stops:	3	
max up grade:	0	%
avg up grade:	0	%
max dn grade:	0	%
avg dn grade:	0	%

Fig.7.58 ECE (Elementary Urban Cycle Driving Cycle)

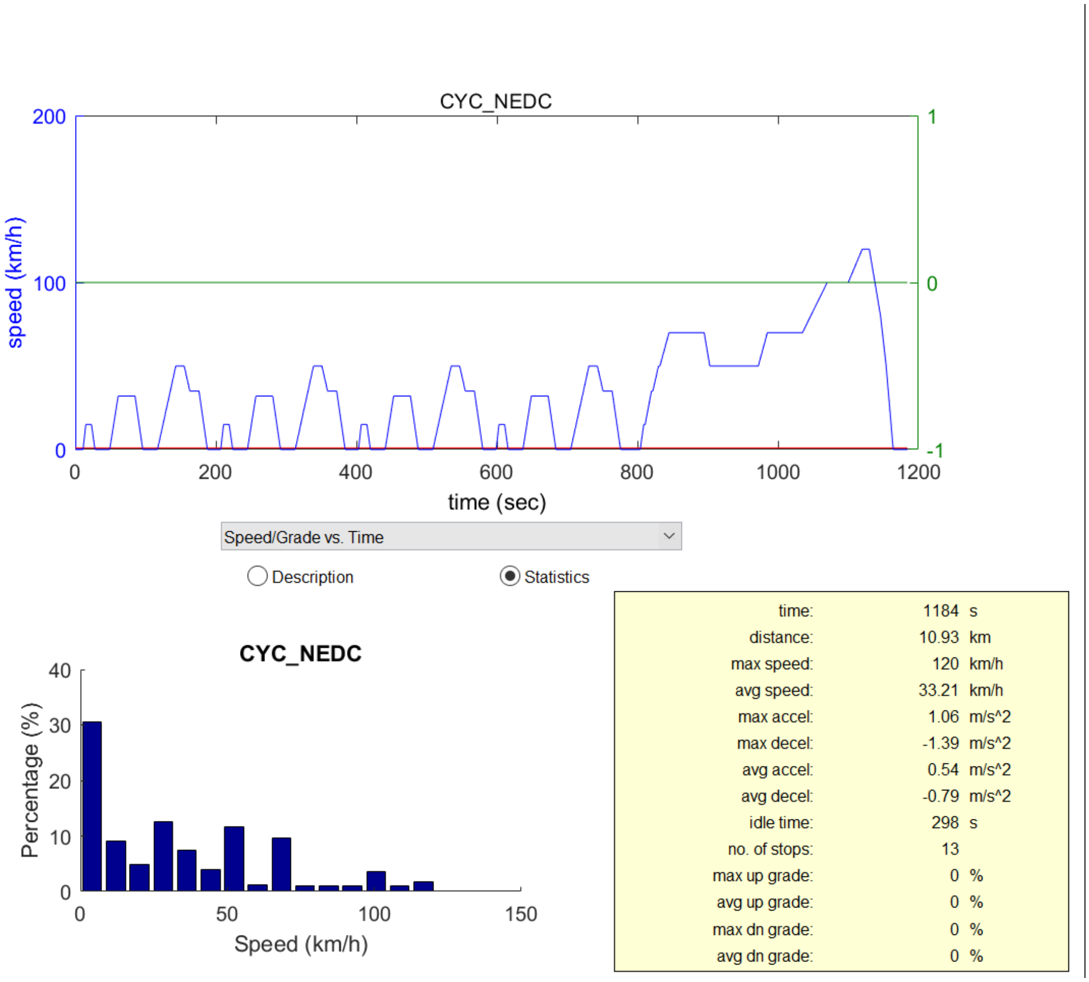
The ECE cycle is an urban driving cycle also known as UDC. It was created in order to represent the driving conditions of cities such as Paris or Rome. This driving cycle is characterized by low vehicle speeds, engine loads and exhaust gas temperatures.



time:	400	s
distance:	6.95	km
max speed:	120	km/h
avg speed:	62.44	km/h
max accel:	0.83	m/s^2
max decel:	-1.39	m/s^2
avg accel:	0.38	m/s^2
avg decel:	-0.93	m/s^2
idle time:	42	s
no. of stops:	1	
max up grade:	0	%
avg up grade:	0	%
max dn grade:	0	%
avg dn grade:	0	%

Fig.7.59 EUDC (Extra European Driving Cycle)

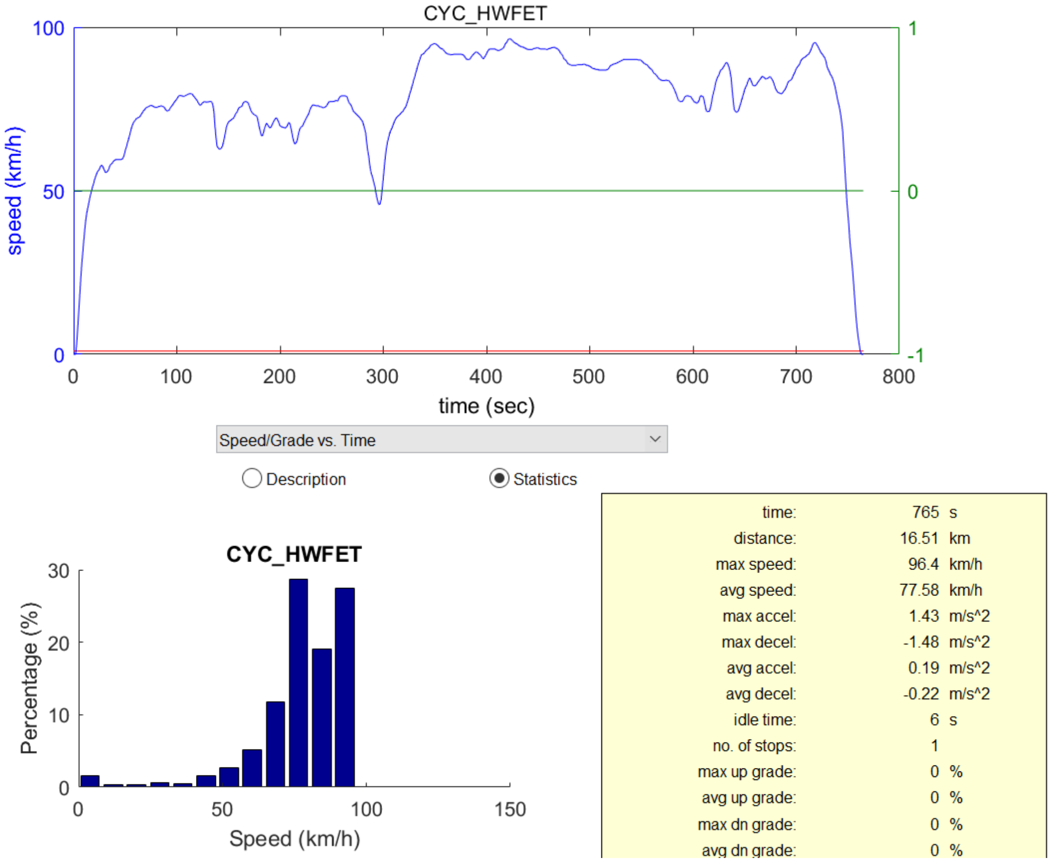
This drive cycle test is carried out for emission certification of light duty vehicles in Europe. The parameters are shown above. Before the test, the vehicle is allowed to soak for 6 hours at a test temperature between 20 to 30 degrees Celsius. This cycle is also known as MVEG-A. This cycle’s highest speed is 120km/h which accounts for aggressive driving. An alternate form of EUDC is the EUDC_LOW cycle where the maximum speed is limited at 90 kmph.



time:	1184	s
distance:	10.93	km
max speed:	120	km/h
avg speed:	33.21	km/h
max accel:	1.06	m/s^2
max decel:	-1.39	m/s^2
avg accel:	0.54	m/s^2
avg decel:	-0.79	m/s^2
idle time:	298	s
no. of stops:	13	
max up grade:	0	%
avg up grade:	0	%
max dn grade:	0	%
avg dn grade:	0	%

Fig.7.60 NEDC (New European Driving Cycle)

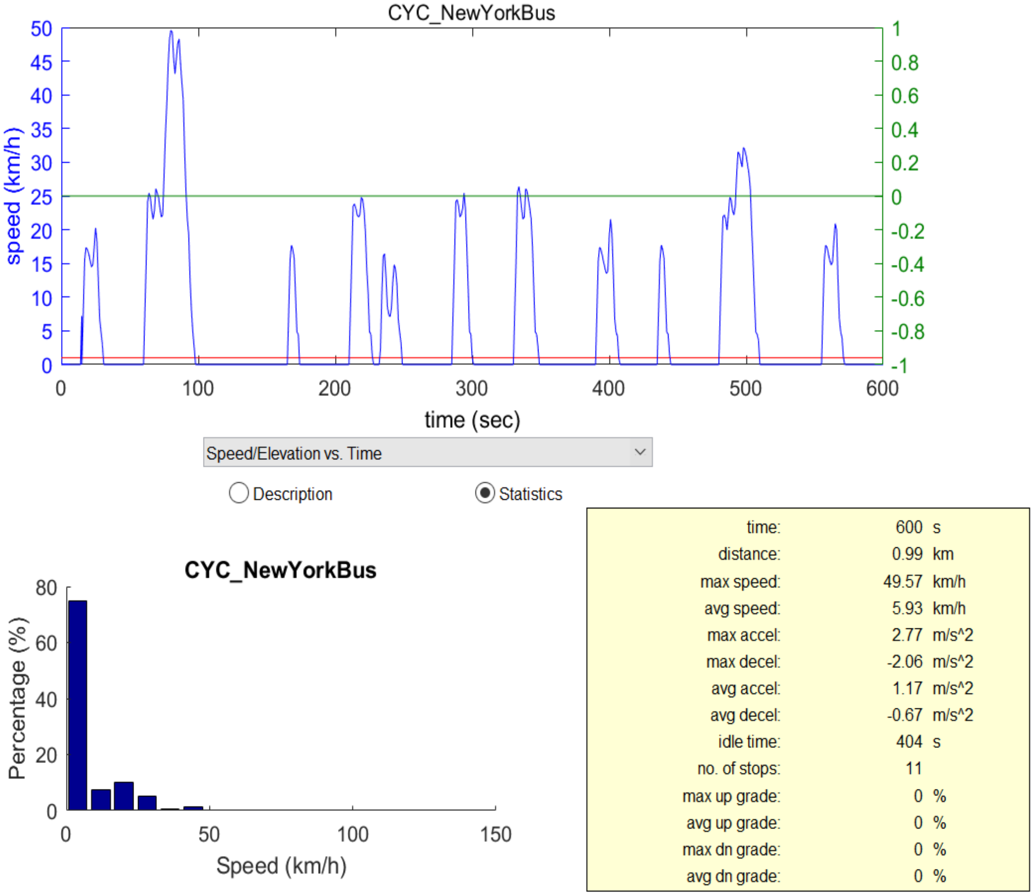
The NEDC cycle is a modified form of EUDC where colder temperatures are used is the NEDC cycle.



```
          time:      765  s
      distance:    16.51  km
     max speed:     96.4  km/h
     avg speed:    77.58  km/h
     max accel:     1.43  m/s^2
     max decel:    -1.48  m/s^2
     avg accel:     0.19  m/s^2
     avg decel:    -0.22  m/s^2
     idle time:        6  s
  no. of stops:        1
 max up grade:        0  %
  avg up grade:        0  %
  max dn grade:        0  %
  avg dn grade:        0  %
```

Fig.7.61 HWFET (Highway Fuel Economy Test)

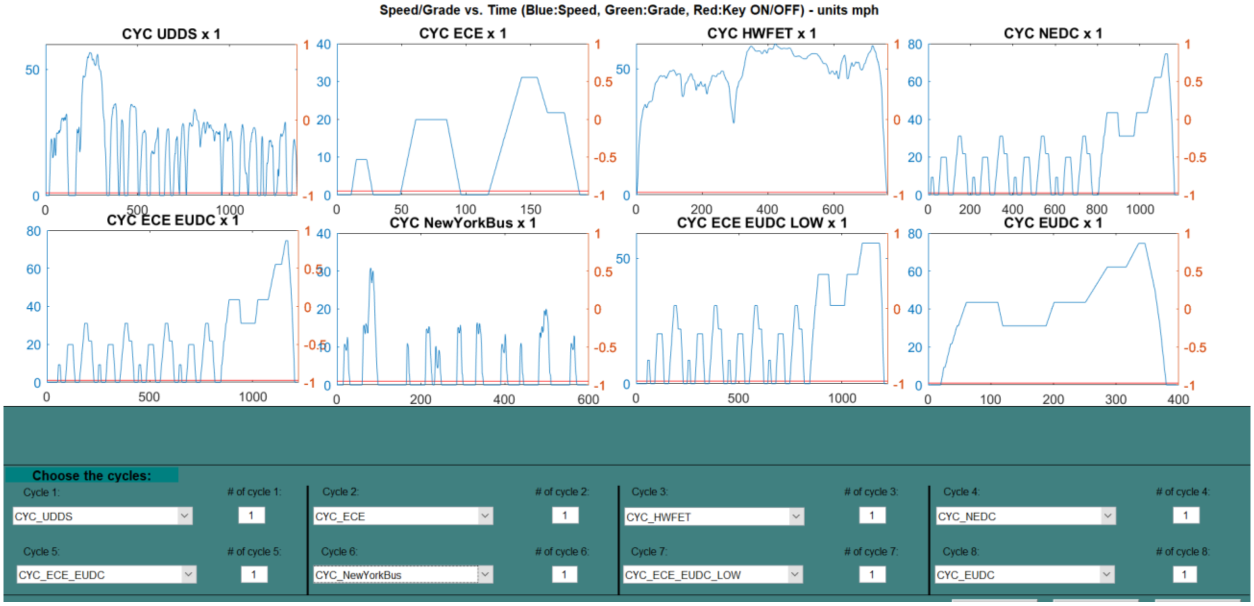
The HWFET cycle is used by US EPA for Corporate Average Fuel Economy certification of passenger vehicles in the US.



time: 600 s
distance: 0.99 km
max speed: 49.57 km/h
avg speed: 5.93 km/h
max accel: 2.77 m/s^2
max decel: -2.06 m/s^2
avg accel: 1.17 m/s^2
avg decel: -0.67 m/s^2
idle time: 404 s
no. of stops: 11
max up grade: 0 %
avg up grade: 0 %
max dn grade: 0 %
avg dn grade: 0 %

Fig. 7.62 New York Bus Driving Cycle

The New York Bus cycle was developed from the speed-time data collected from heavy duty vehicles (both trucks and transit buses) in New York City.



Choose the cycles:

Cycle 1: CYC_UDDS — # of cycle 1: 1

Cycle 2: CYC_ECE — # of cycle 2: 1

Cycle 3: CYC_HWFET — # of cycle 3: 1

Cycle 4: CYC_NEDC — # of cycle 4: 1

Cycle 5: CYC_ECE_EUDC — # of cycle 5: 1

Cycle 6: CYC_NewYorkBus — # of cycle 6: 1

Cycle 7: CYC_ECE_EUDC_LOW — # of cycle 7: 1

Cycle 8: CYC_EUDC — # of cycle 8: 1

Fig. 7.63 Multiple Driving Cycles

This chart above demonstrates the drive cycles shown above in a combined format. The ECE_EUDC, ECE_EUDC Low are four cycles of ECE followed by EUDC and EUDC_LOW respectively. EUDC represents a maximum of 120kmph and the EUDC_LOW limits that to 90kmph.

Chapter 8
Conclusion

8.1 Summary

In conclusion, an in-depth perspective into the world of automotive vehicles, with a particular focus on Electric Vehicles, has been presented. The above analyses into the effectiveness of Electric Vehicles prove them to be a worthy successor to the present day IC engine vehicles. Due to the technological limitations present in the 19th Century and early 20th century, they proved **not** to be an effective solution, which was why the shift to IC engines was wildly popularized. Those technological limitations have largely been overcome today, and similar, if not more superior performance has already been achieved by their Electric counterparts and in the upcoming years it is certain that these EVs shall turn out to become unmatched and unrivaled as they are far more efficient and cleaner.

This technological breakthrough in automotive transportation was made possible largely due to the breakthrough in battery technology, namely the Lithium-ion battery, which has been described in detail above. The first practical breakthrough had been achieved by Toyota's Nissan Leaf and following its success, other major automotive giants, such as BMW with the BMWi3 followed suit. Furthermore, the sensational performance and success of Tesla Motor's Tesla Model S and Tesla Model 3 further continued to motivate automotive manufacturers to drive the industry forward with Electric Vehicles and Mercedes in 2019 shall now be joining the race.

In our Thesis, we have presented analytics pertaining to Electric Vehicles, Hybrid Electric Vehicles and also on IC vehicles. A study on the lithium ion batteries, where improvements can be made was also mentioned; the dynamics of vehicles and the motor control have also been discussed in detail. Based on the information here further research into the field of Electric Vehicles should be made more effective, interesting and engaging.

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