Inception of Electromechanical Bike Incorporating Torque Sensor Technology and Solar Charging Kit

A Thesis

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Inspiring Excellence

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DECLARATION

We hereby declare that research work titled "*Inception of Electromechanical Bike Incorporating Torque Sensor and Solar Charging Kit*" is our own work. The work has not been presented elsewhere for assessment. Wherever material has been used from other sources, it has been properly acknowledged/referred.

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ABSTRACT

Bicycles are one of the most efficient methods of travelling in Bangladesh, given the country's narrow roads and heavy traffic. Pollution, and load-shedding are also two problems largely faced by the country. Thus, in our paper, we have tried to focus on all the aforementioned problems and find a solution to them with the help of our torque sensor-based e-bike. The torque sensor-based e-bike will reduce the strain on the batteries of the bike, as the torque from the user will be providing pedal-assistance. We have also ensured that our bike has an option of charging off-grid via our solar panel charging station, where the batteries of the bike will be charged using the battery swapping method. This method will ensure, that people living in the remote or rural areas do not depend on the national grid; rather on renewable energy sources. This paper describes the data obtained from field test to determine its performance, feasibility and user friendliness. The solar battery charging station is designed and its performance analysis is included as well. The model was developed to save energy, use sufficient solar energy and ensure that it has an option of operating off grid if need be.

CONTENTS

1. Introduction

1.1 Bangladesh and the Potential of Bicycles

At an area of 147,570 km², Bangladesh is 1/6th the size of the state of Texas in the United States of America. Not only there is a scarcity of space, but the population density of Bangladesh as of 2016 is 1,252 people per square kilometer, thus making us the 13th most populated country in the world! [1.1.1] [1.1.2] To add fuel to the fire, the road system in Bangladesh is not very efficient either. The capital; Dhaka's, most popular areas are host to narrow lanes weaving in and out, almost as if an obstacle course. This, paired with the fact that the number of registered motor vehicles in Bangladesh is on the rise, due to a booming economy, leads to obvious problems. Small area, paired with high population density and poor road system leads to unbearable daily traffic. Traffic in Bangladesh is immense and commuting from one point to another has become a routine hurdle that is faced by all citizens. Carrying out basic day-to-day activities have become increasingly difficult. To cover a distance of only 2 kilometers, people head out with an hour on their hand to factor in the traffic for that day. To many, this has become a part of their daily life that they have accepted. However, what most people do not realize, this traffic causes an individual to lose almost 3-4 hours a day on an average! That is 21-28 hours a week, 84-112 hours a month and 1,008-1,344 hours a year! As a country, that sets us back as well, if an average of 100 hours a day is spent stuck in traffic every year. How will we as country be advancing forward if so much time is wasted by the nation's working class sitting in one place? Though, there is a solution to this problem, it is a long process. Developing roads to become wider and accommodate the growing number of vehicles in a systemic fashion is a feat that cannot be done overnight. This brings us to an easy solution, why not try and overcome this problem in a way that can be effective immediately?

Bicycles are an extremely efficient method of transportation. They are quick and adequate for a country such as Bangladesh that is facing extreme traffic problems. Many countries, such as the Netherlands, have opted the use of bicycles to avoid traffic and improve overall efficiency of an individual and the country. Similar to the Netherlands, Bangladeshi citizens could also opt for a bicycle as their primary method of transportation. As previously mentioned, since Bangladesh is a small country and the cities are even smaller, getting around in a bicycle is completely pragmatic, as not very long distances have to be covered. Rather, an individual would be saving ample amount of time, which he/she could now be spending elsewhere.

This does not apply just for the urban areas but for the rural areas as well. Although rural areas do not face the problem of traffic, the conditions of the roads make it impossible to commute, thus rendering large areas completely inaccessible from the larger cities. Many people, due to lack of accessibility are as a result cut off from modern advancements

Most of us are have fond childhood memories of riding a bicycle. In fact, it has also become almost a stereotype that every child must have a “learning to ride a bicycle” phase in their childhood. But let’s back up here. What is a bicycle? According to Wikipedia, a bicycle is a human-powered, pedal-driven, single-track vehicle, having two wheels attached to a frame, one behind the other. But what is a bicycle to the average person? Well, since bicycles were first introduced in the early 21st century, they have been one of the most popular modes of transport, having surpassed even the number of cars produced by a large margin. A large part of that comes down to just how reliable a bicycle is. It can be used to traverse both long and short distances and maneuver around traffic and narrow alleyways and is a cheap, efficient and healthy way of travelling. In Bangladesh, we have a niche community of bicycle enthusiasts but not really an established system of transport for bicycles like most other countries. A great example of a country that has adopted bicycles as a primary mode of transport is Japan. In Japan, there are amazing public transportation systems like the subway and buses but most people prefer to ride a bicycle, especially if the distance isn’t too far. They have infrastructure supporting the bicyclists and a system of law [1.1.3] that makes life easier as someone who rides a bicycle. Even for tourists, they have rental bicycle agencies which can be used to tour the beautiful countryside. To adopt a similar approach to bicycles here in Bangladesh will undoubtedly enrich the lives of the people of this country and be a step towards its progress.

1.2 The Electric Bicycle (e-bike)

As we have seen so far, bicycles are probably a great, all-round form of transport that excels in almost everything. If there was one area that it would falter, however, it would be the distance which can be covered. For the average, healthy male, travelling somewhere between 60 km to 90 km in a day is perfectly feasible. This being said, travelling longer distances can be seen as extraneous tasks and people are more likely to switch to other modes of transport. The old and ailing would have a harder time pedaling it to go to even places nearby and even the most physically fit cyclist can feel the exhaustion from cycling to faraway places all the time. Enter, the Electric Bicycle. An Electric Bicycle aka an e-bike is basically a bicycle with a motor system attached to it that provides an assistance to the rider when the rider is no longer able to or no longer feels like pedaling to get to his destination. It is an easier and more convenient form of the bicycle that basically throws out the disadvantages of a regular bicycle. When problems like hills, fitness levels, health or even simple convenience get in the way of enjoying a bicycle ride, it is the e-bike that can take to the scene and provide a solution. As mentioned above, Japan is a nation that heavily favors bicycles. Being as ahead of the curve as they are, they realized the importance of e-bikes and they are now also one of biggest e-bike hubs in the world. Even the west has slowly realized the prevalence of e-bikes, slowly having built infrastructure and become one of the largest e-bike markets in the world, second only to Asia.

1.3 Motivations

The state of traffic in Bangladesh is horrendous to say the least. In a survey done in mid-2017, it was found that Dhaka traffic takes up about 3.2 million hours of working hours per day. In the 2016 Global Livability Survey, a quality of life report issued annually by the Economist Intelligence Unit, ranked Dhaka the 137th out of 140 cities with the worst traffic. The only cities below it were the likes of Lagos, Tripoli and the war-torn Damascus. The level of traffic got so bad, in fact, that the New York Times even wrote an article on it, calling Dhaka's traffic problem the great symbol of the 21st century's urban dysfunction. Traffic aside, Air pollution is another major problem plaguing the country. Early 2018, a report published by Clean Air and Sustainable Environment (CASE) showed that the Air Quality Index of Dhaka city was the worst in the world [1.1.4], ergo making the city the most polluted city in the world. Pairing all this up with the fact that the supply for electricity for the country cannot keep up with the demand, i.e. the load shedding crisis, the overall living quality of the citizens of the country is significantly low.

Our goal with the torque sensor-based e-bike is to create a more comfortable, easily accessible transport alternative that can circumvent the heavy traffic of the city, provide a more environmentally friendly way to traverse the roads and to create a system that will not have to rely on the power grid of the country and therefore be an off-grid system.

2. Overview of the System

2.1 Introduction

When designing our e-bike, we wanted to ensure that our bicycle had something extra to offer that no other e-bike in the Bangladeshi market currently was offering. Thus, we introduced the torque sensor in the e-bike pedal, chose lead acid batteries over lithium ion batteries and also had two charging options; one is that via solar panel power and two would be that of power from the national grid. These features, along with more will be discussed in the following section.

2.2 Bicycle Frame

Picking the correct bicycle frame was one of the most crucial parts of this project. This was because the bicycle will have to be strong enough to hold up the heavy batteries we would be placing on its back and also durable enough to go through the field tests unscathed. We decided from the beginning that we would try and opt for components that were of high quality but the pricing was affordable. Thus, after surveying around, we picked a black and green bicycle manufactured by Hero Ranger Max. This bicycle was the perfect match for the e-bike we had in mind as it checked all our requirement boxes of having to be durable, steady, light-weight and also fit our budget.

The size of the frame is 18". The bicycle is like any standard bicycle, comprising of two steel frame wheels with steel rims, each rim measuring at 26”. The bicycle has a V brake (linear-pull brakes) which have a very good safety history. Also, with the bicycle, there were steel mudguards which would allow the user to cycle through muddy or wet conditions, specially factoring in the element that rain constitutes a large portion of Bangladeshi weather. Other features of this bicycle frame include a rod carrier and a round chain cover.

Fig 2.1: The Bicycle Frame of Our Choice

2.3 Batteries

Choosing the correct battery was an extremely challenging task. We were constantly faced with the option of having smaller batteries but increasing the overall manufacturing price of each bicycle by 30% or opting for larger, bulkier batteries but keeping the overall price of the bicycle at a minimal. Eventually, we decided to choose affordability over weight and picked two sealed lead acid batteries. Each battery weighs around 9.5kg; therefore, leading to a grand total of 19kgs on the back of the bicycle. The batteries are rated at 12V each with 30Ah. When connected in series, the overall battery system will be of 24V.

Fig 2.2: 12V 30Ah Battery on the Back of Our e-bike

2.4 The Motor

In our system we used a MY1016Z 24V, 250W brushless DC (BLDC) gear motor. This BLDC motor has a rated speed of 2700 rotations per minute (RPM) and a no-load speed of 3000 RPM. The full load current for this motor is 13.7A or less and the no load current is 2.2A or less. Though not locally made, this motor was purchased from "Bangshal Thana" in the Dhaka district and was our preferred choice of motor as it was powerful and light. To further ensure stability of the e-bike, the motor is placed with the outside of the rear wheel shown in the figure below.

Fig 2.3: BLDC Motor on the e-bike Wheel

A BLDC has a rotor and stator part. On the rotor there is a permanent magnets and stator has an electrically controlled rotating field, using sensors (rotary encoder or back-EMF) is used to detect the rotor position. In the BLDC motor there is no commutator, due to which this becomes more efficient than the commutator motors. As a result, these kinds of motors can produce maximum amount of torque which is decreased linearly with the decreasing amount of voltage. As they give more torque per weight, they are the most suitable choice for our e-bike. The more the torque the more advantageous it is for the vehicle. A higher torque per watt increases the efficiency, reduces noise, increases reliability, eliminates the ionization sparks from the commutator, longer lifetime, and lastly reduces the electromagnetic interference (EMI).

Fig 2.4: Close-Up View of the BLDC Motor

2.5 Motor Controller

To regulate the voltage of the BLDC, we used a motor controller on the e-bike. Due to the unavailability of having a proper data sheet, we got the controller wire connections from some online resources and experiments. The motor controller has the following connections:

- Battery
- Motor Hall sensor
- Charging port
- Indicator
- Accelerator
- Power lock
- Brake
- Brake light

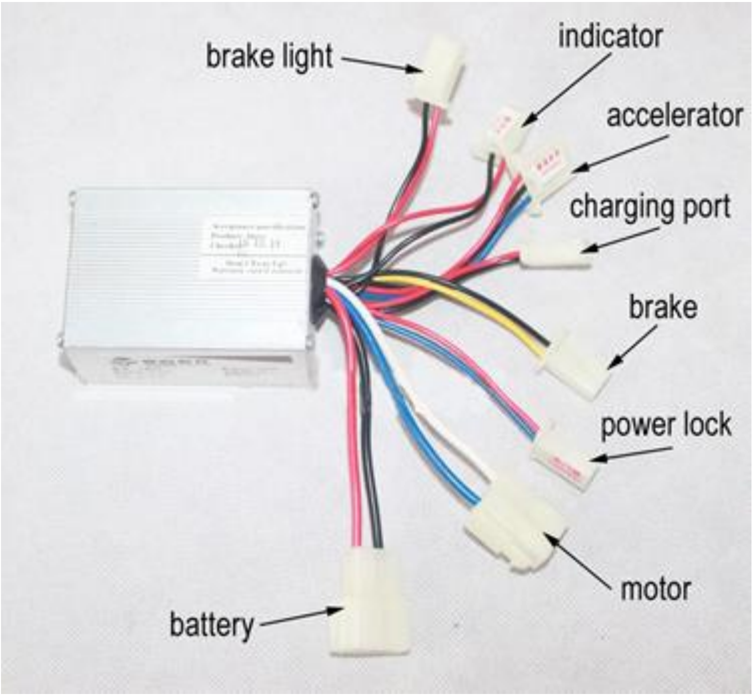

Fig 2.5: Connections of the Motor Controller

2.6 The Throttle

The speed of the motor is being controlled by the throttle. Throttles are generally used in all kinds of e-bikes to control the speed of the motor and in our e-bike, it serves the same purpose. A throttle is a specially designed potentiometer through which a voltage signal (usually not more than 5V) can control the minimum and maximum speed of the motor. The biasing voltage of the throttle is 5V which is provided by the motor controller unit. The output voltage depends on the angle of the throttle which will be applied by the user. As the speed of the throttle increases, the output voltage will also increase. The motor will start when it gets an output voltage of 1.4V from the throttle and at 3.5V, the motor will rotate at its maximum speed.

Fig 2.6: Throttle

2.7 Torque Sensor

The torque sensor is a device that is used to record and measure the torque of a rotating system. The torque sensor gets an input from the pedal torque which it then converts the mechanical torque into the electrical output. From the DC source (in the case of our e-bike this comes from the torque sensor circuit), it gets 5V which it needs for biasing. The output voltage is linear with the applied torque within its operating region. With the increasing voltage of the torque, the output voltage will also increase. The motor speed is also directly proportional to the output voltage, i.e. an increase in the output voltage will result in an increase in the motor speed. For our e-bike, the use of the torque sensor features ease of pedaling for the rider. This feature is assisted by brushless motor controllers. These controllers provide instant response when the pressure is applied. The torque sensor that has been used in our vehicle is given below and a more detailed explanation is given in Chapter 4 of this paper.

Fig 2.7: Torque Sensor Paddle and Module Blinking Red on the e-bike

2.8 The Brake System

The brakes in our e-bike are of the linear-pull brake system also known as the "V-brake" system as referred by Shimano's trademark. V-brakes, are a side-pull version of cantilever brakes and mount on the same frame bosses [2.1.1]. The arms however are much longer, with the cable housing attached to one arm and the cable to the other. As the cable pulls against the housing, the arms are drawn together, thus putting the brake into full effect.

Fig 2.8: Brakes

2.9 Safety Features

As a safety measure, to the handlebar of the e-bike, we have added a traditional bell. However, due to the loud cacophony that is Dhaka traffic, we decided to add an extra bell on the handlebar which is loud and clearly be heard from passerby vehicles. Alongside two bells, we have also attached an LED safety light that has three forms of blinking; monotonous, slow blinking and fast blinking. The first constant light supply would help during night time as a constant light supply will help with visibility. The other two forms of fast and slow intermittent blinking would also act as safety features to warn oncoming vehicles of the e-bike's presence.

Fig 2.9: LED Light, Digital Bell, Traditional Bell (left to right)

2.10 Culmination of the Components

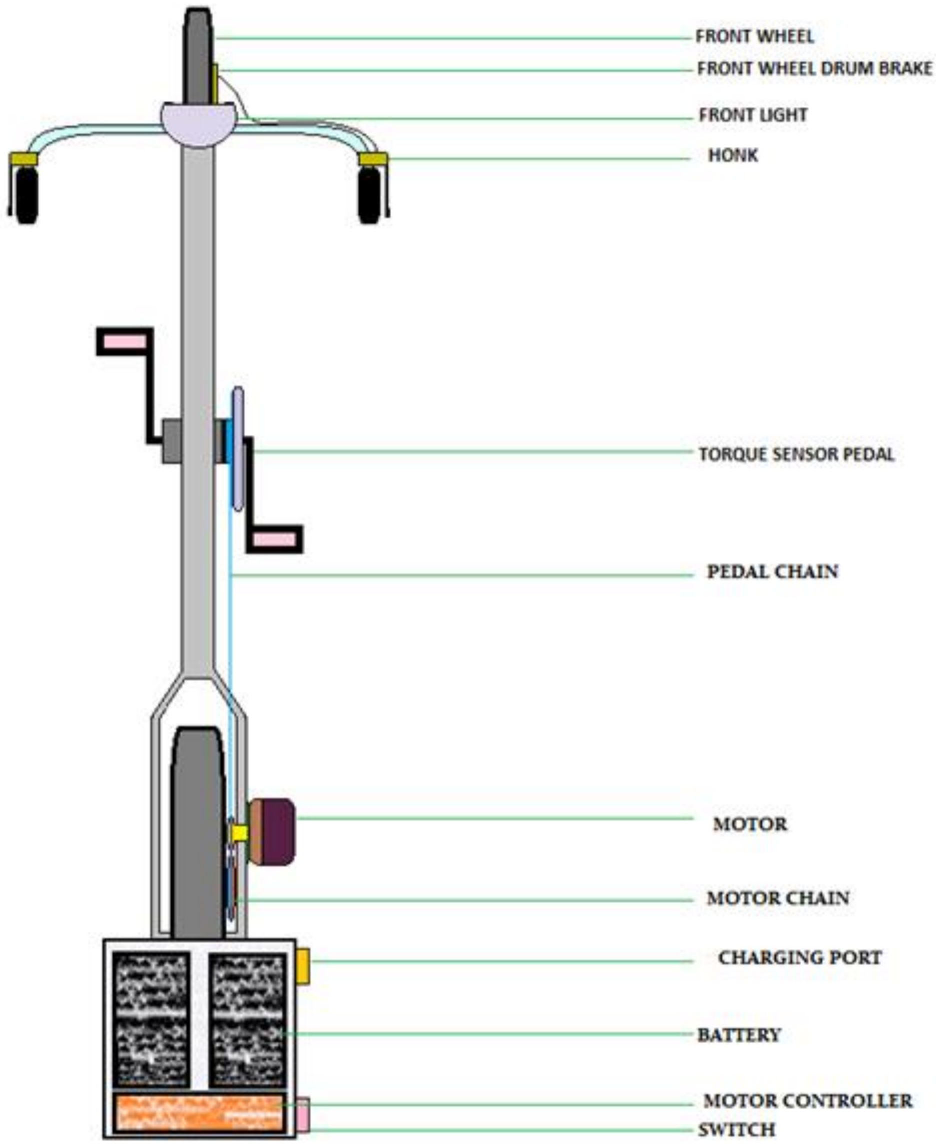

Fig 2.10: Overall Skeleton of the e-bike

Fig 2.11: Side View of the e-bike

Fig 2.12: Front View of the e-bike

Fig 2.13: Back View of e-bike *Fig 2.14: Top View of e-bike*

2.11 The Solar Panels

Fig 2.15: 100 W Solar Panels

Two 100W solar panels were used to charge the e-bike. Details of the procedure are mentioned in section 5 of this paper.

2.12 Charge Controller

Fig 2.16: Electro Charge Controller

The above charge controller was used to protect the batteries from sudden rises in current, overcharging and discharging during night time.

3. Design and Construction

3.1 Introduction

The design of the e-bike can be categorized into two major parts: the mechanical design, for choosing the correct type of bicycle, and the electrical design, which focuses more on the electrical components used in the system. To further aid these design purposes, the limitations and drawbacks of the various existing e-bikes were also sincerely considered. Another point of consideration was the country we live in and how the mindset of the people living here would be positively affected by the e-bike. The following chapter, therefore, is a culmination of all these.

3.2 Mechanical Design Overview

When choosing the type of bicycle frame, we wanted for our e-bike, we considered the following points:

- Durability and sturdiness
- Weight of the frame
- Price

The bicycle frame needed to be durable and sturdy, so that the e-bike would not deteriorate over the course of time and wear and tear after use would be minimal. Weight was also a crucial factor we had taken into account, as we knew that an extra weight of almost approximately 19kgs would be added at the back of the bicycle due to the lead acid batteries. A heavy bicycle would slow the rider down, resulting in poor rider experience. The final point, i.e. the price of the bicycle, was ensured to be such that it would not affect the overall price of the e-bike. Otherwise, we would be missing our target of making sure that the e-bike is a sustainable, cheap method of transportation.

3.3 The Base Bicycle

For the purposes of this thesis, our goal was to create an e-bike that was sustainable and cheap while simultaneously being durable and being able to withstand the wear and tear of everyday life. For this purpose, we went ahead to select the bicycle that we felt that would suit our needs the best. The bike that best fit the bill was the Hero Ranger Max bicycle.

Fig 3.1: The Hero Ranger Max Bicycle

The bicycle in question has a weight of 18 Kg and has a sturdy frame [3.3.1] and holds to the set standards nicely.

3.4 Electrical Design Overview

For the design of the electrical system to be incorporated into our e-bike, we did a lot of research into existing e-bikes and how they operate along the globe. The design objectives here were to do the following:

- Follow a standard, existing e-bike system
- Incorporate the torque sensor system into it
- Incorporate a power system is powered through a single source

3.5 Analysis of Existing e-bikes

For many parts of the developed world, e-bikes have become a staple form of transport. Using the systems used there as a reference, we were able to discover the standard parameters for an e-bike system. First of all, we looked into the top manufacturers of e-bikes like Haibike, Faraday and Easy Motion [3.5.1] and tried to see what would fit best both logistically and thematically for our country. We decided to go with Volton's Boulevard DLX as the base model and then work our way from there. The Volton Boulevard DLX had a 36V 500W system [3.5.2], however, which we could not incorporate. The reason for this being the case is that the European product safety standard EN 15194 prohibits the use of e-bikes above the power rating of 250W [3.5.3] and thus this kind of bike wouldn't comply with these regulations. Thus, we settled on a 24V 250W system as commonly found in the electric rickshaws of the country.

Fig 3.2: The Volton Boulevard DLX

3.3 Battery Compartment

The e-bike's batteries and other circuitry would have to be put into a box and located in such a manner that it would cause minimal disturbances to the rider and be mostly out of the way. This resulted in the first model of our Battery Box placement. The Battery Box was placed in the middle of the chassis in the gap right above the pedal. It was nice and compact and seemed mostly out of the way, also helping with keeping the center of gravity somewhere near the center of the bike. Upon rider feedback, we discovered that the box was constantly scraping the knees of the riders and caused the overall ride to be a minimally irritating rider experience. Thus, to correct this we relocated the box to the back of the bicycle.

In placing the battery box at the back of the bicycle, our first concern was how this would affect the shift in center of mass. While this change resulted in the center of mass being shifted more towards the back of the bicycle, when the rider sits on it, the center of mass once again shifts near the center of the bike. Thus, this problem was also averted. Another problem we faced, however, was the fact that normal bicycles usually reserve the back for carrying luggage and the like. Placing our Battery Box at the back would cause us to deprive the rider of this feature that is enjoyed by almost all bicycles. Thus, we came up with the Battery Compartment. This is essentially a bigger box that incorporates not only the Battery Box but also keeps space for the rider to keep any luggage or other material that they may need to carry along with them.

Fig 3.3: The Evolution of the Battery Compartment. Original Box Placement (top); New Box Placement (bottom left); Box After Recolour (bottom right)

Now that we had finally replaced the Battery Box with the Battery Compartment, we recolored the new, bigger box to fit with the color scheme of the bike.

4. Integrating the Torque Sensor

4.1 Introduction

Torque is a term that everyone is accustomed using in their daily language. In this chapter we will discuss the general features of the torque sensor, its working mechanism and the process of integrating it with our system. We will also be discussing the power management of the system along with the mechanical integration of the sensor with our system.

4.2 Introduction to the Torque Sensor

A torque sensor or torque transducer is a device for measuring and recording torque on a rotating system, such as an engine, crankshaft, rotor, gearbox, transmission, a bicycle crank or cap tester [4.2.1]. It is a transducer that converts torque based mechanical input into an electrical output signal. There are two types of torque sensors, a reaction that measures static torque and rotary that measures dynamic torque [4.2.2]. Taking input from a DC voltage source, the torque sensor generates output voltage corresponding to a torque applied on specific crank or shaft. Within its operating region, the voltage output is linear with the applied torque.

Fig 4.1: The Torque Sensor Paddle and Module

4.3 Types of Torque Transducers and Torque Sensors [4.3.1]

- Brushless Rotary Torque Transducers
- Flange Torque Sensors
- Shaft Torque Sensors
- Multi-Axis Torque and Axial Force Transducers
- High Capacity Torque Transducers (>5000Nm)
- High Speed Rotary Torque Sensors (>55000rpm)
- Low Capacity Torque Transducers (<1N)
- Rotary Slip Ring Torque Sensors
- Miniature Torque Transducers
- Square Drive Torque Sensors
- Static / Reaction Torque Transducers
- Wireless Radio Telemetry Rotary Torque Transducers

4.4 Technical Parameter Data [4.5.1]

- Vcc = 5.15 V (+/- 0.15V)
- Output, linear, zero-start, 0.5~4.5V
- Output torque >15N-m
- Delay time < 50ms

4.5 Features [4.5.1]

- Brush/Brushless motor controllers are compatible with it
- The hardware may be installed like a normal chain wheel crank
- The electrical system is sensor/sensor-less motor type
- Main body parts are made of aluminium alloy
- Provides instant response while pressure is applied on pedal and pedaling is stopped or pressure on pedal is reduced
- Data collection per crank rotation ranges from 18 to 96 times
- Magnet ring integrated with multi-pole improving greatly the precision of signal sampling
- The system is fully sealed against ingress of water and dirt

4.6 Applications [4.3.1]

- Torque and Power Management on Drive Shafts

- Marine
- Steel Manufacturing
- Torque Wrench and Tool Testing/ Calibration
- Automotive and Motorsport
- Wind Turbine Development
- Aircraft Component Testing and Development
- Pump Development
- Production Process Monitoring

The torque sensor setup was purchased from Suzhou Victory Sincerity Technology Company Ltd (http://www.jc-ebike.com) which is located in Suzhou, China in order to use with the system. They undertake to develop, design and produce the components of e-bikes, mainly torque intelligent sensor system and relevant parts. The company has a group of experienced experts at designing and developing various e-bikes. The company has developed torque intelligent sensor system which conforms to the European standard ---EN 15194, Japanese JIS standard [4.5.1]. Torque Sensor is their national patent product. To use with bicycles, they have integrated the sensor technology inside the pedal-system. In the system, only the sensor and module were used.

4.7 Electrical Connections

The torque sensor paddle had already been built in such a way that it would fit naturally into any e-bike. For our project we have used the paddle along with the sensor's signal-producing module, whose connection diagram is shown below.

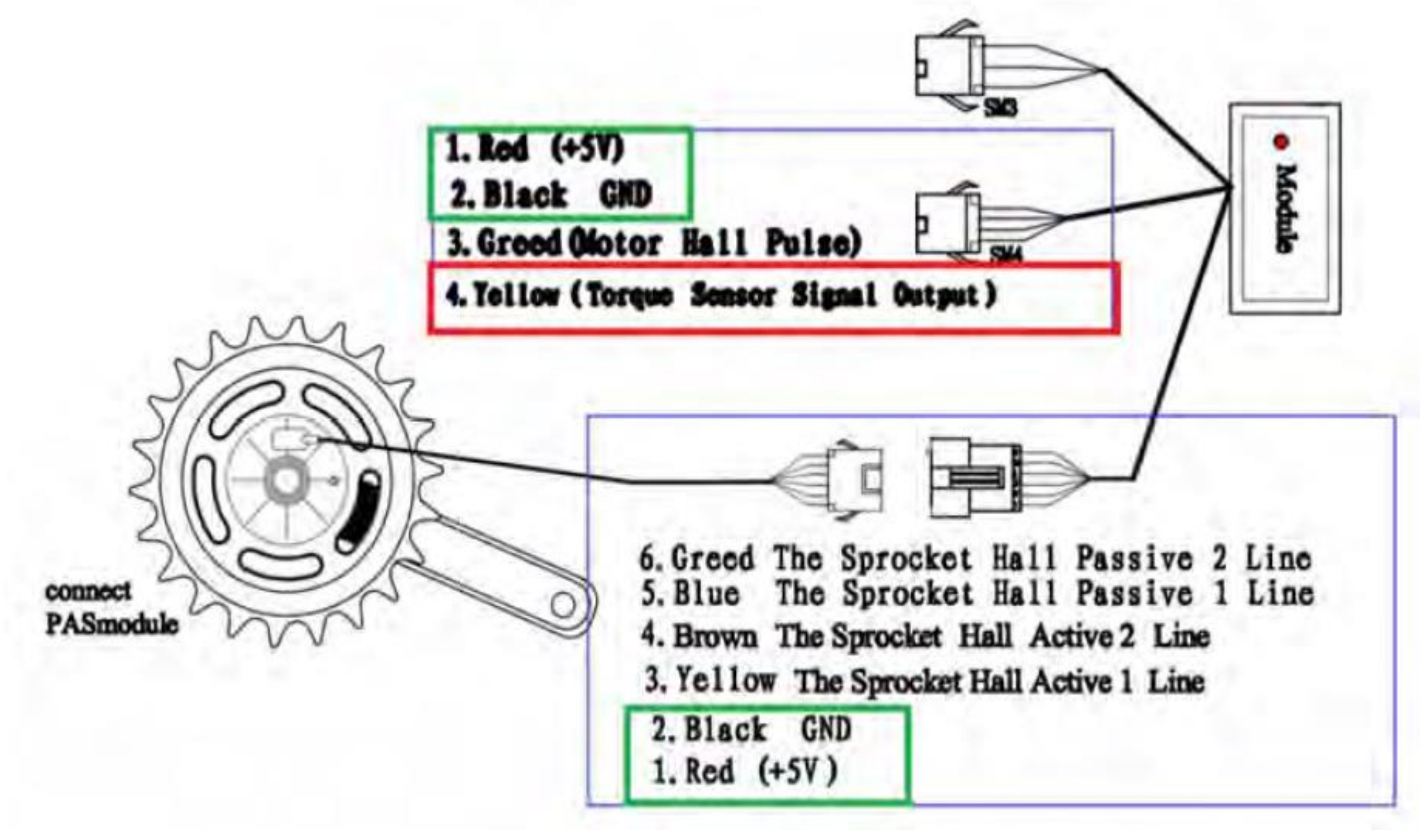

Fig 4.2: Electrical Connection Diagram for independent operation of the sensor and module [4.5.1]

The Fig 4.2 shows that the input biasing terminals for the sensor are the Red and Black wires from SM6 (marked as +5V and GND). This biasing voltage turns the module ON to come into the operation. The yellow wire from SM4 is the input voltage for the module which is the processed output from the torque sensor. This wire gives the output voltage with respect to GND according to applied torque in the pedal-crank of the sensor. So, this is the output which is supposed to be fed to the external control circuit.

4.8 Power Management

It is necessary for us to power the entire system with a single power source. Thus, we are using two 12V batteries in series. The external circuit design and the torque sensor specification setup require that only a +5V source is necessary to power all these devices. So, to solve this purpose, a DC-DC Buck converter was used to supply 12V to an LM7805 which would then, in turn, provide a +5
V bus to power all these external devices.

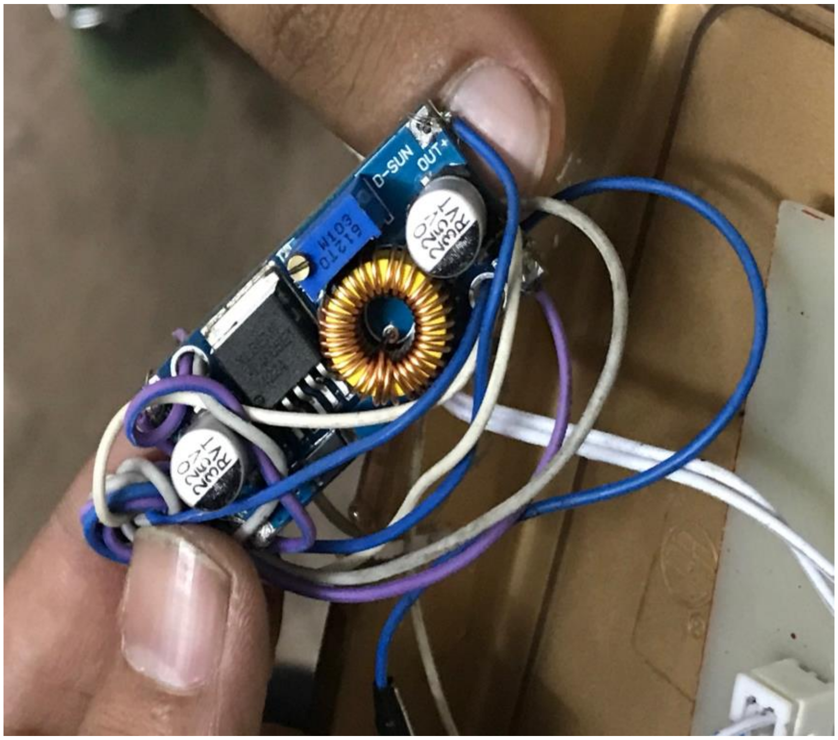

Fig 4.3: The DC-DC Buck Converter

From this +5V bus, a signal will be fed to the amplifier circuit as biasing and also to power up the torque signal producing module. When pressure is created on the pedal, there will be a certain torque for which the torque sensor and module will provide a corresponding voltage to the amplifier circuit. The amplifier circuit will eventually output a voltage corresponding to the voltage provided by the sensor and module maintaining the ease while pedaling. This voltage is fed to the motor controller unit and eventually to the motor.

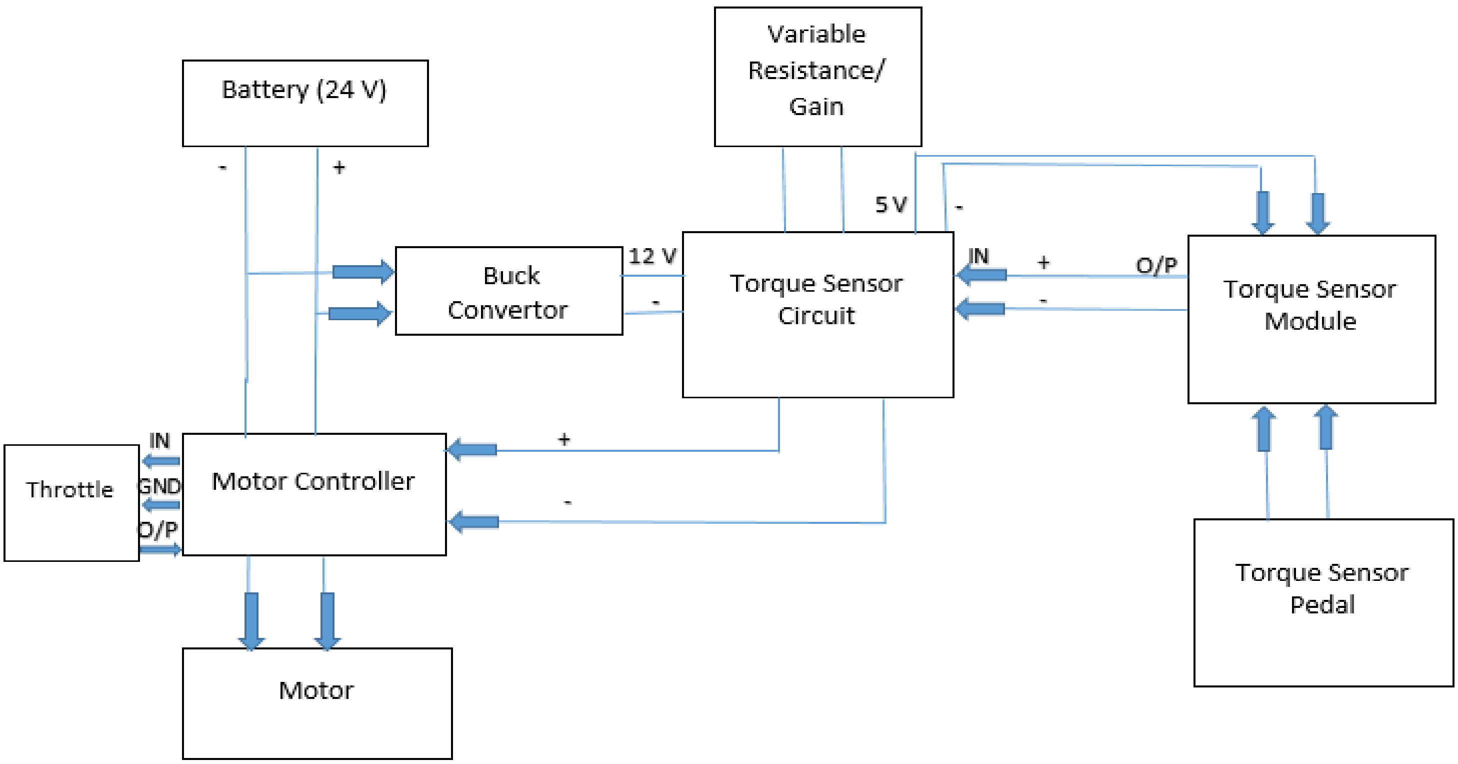

Fig 4.4: Signal Flow Diagram of the Entire System

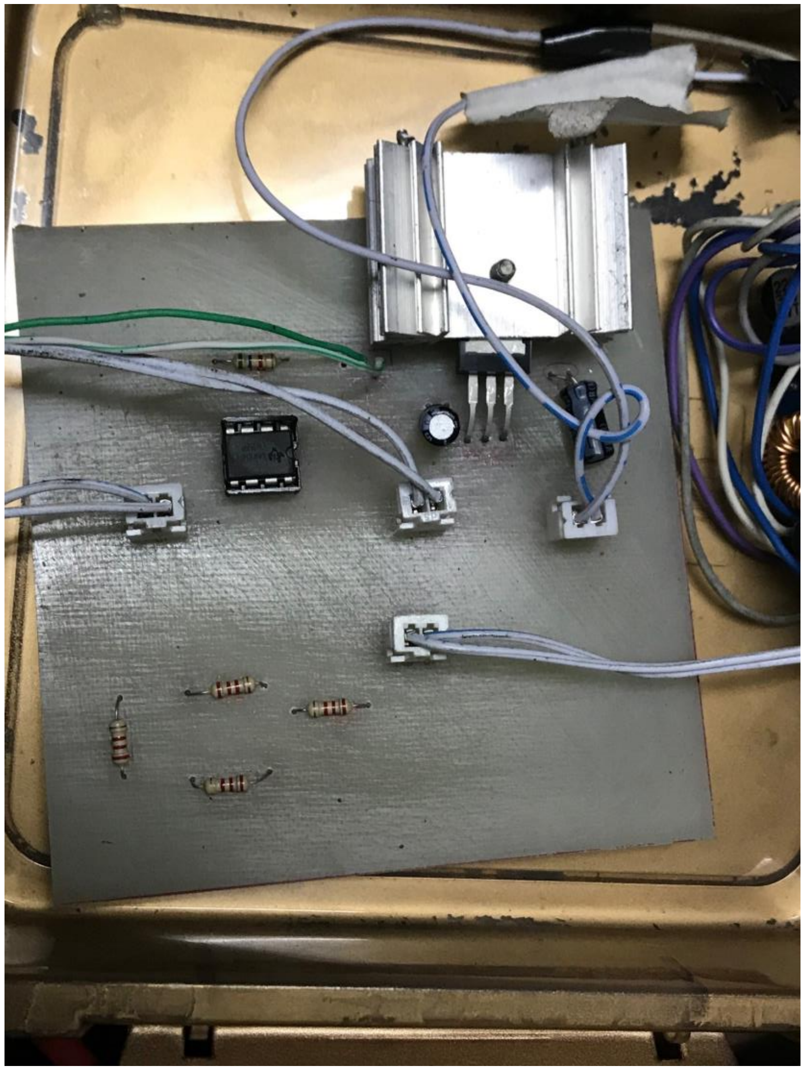

Fig 4.5: The Voltage Regulator and Amplifier Circuit

This torque adjuster and amplifier circuit, along with the voltage regulation by the LM7805 were constructed together in PCB. This way it will be a compact system and will eradicate problems arising due to the use of breadboard and a lot of wires connecting the components. While going for lab test and later on field test, the roads might not have been smooth, so hardware implementation resolved the problem as each of the components are soldered onto the PCB board and there is no chance of any component falling apart due to shakiness of the road.

4.9 The Voltage Divider & Amplifier Circuit:

A notable part of the amplifier circuit is the use of a voltage divider circuit in it. Instead of directly feeding the voltage coming from the torque sensor and module to op-amp, the input signal for the amplifier circuit passes through a voltage divider to reduce the incoming voltage to 0.6 times of the input voltage. This reduced voltage is then fed to the op-amp. If the incoming voltage is somehow very much high, it will be reduced to a certain value in this way and eventually limit the use of motor. While running the e-bike practically, sometimes the voltage generated by the torque sensor can be reached too much higher value around 3-4 V. To minimize this voltage the voltage divider is used in such a way that the output voltage becomes 0.6 times less than the input voltage. That is, VOUT = 0.6*VIN. The circuit diagram is shown in figure. Here a voltage divider circuit has been used in order to limit the torque sensor input voltage.

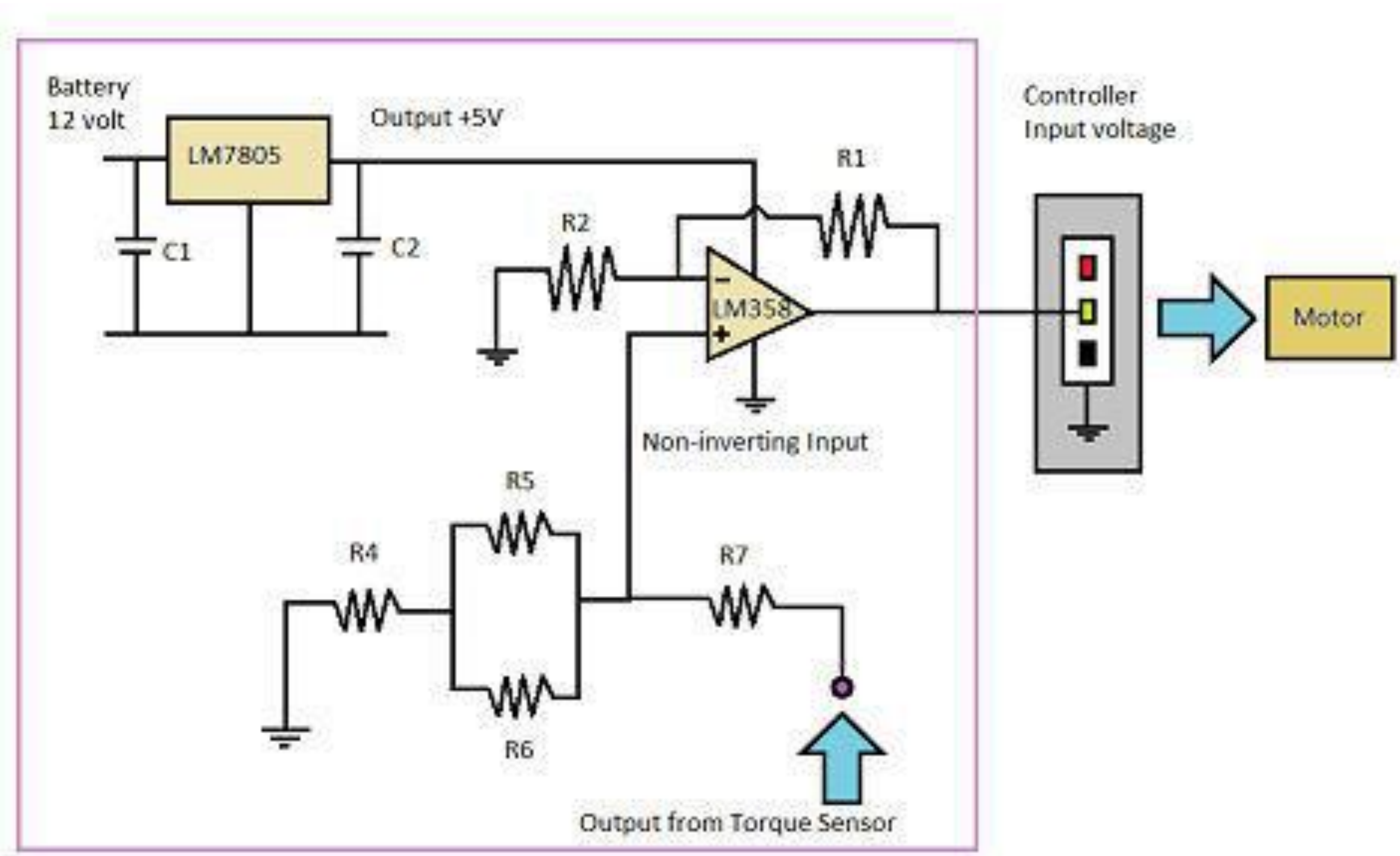

Fig 4.6: Circuit diagram of the amplifier circuit

The circuit will eventually output a voltage corresponding to the voltage provided by the sensor and module maintaining the ease while pedaling. This voltage is fed to the motor controller unit and eventually to the motor. Gain of the amplifier can also be adjusted by a potentiometer.

5. Dedicated Solar Charging Kit and Battery Swapping

5.1 Introduction

Electricity is a valued commodity in Bangladesh. The rural areas suffer from the lack of it, whereas the urban areas undergo severe load shedding during peak hours. Thus, many are now choosing to opt for a more readily available source of energy; solar energy. As of April 2018, more than four million solar home systems (SHS) were installed domestically. These SHSs have uplifted the lifestyle of the impoverished people by providing small-scale power at their homes during times of need. According to the government plan, renewable sources will be providing almost ten percent of the total power generation capacity by the year 2021. [5.1.1]

. *Fig 5.1: The Solar Panels used for the Solar Charging Station*

5.2 Introduction to Our Solar Charging Station

The average sunlight hours in Bangladesh is approximately 6 hours [5.1.1]. Thus, when designing our electric bike, we felt that a solar battery charging station (SBCS) would be the best choice for an off-grid charging option.
This would make certain that there was a method of charging the e-bike that would not let hurdles such as load shedding hamper the usability of our electric bike. This option is in the form of an SBCS on the rooftop of BRAC University building 2. The SBCS present there assisted us in formulating a charging station which would be compatible with our e-bike.

Every e-bike will be equipped with two sets of batteries, creating a system of 24V and 30Ah. The function of having two sets of batteries is that so when one set of battery is discharged down to 50% state of charge (SOC), then that set of battery will be placed at the SBCS for charging. In the meanwhile, there will be another set of 100% fully charged batteries that will replace the old sets of batteries. These fully charged batteries will now be used in the e-bike until SOC reaches 50%.

When designing our solar battery charging station, we took into consideration the following factors [5.1.2]:

- Geographic location, climate and peak sunlight in the area
- Orientation of the roof of the station, rack amount, solar exposure
- Shading obstacles

5.3 Operation of the Solar Battery Charging Station

As previously stated, our e-bike comprises of two 12V 30Ah lead acid batteries. This means that our entire battery system will comprise of 48V and 30Ah. As lead acid batteries usually give 50% of their rated power, a 30 Ah battery thus in practice provides 15 Ah. Thus, the battery can supply 180 Wh, i.e. it can supply 180W every 1 hour.

The next step was to determine the sunlight hours of Bangladesh throughout the year.

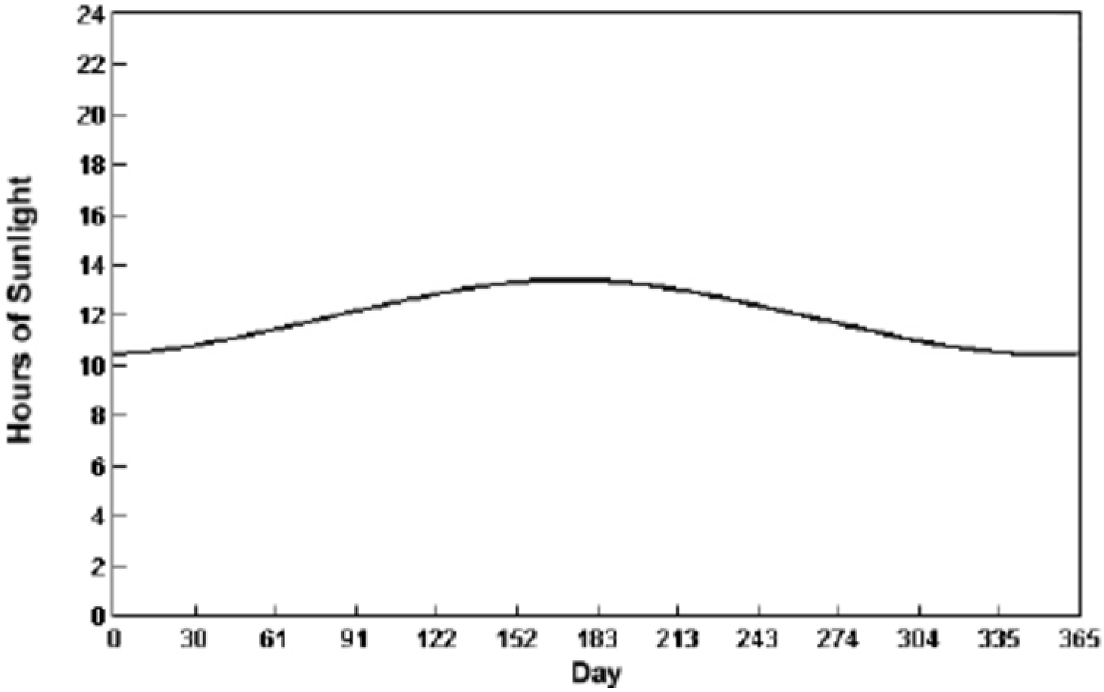

Fig 5.2: Line Chart Showing Yearly Sunlight Hours in Bangladesh [5.1.3]

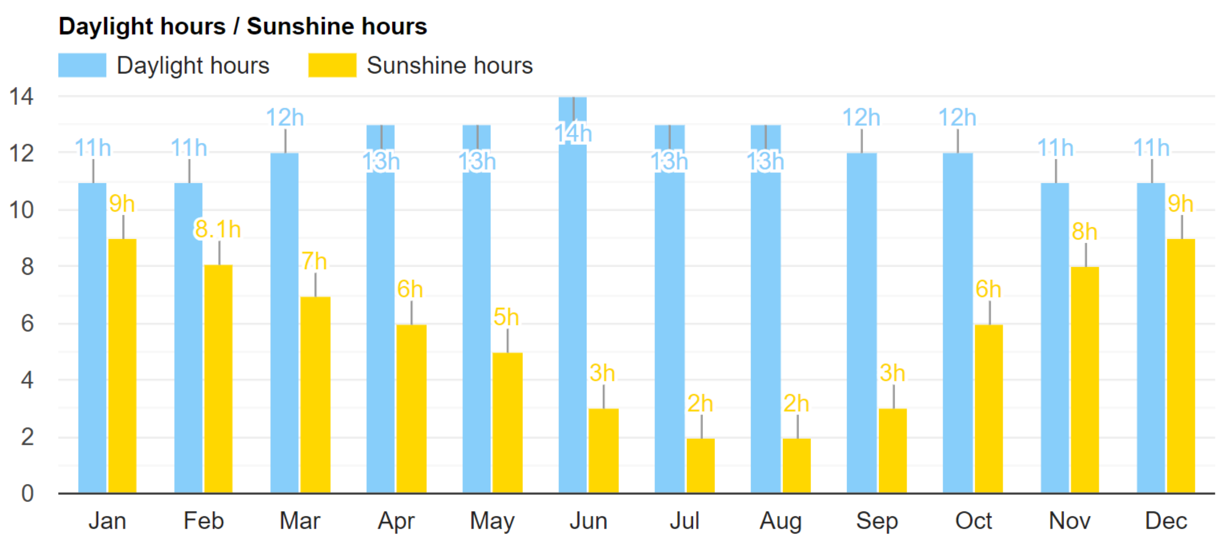

Fig 5.3: Bar Graph Showing Total Hours of Daylight and Sunshine Over a Period of a Year (2014) [5.1.4]

The average sunshine in January: 9h
The average sunshine in February: 8.1h

The average sunshine in March: 7h
The average sunshine in April: 6h
The average sunshine in May: 5h
The average sunshine in June: 3h
The average sunshine in July: 2h
The average sunshine in August: 2h
The average sunshine in September: 3h
The average sunshine in October: 6h
The average sunshine in November: 8h
The average sunshine in December: 9h

From the above graph and table, we calculated the following values:

Total Hours of Sunlight: 2066.8
Average Hours of Sunlight: 5.67
Total Hours of Sunlight in Summer: 856
Average Hours of Sunlight in Summer: 4
Total Hours of Sunlight in Winter: 1210.8
Average Hours of Sunlight in Winter: 8

The next step was to calculate the amount of energy that our batteries were able to store. The 30Ah 24V lead acid batteries being used in our e-bike can store 720Wh. This means that in one hour, the batteries can provide 720W of energy and in two hours 360W.

The solar panels we used were GTS monocrystalline panels, each having peak hours of 100W. As mentioned above, since the average sun hours in Bangladesh is 6 hours, each 100W panel will be providing 600W to the battery. The specifications of the battery are given below:

- Peak hour (pm): 100W
- Open circuit voltage (Voc): 22.35V
- Short Circuit Current (Isc): 5.72A
- Maximum Power Voltage (Vmp):18.80V
- Maximum Power Current (Imp):5.34A
- Power Output Tolerance: +/-3
- Series Fuse Rating:10A
- Weight: 7.5kg
- Module Size:1195*541*35

Thus, accordingly, two solar panels will be enough to charge the e-bike batteries.

Fig 5.4: Two GTS Solar Panels

5.4 Charging the e-bike Using Solar Panels

After 50% discharge, using battery swapping technique, we then replaced our old batteries with the already solar charged ones as shown in the images below.

Fig 5.5 Step by Step Battery Swapping

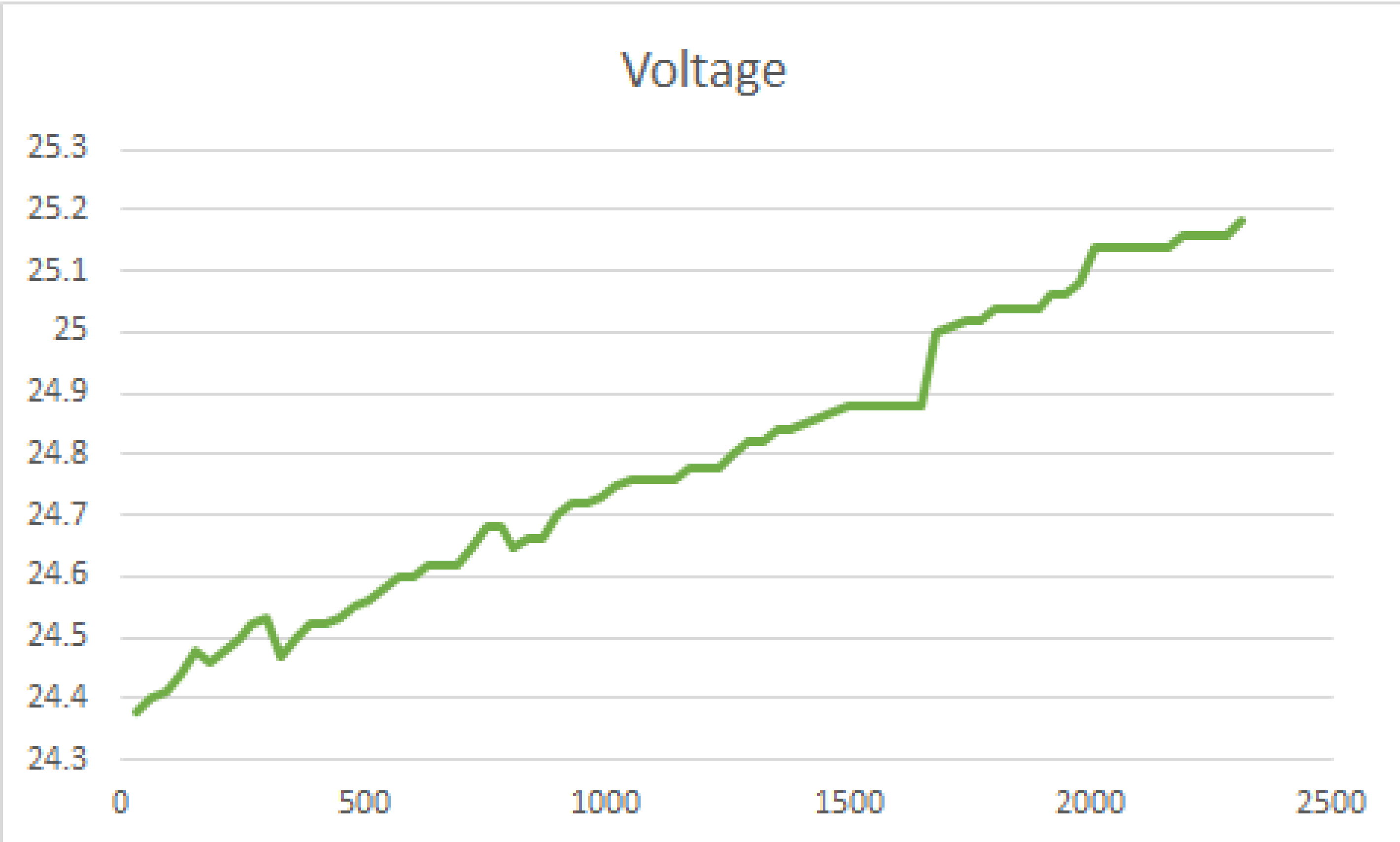

Fig 5.6: Line Graph Depicting Increasing Voltage with Time

After the batteries were swapped. The used batteries were then placed to charge through the solar panels until they were in fully charged state. Voltage readings were taken at every 30 second interval and the above line graph was obtained.

Fig 5.7: Charging Set-Up with Charge Controller

5.5 Easy Battery Swapping

A large area of concern was that since the lead acid batteries are so heavy, moving them would be strenuous for the E-bicycle user. However, after carrying it out practically, it was seen that since the e-bike could be parked right next to the charging station, swapping the batteries was genuinely not as exhausting as previously expected.

6. Mathematical Model and Simulation

6.1 Introduction:

For collecting data from simulation for our ebike we have used MATLAB software to analyze the whole system. First of all, we have developed a mathematical model [6.1.1] for our vehicle and done MATLAB Simulink simulation for the system analysis of the e-bike.

6.2 Developing Mathematical Model:

Our system gives two inputs which are throttle input and pedal input. From the help from paper [6.1.1] we have attained functional block diagram for our whole system. The block diagram is given below:

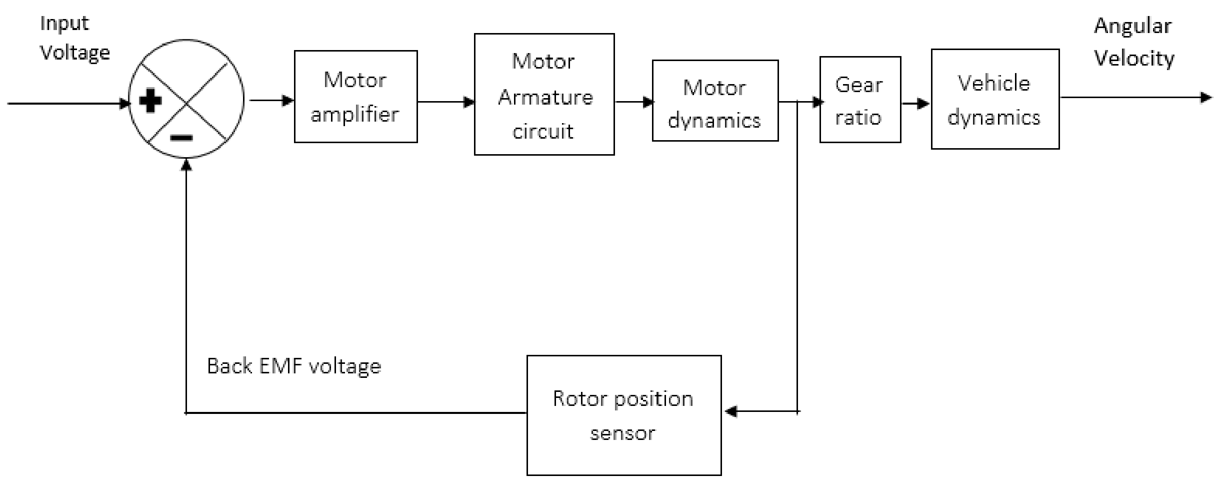

Fig 6.1: Functional block diagram of the motor

6.3 Obtaining Constants for Mathematical Model

Basically, torque sensor converts mechanical input (the pedal torque) to electrical signal which is later supplied to the motor. The parameter for the torque sensor is given below:

V_{cc} = 5.15(+/- 0.15V)

Output, linear, zero start, 0.5~4.5V

Output torque >15Nm

Delay time < 50ms

To obtain the torque sensor gain we need maximum output voltage which is 4.5V and also the minimum applied torque needed to get the output voltage which is 15Nm. Therefore,

Torque sensor gain, $k_p = \frac{4.5}{15} = 0.3$

The output voltage from torque sensor module passes through the voltage divider of the torque sensor circuit and gives 0.6 times the voltage of the torque sensor to the LM358 amplifier.

So, torque adjustor gain, k_a = 0.6

Since, the maximum resistance of gain adjustor/potentiometer in our torque sensor circuit is 5k.

So, LM358 Amplifier gain, $k_{amp} = 1 + \frac{5.6k}{5k} = 2.12$

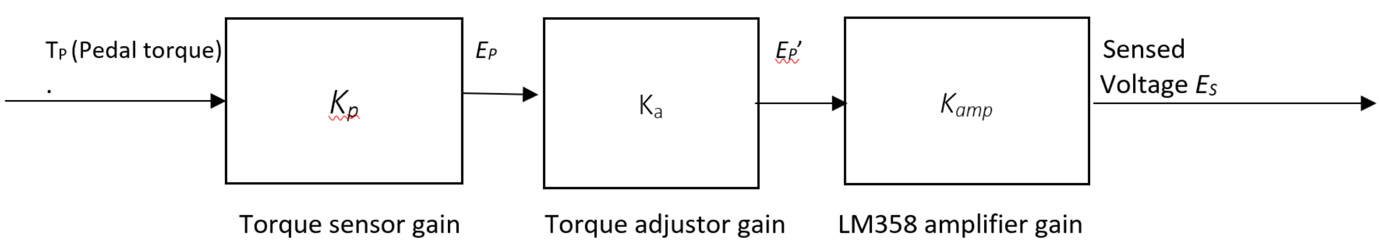

Fig 6.2: Mathematical representation of the torque input

From the figure we can see that, kpedal = kp*ka*kamp = 0.3816

Throttle information [6.1.1]:

Parameters for the throttle of e-bike are given below:

Working voltage, E_t: +5 V dc

Voltage output, E_{in}: 0.8-4.2 V

Radius, r: 0.5in~ 0.0125m

Degrees rotation angle: $0° - 70°$ ~ 0-1.22173 radian (θ_{tmax} = 0.122173rad)

Weight: 150g

F_{max} = 1.4715N

T_{tmax} = 0.018 Nm

Therefore, spring constant [6.1.1], $k_s = \frac{(\Theta_{tmax} * T_t)}{(E_t * \quad E_{in})} = \frac{1.22173*0.018}{5*4.2}$ = 0.001 Nm/rad

Equivalent inertia, $J_{eq} = J_{m-} + \frac{J_b}{N^2}$

$$B_{eq} = B_m + \frac{B_W}{N^2}$$

Here, Gear ratio, N= 0.78 (the efficiency of our motor is 78%)

Rotor inertia, J_m = 0.0000173 kgm^2 [Table 3.1]

Body inertia, $J_b = \frac{1}{2} m r^2$ = 0.5*110*0.3302^2 = 6 kgm^2

At 78% efficiency of motor angular velocity of the wheel, W_w = 469.89 rad/sec

The radius of the wheel, r_w = 13in ~ 0.3302m

So, J_{eq} = 9.86 kgm^2

Now, $B_w = \frac{110*9.81*0.3302}{469.89}$ = 0.758 Nm/rad/s

B_m = 0.0016 Nms/ rad

So, B_{eq} = 1.25 Nm/rad/s

6.3 Mathematical model of the overall system:

After calculating all the constants for the mathematical model, we can find the final block diagram of our system [figure 6.3]. The block diagram is given in the figure below:

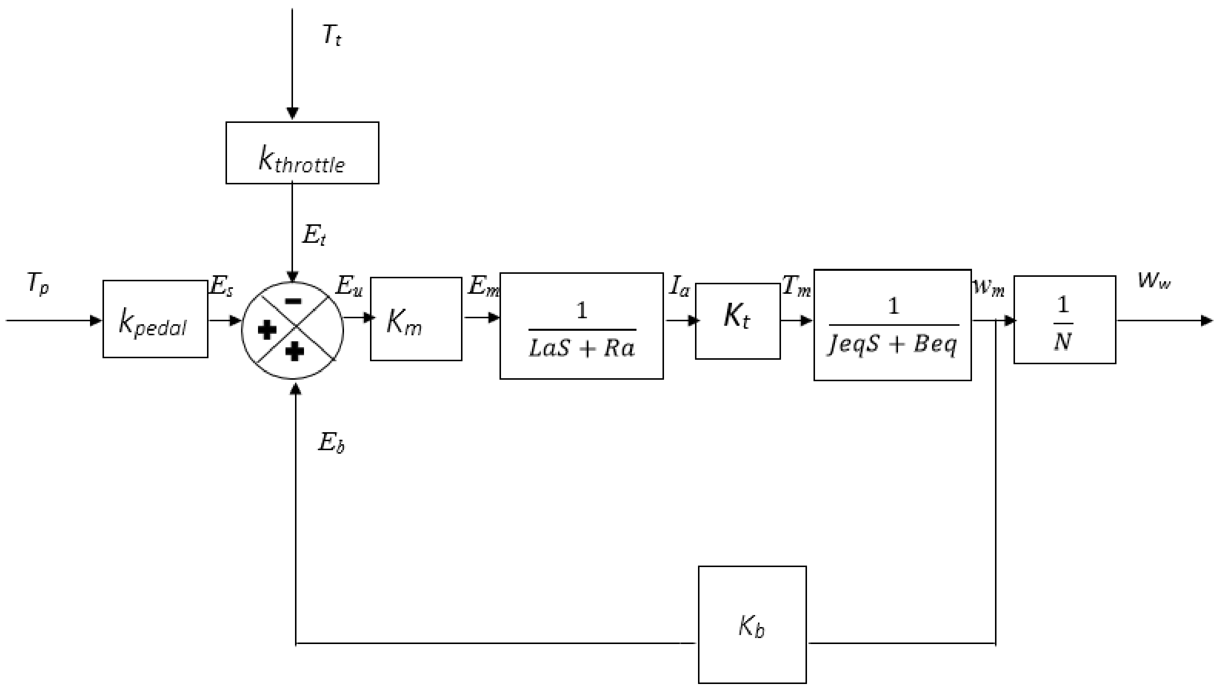

Figure 6.3: Mathematical block diagram of the full system

Finally, we get two transfer function of the two input to the system which are pedal torque input and throttle input. [6.1.1]

Finally, we get two transfer function of the two input to the system which are pedal torque input and throttle input. [6.1.1]

Pedal torque input, $\frac{\omega_{\omega 1}}{T_P} = \frac{\frac{k_m k_{pedal} k_t}{N}}{(L_a J_{eq})s^2 + (L_a B_{eq} + R_a J_{eq})s + R_a B_{eq} + k_m k_t k_b}$

$= \frac{0.505}{0.000986s^2 + 0.96s + 0.154}$

Throttle input, $\frac{\omega_{\omega 2}}{T_t} = \frac{\frac{k_m k_{throttle} k_t}{N}}{(L_a J_{eq})s^2 + (L_a B_{eq} + R_a J_{eq})s + R_a B_{eq} + k_m k_t k_b}$

$= \frac{323.288}{0.000986s^2 + 0.96s + 0.154}$

6.4 Simulation and results

The MATLAB Simulink simulation of the mathematical model was done on the transfer functions and other equations that were obtained in the above sections [6.1.1]. The input of the simulation was made with two kinds of input which are constant pedal torque input and torque sensor output voltage of the acquired field tests. In the output we will be able to see the time vs speed graphs.

Simulation using constant pedal torque input and throttle step input is given below:

Simulation of constant pedal torque input and throttle step input:

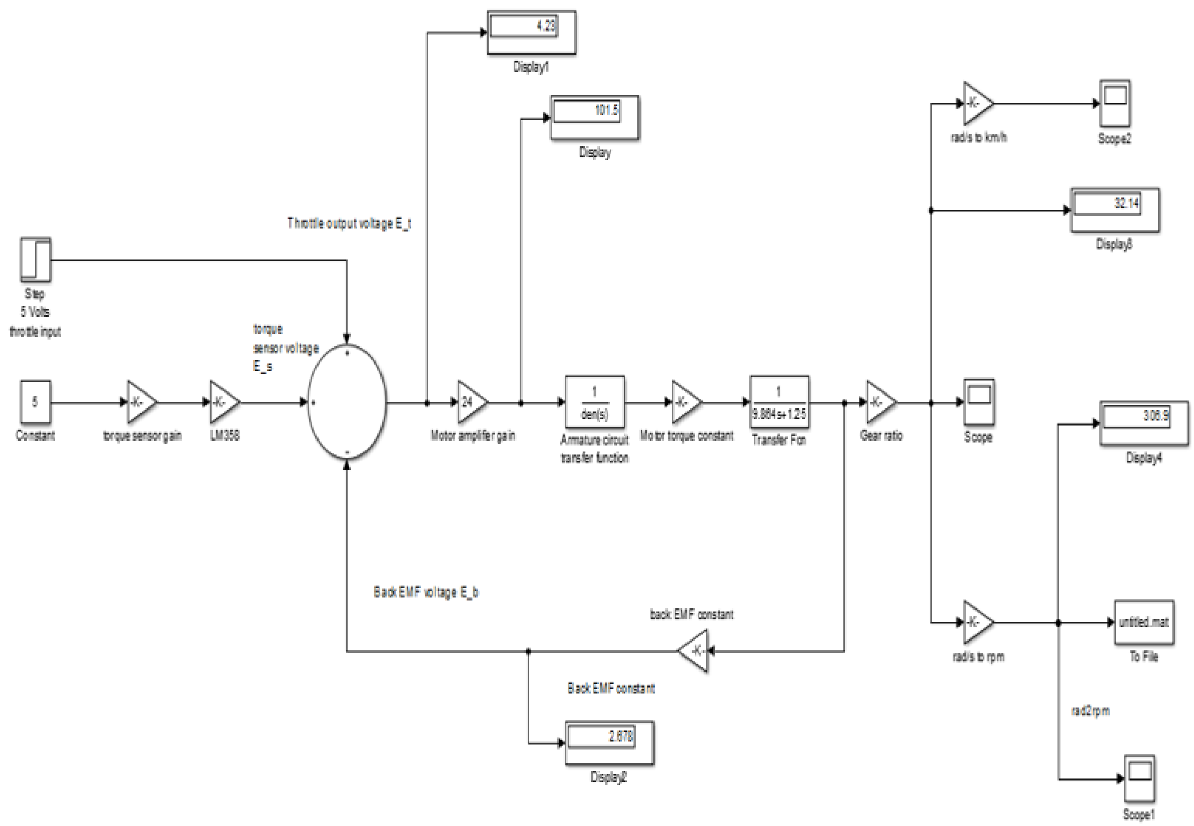

Fig 6.4: Simulink model of the system using constant pedal torque and throttle step input

The results of the Simulink simulation are given below:

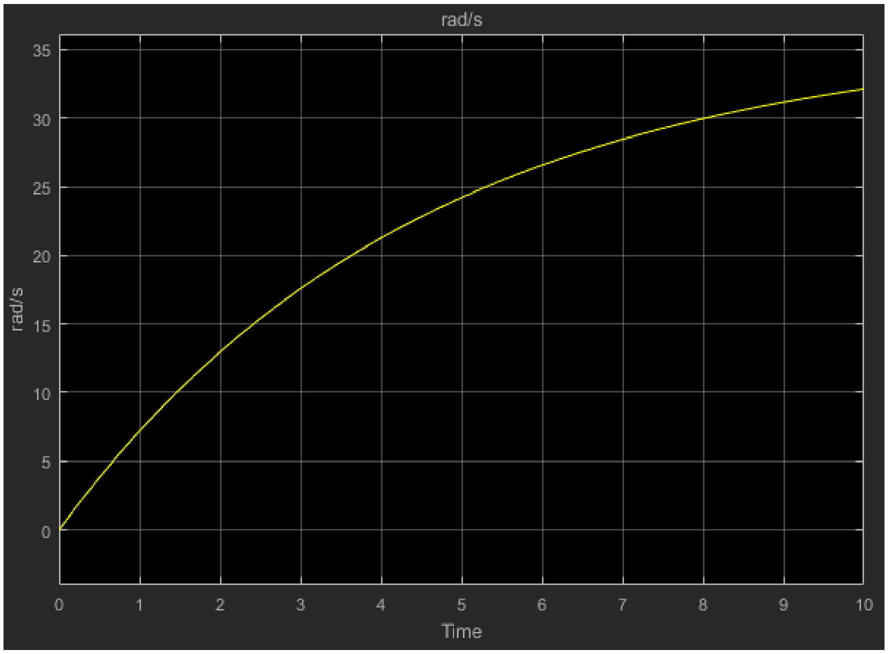

Fig 6.5 (a)

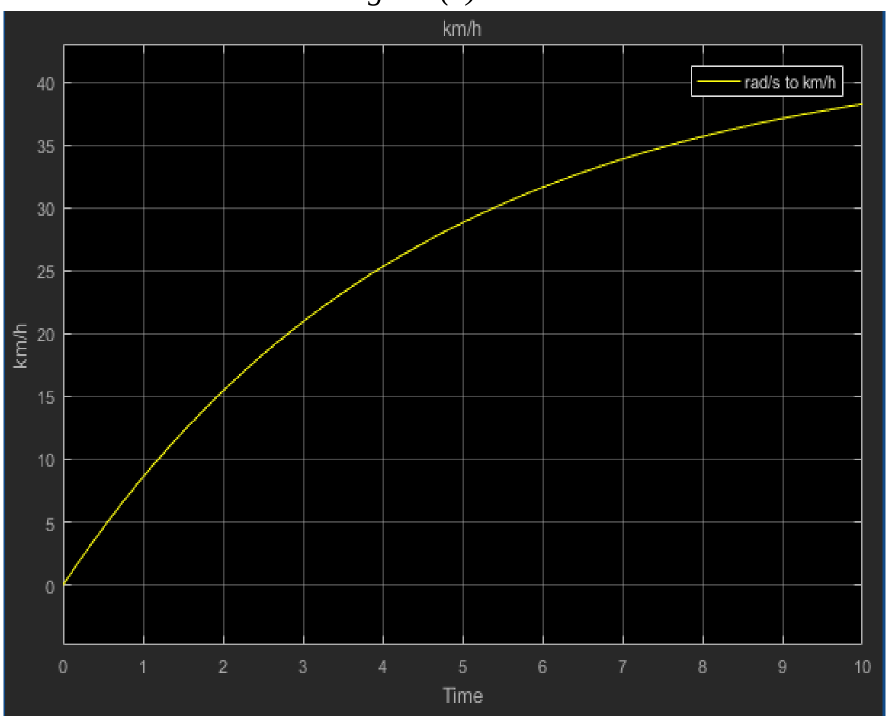

Fig 6.5(b)

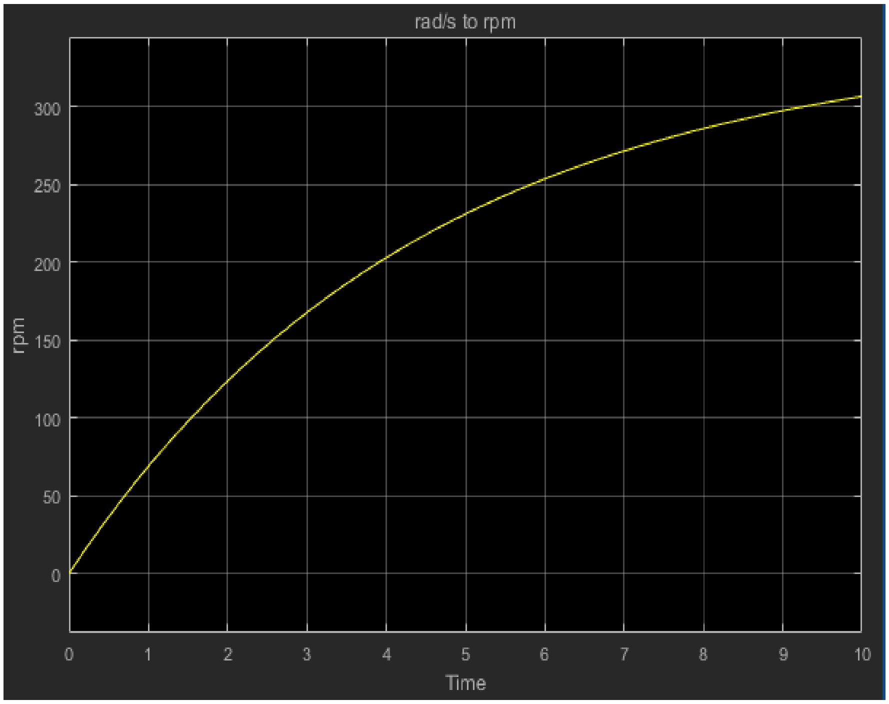

Fig 6.5(c)

Fig 6.5: (a) rad/sec (b) km/hr, (c) rpm vs time graphs, for the wheel closed loop angular and linear velocity/time

For unit step throttle input and constant throttle input the system gives us the result like unit step response. For 15 Nm pedal input and 1 v step throttle, the speed curve shows peak value of 38.16km/hr, 306.9rpm and 32.14rad/s output at steady state.

6.5 Motor electrical and mechanical parameters [6.5.1]:

The parameters for the motor were taken from a NanotechTM BLDC motor [] that matches the specifications for our motor. Parameters are given below:

Motor parameter table

Nominal output	250 W
Nominal torque	0.6 W
Nominal voltage	24 V

Speed	3500 rpm
Torque constant, Kt	0.043 Nm/A
Resistance, R	0.07
Inductance, L	0.0001 H
Rotor inertia, Jm	0.0000173 kgm2
Viscous damping, Bm	0.0016 Nms/(rad/s)
Back EMF constant, Vb	0.065 V/(rad/s)
Motor amplifier gain, Km	24

Parameters of the equation

Parameters	Values and units
Kp	0.3
Ka	0.6
Kamp	1.89
θtmax	1.22173 rad
Ein	5 V
ks	0.001 Nm/rad
Jeq	9.86 kgm2
Beq	1.25 Nm/rad/s

6.6 Root locus plot for pedal torque, TP

The code for root locus plot is in figure 6.6

```
clear all
clc

k_m=1;

Gnum=0.505;
Gden=[0.000986 0.69 0.154];
G=tf(Gnum, Gden);

H=0.133;
figure(1)
Pedal=feedback(G*k_m,H)
rlocus(Pedal)
figure(2)
step (Pedal)

```

Fig 6.6: Code for Root Locus plot with step response

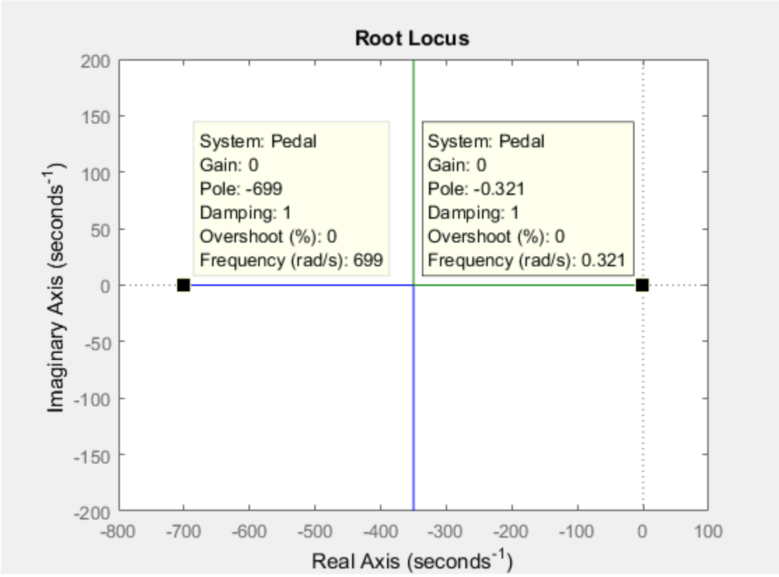

Fig 6.7: Root locus graph for pedal

In this above figure it is showed that,

1. There are two poles at -699 and -0.321
2. On this pole the gains are zero as well
3. The gain k_m can be varied between two poles
4. When k_m increases the two roots move horizontally towards each other and then collides. After that it moves away vertically from each other.
5. The starting point of the path of roots -699 is blue which means its start from negative x axis and then its end up with negative imaginary axis.
6. On the other hand, if the path of roots starts from -0.321 is green and it's end up with positive imaginary axis.

7. It is shown in the display that there are no poles at the right-hand side of the S-plane. So, from the graph we can say that both roots never go to the right-hand side but goes to the infinity. In this case for the pedal torque input the system is inherently stable.

6.7 Root locus plot for the throttle input, T_t

The code for Root locus plot is in figure 6.8

```
clear all
clc

k_m=1;

Gnum=28.59;
Gden=[0.003 1.95 0.26];
G=tf(Gnum, Gden);
H=0.00042;
figure(1)

Throttle=feedback(G*k_m,H);
rlocus(Throttle)
figure(2)
step (Throttle)

```

Fig 6.8: Code for Root Locus plot with step response

And the result is shown below:

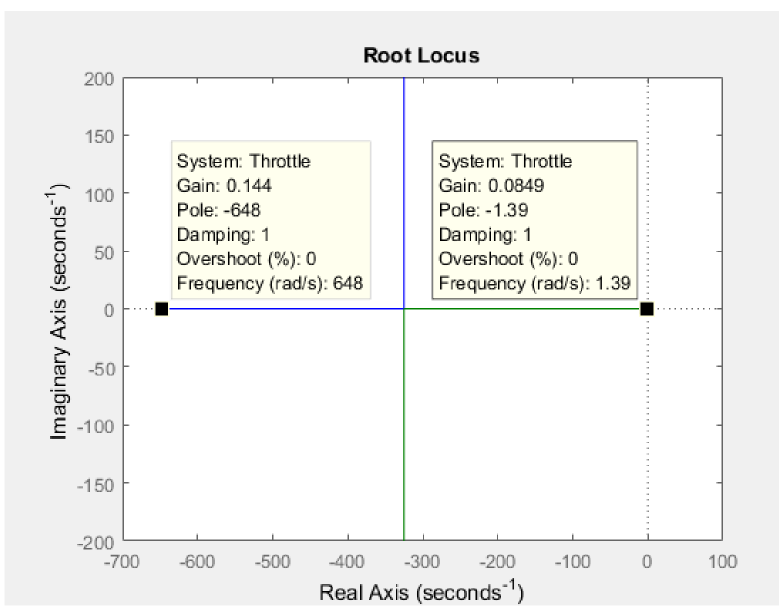

Fig 6.9: Root locus graph for Throttle

In this above figure it is showed that,

1. There are two poles at -648 and -1.39
2. On this pole the gains are zero as well
3. The gain km can be varied between two poles
4. When km increases the two roots move horizontally towards each other and then collides. After that it moves away vertically from each other.
5. The starting point of the path of roots -648 is blue which means its start from negative x axis and then its end up with positive imaginary axis.
6. On the other hand, if the path of roots starts from -1.39 is green and its end up with negative imaginary axis.
7. It is shown in the display that there are no poles at the right-hand side of the S-plane. So, from the graph we can say that both roots never go to the right-hand side but goes to the infinity. In this case for the throttle torque input the system is inherently stable.

7. Field Tests

7.1 Objective

The objective of our field tests was to determine the percentage of power saved by the use of the torque sensor technology to reduce the overuse of the battery bank. These tests were used to identify the energy supplied from the battery, the energy consumed by the load and the overall effectiveness of using the torque sensor in helping reducing the stress on the battery bank.

The tests were carried out near the National Institute of Diseases of the Chest and Heart (NIDCH) area which had a free enough road for the e-bike to move freely without hindrances from oncoming traffic and allowed us to have free reign over the range of testing. Most of these tests were carried out using fixed time intervals for which data was collected.

7.2 Test Setup

Because our e-bike is a moving vehicle, it became hard for us to really determine all the voltage and current readings we would have to take while the bike was in motion. To combat this issue, we came up with the setup as shown in Fig 7.1.

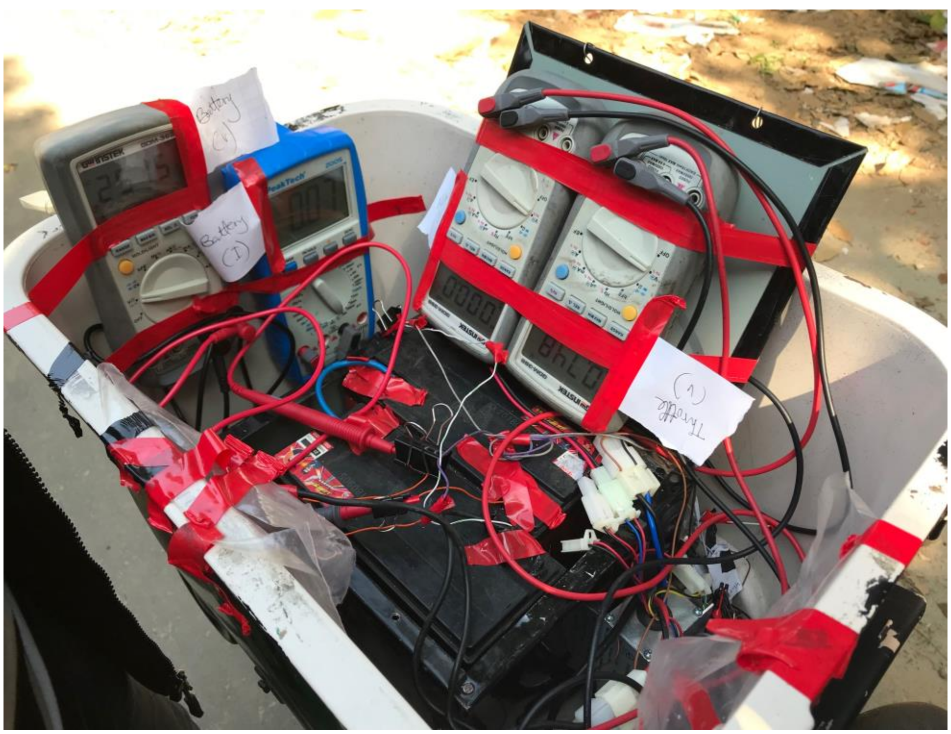

Fig 7.1: The Field Test Setup

Here, we are using a total of 4 multimeters, with one used to measure the battery voltage, another used to measure the battery current, another used to measure the load voltage and another used to measure the torque sensor voltage.

This kind of setup in the field to test was extremely risky as there was always a chance of the connections coming off and becoming loose. There was also the fact that tests would have to be momentarily paused every 15 minutes to reset the multimeters as they have an auto-off feature that would be a hindrance to long-time field testing. Another issue was actually taking the data, which we managed to do using phone video cameras attached to the box as shown below.

Fig 7.2: Using a phone's camera to take field test data

The test data could mostly be taken fine except for those few rare data values that became unreadable due to the glare of the sunlight.

7.3 Data Acquisition Technique

All the data taken used the setup mentioned in section 7.2 was taken at 10 second intervals from the footage. The measurements for distance and speed were taken using a mobile phone app used to measure these sorts of things for bicycles vie the help of GPS.

7.4 Field Test Data without Torque Sensor

For the first leg of the field tests, we took measurements by disconnecting the torque sensor circuitry and using only the motor and throttle to drive the bike. The battery voltage and current along with the load voltage was also measured here. The data for this test can be found in Appendix A, Table 1. Fig 7.3 represents the Battery Supply Profile while Fig 7.4 represents the battery power and Fig 7.5 is the graphical representation of the load power.

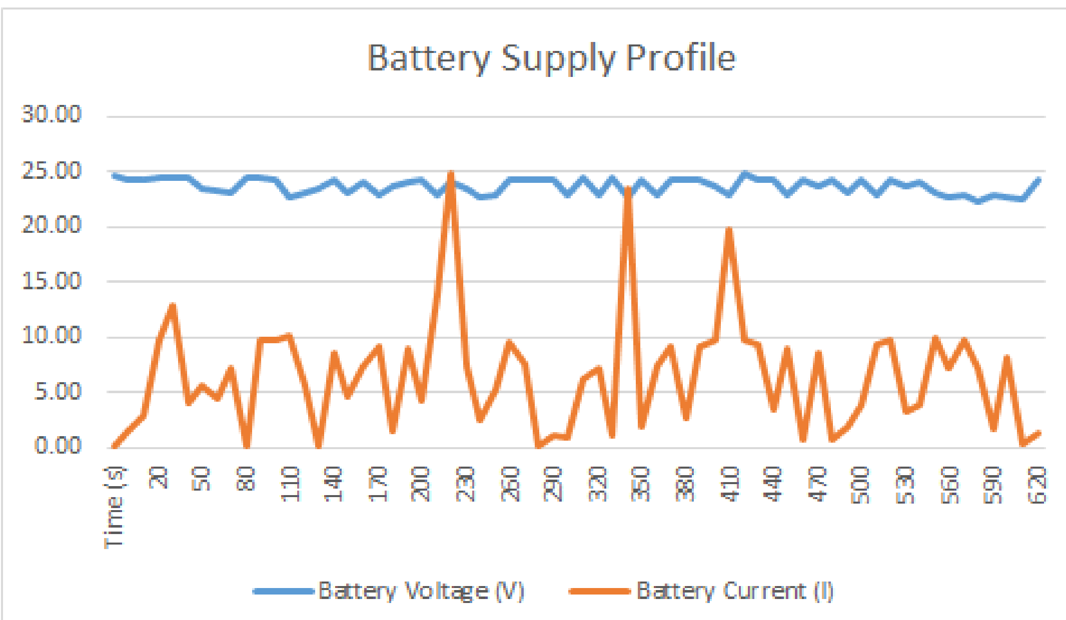

Fig 7.3: The Battery Supply Profile without Torque Sensor Technology

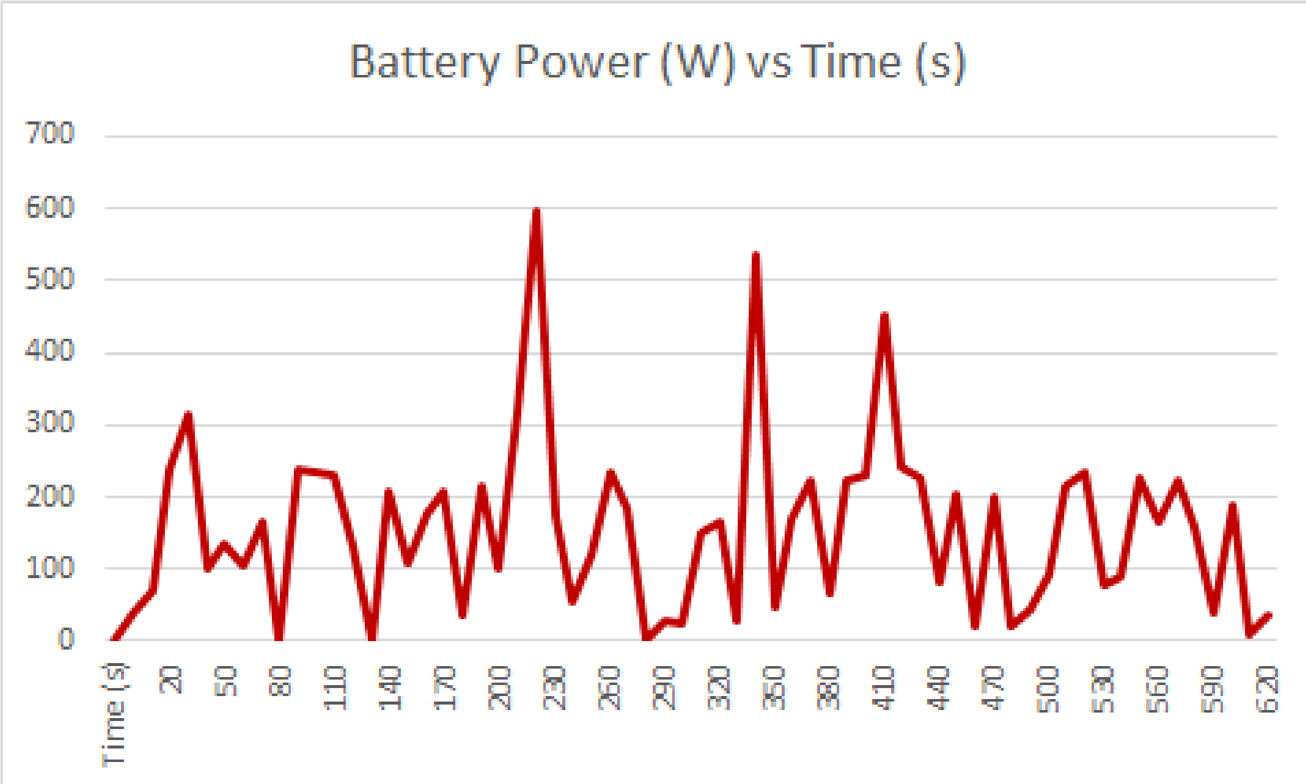

Fig 7.4: Battery Power (W) vs Time (s)

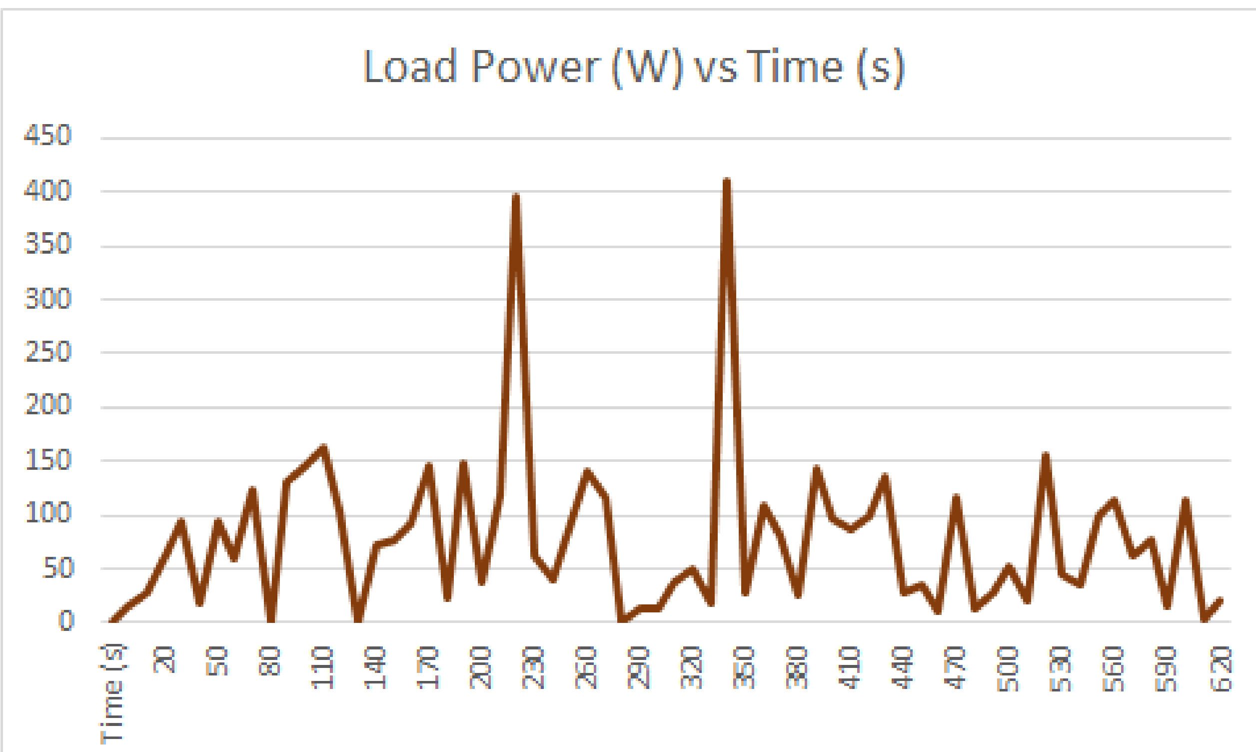

Fig 7.5: Load Power (W) vs Time (s)

The graph of battery power (watts) vs time (seconds) can be used to calculate the energy consumed from the battery bank. For our case, the energy supplied by the battery is equal to about 98542.79 joules.

7.5 Field Test Data with Torque Sensor

For this stage of the test, we used the full system, including the torque sensor circuitry. The voltage and current across the battery were recorded, along with the voltage of the load and the voltage supplied by the torque sensor circuit to the motor controller. The data for this test can be found in Appendix A, Table 2. Fig 7.6 represents the Battery Supply Profile while Fig 7.7 represents the battery power and Fig 7.8 represents the load power.

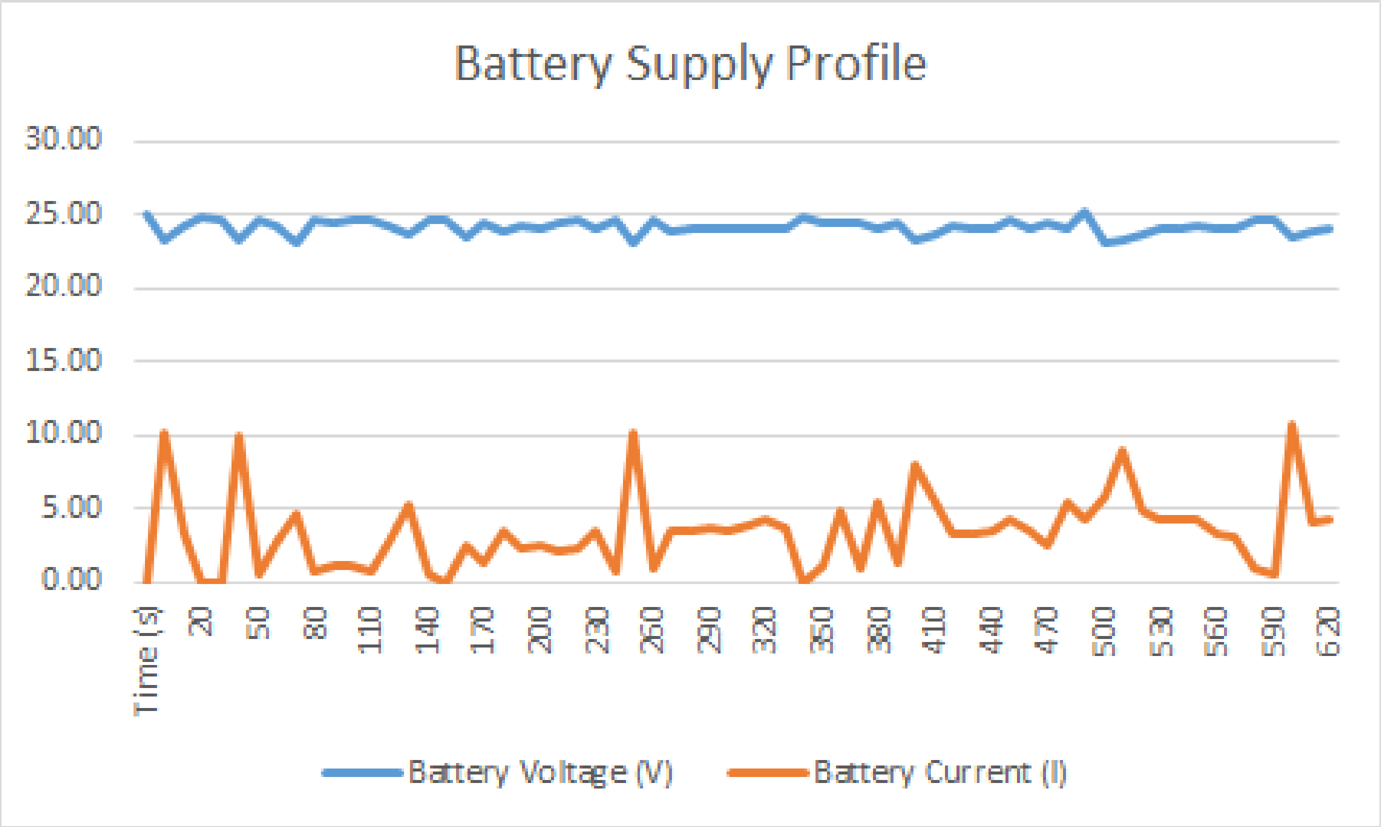

Fig 7.6: Battery Supply Profile with Torque Sensor technology

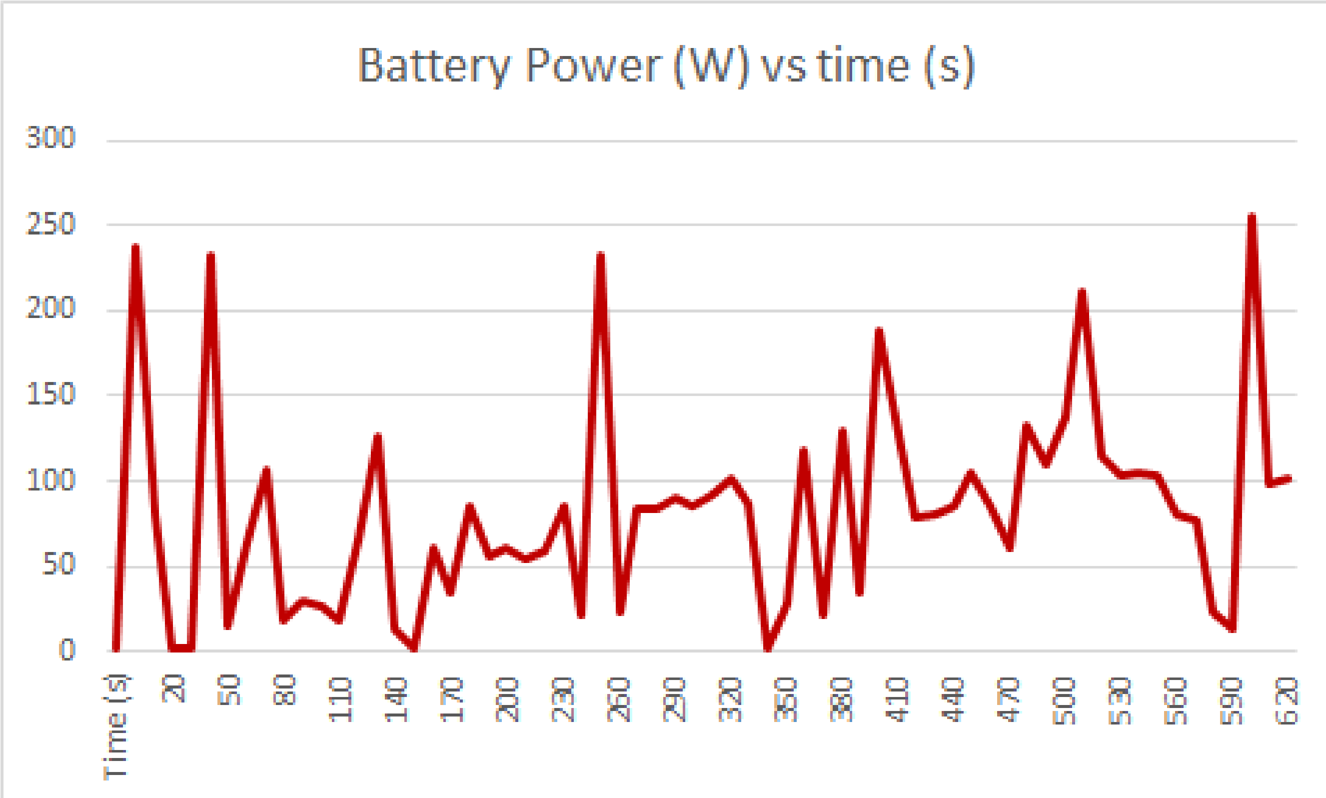

Fig 7.7: Battery Power vs Time

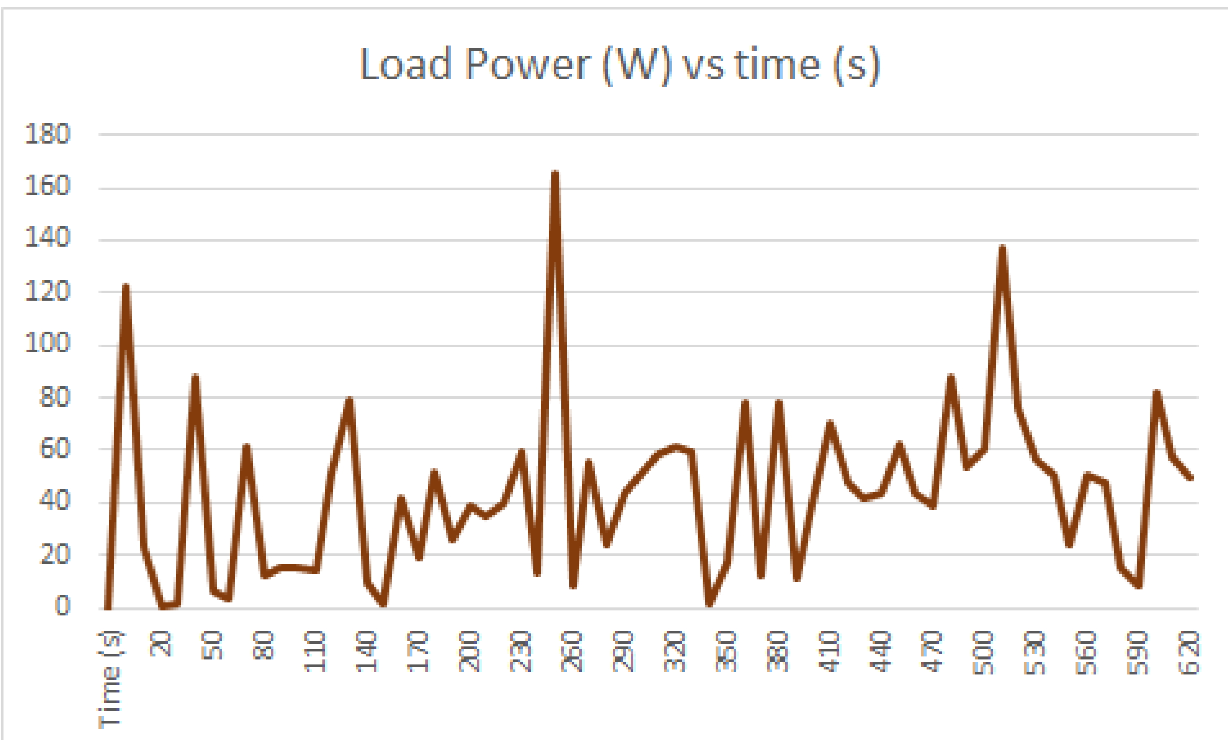

Fig 7.8: Load Power (W) vs Time (s)

The graph of total power vs time can be used to calculate the energy consumed from the battery bank, which results in 51925.95 joules. Thus, we can see that we're saving 47.3% more energy with the torque sensor technology than we would normally do with just the throttle and motor system.

7.6 Testing the Effect of Changing the Gain on the Torque Sensor

For the majority of these tests, the gain for the torque sensor circuit is set to 50% gain. For the following test, we will observe the battery supply profile for changing the gain to 25%, 50% and 100% in Fig 7.9, 7.10 and 7.11 respectively. Then we will do a comparative analysis of the battery power supplied in these three conditions (QG, HG, and FG) in Fig 7.12 and a comparative analysis of the load power in the three conditions in Fig 7.13.

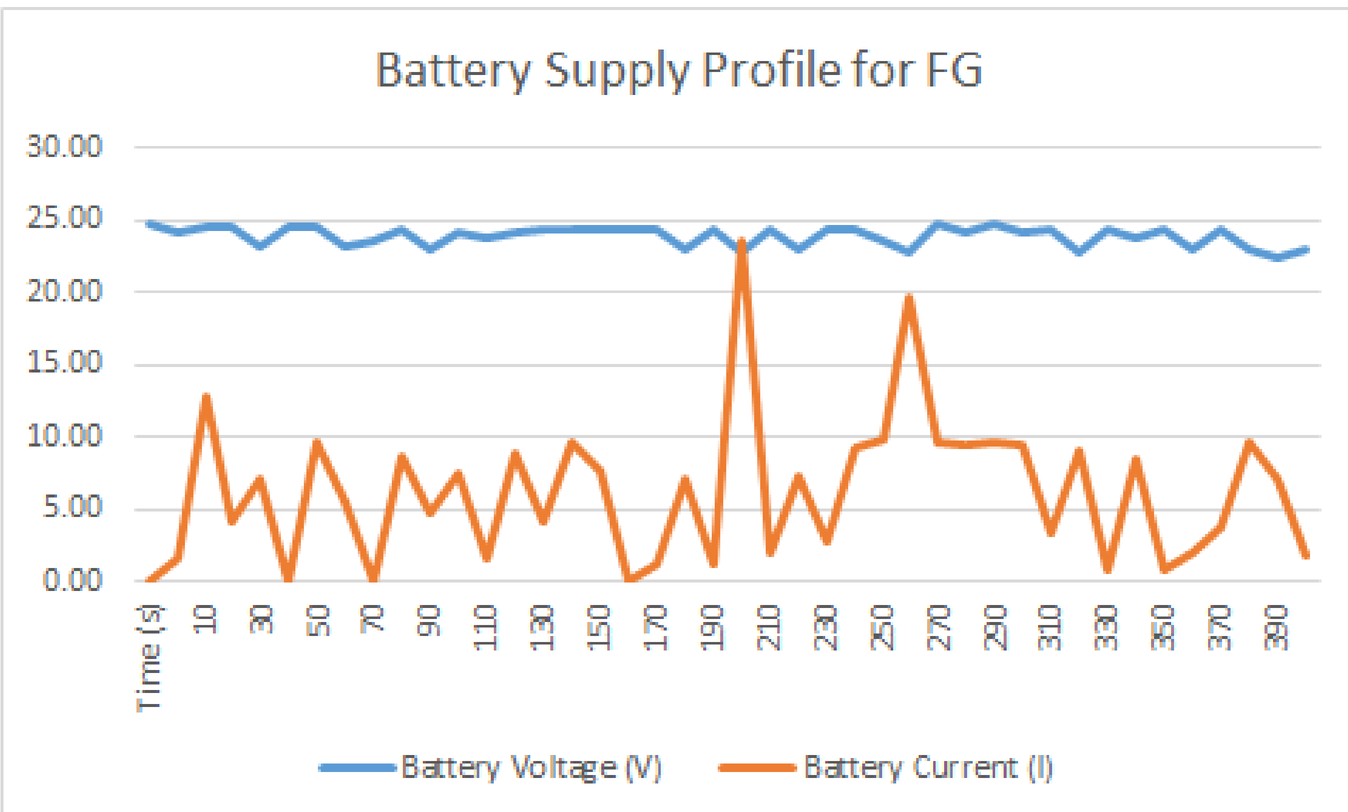

Fig 7.9: Battery Supply Profile for Full Gain

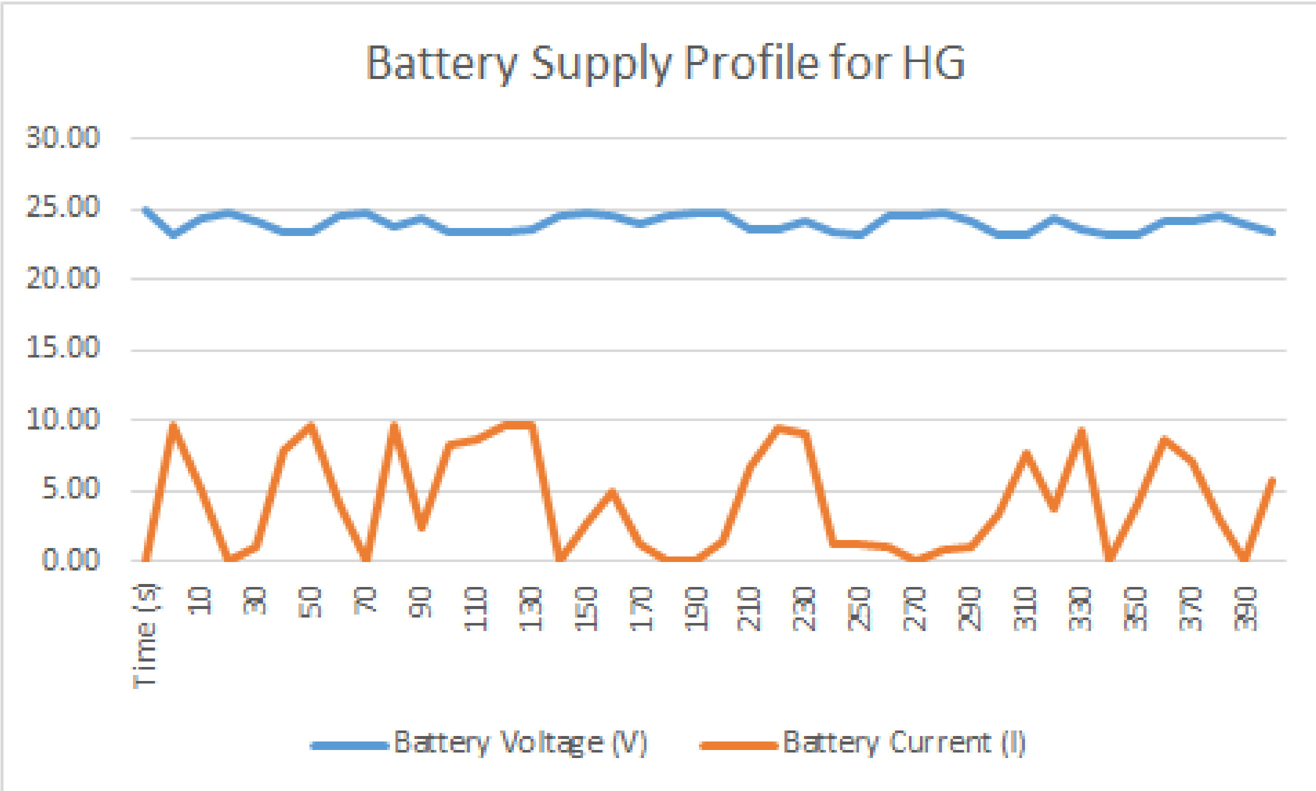

Fig 7.10 Battery Supply Profile for Half Gain

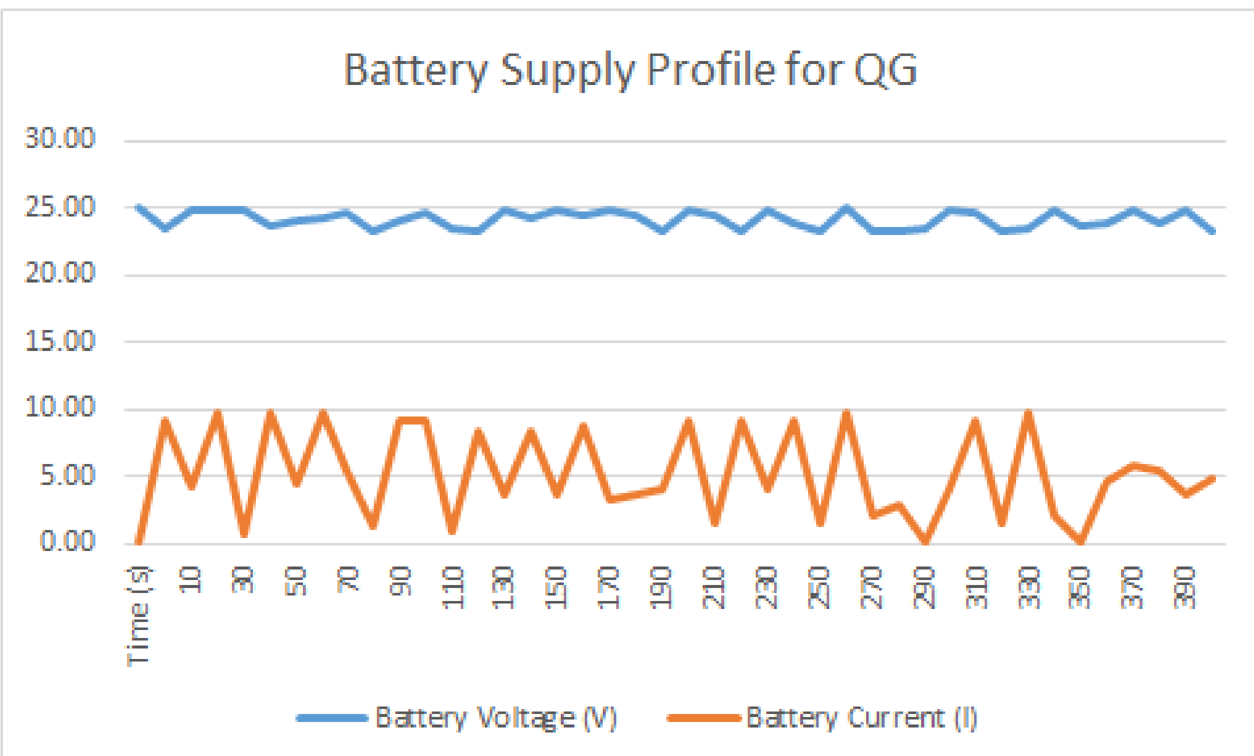

Fig 7.11 Battery Supply Profile for Quarter Gain

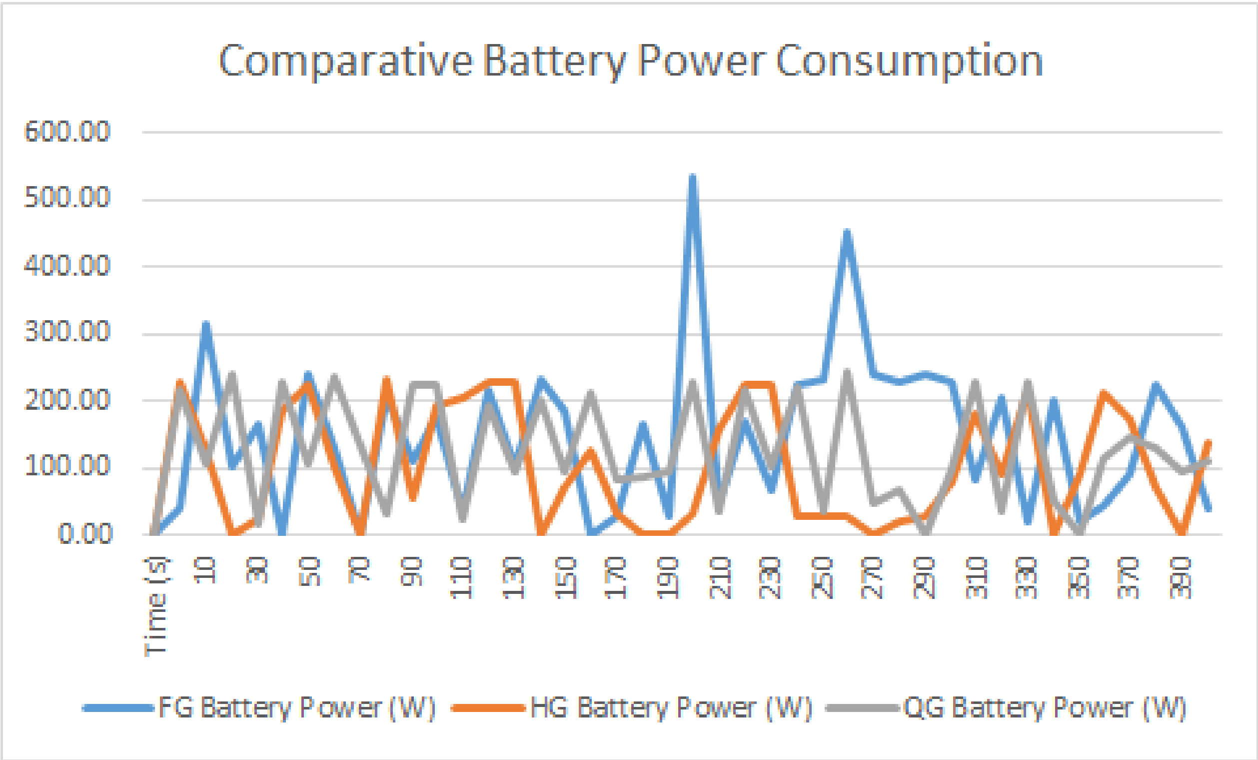

Fig 7.12 Comparative Battery Power Consumption

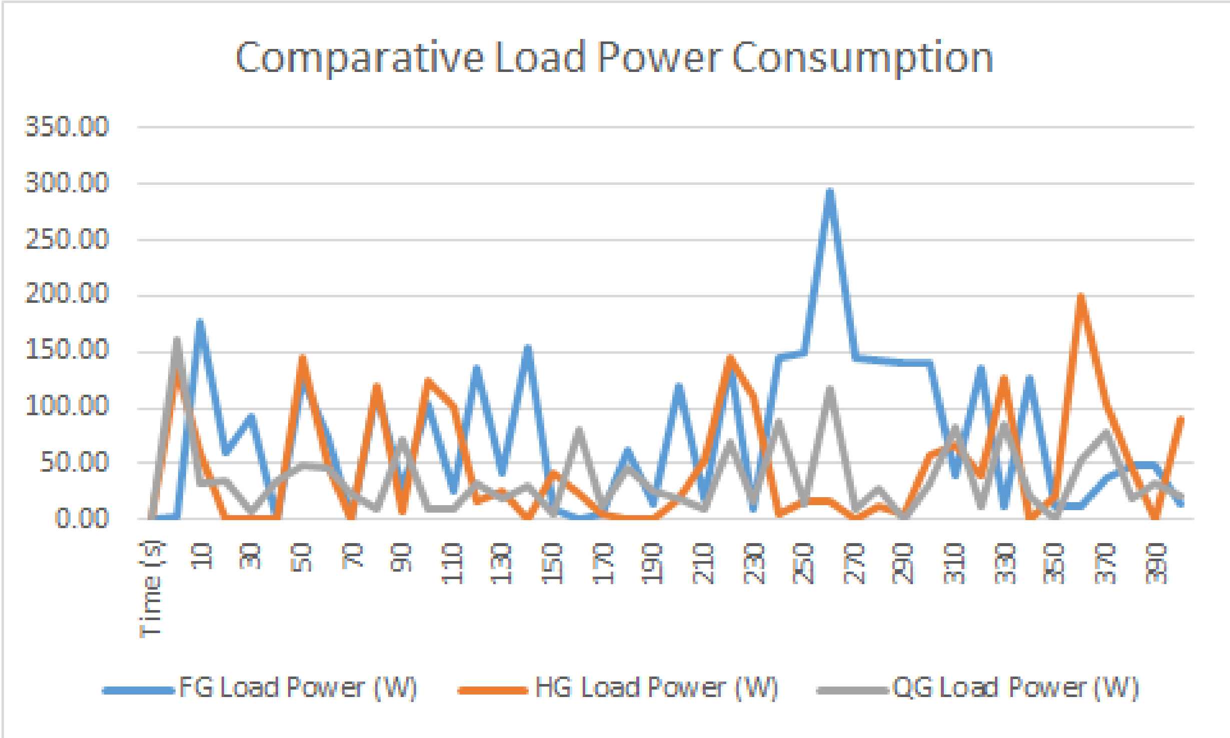

Fig 7.13 Comparative Load Power Consumption

From an analysis of the power consumption we can safely say that when the system is kept at full gain, there is more energy consumed from the battery than when it is kept at half gain and even more than when it is at quarter gain. The total energy consumed by the load was 31522.42 J when the system was at FG condition while the total energy consumed in HG condition was 19497.92 J and the total energy consumed for QG condition was 15453.00 J. Thus, the riders can decrease the gain to increase their battery life.

7.7 Testing the Effects of Different Weight Groups

Thus far the data that has been taken has been for an average weight group of approximately 70 kg for the average male adult. For this test we will analyze the effects of riders of different weight classes riding the e-bike. We have selected three riders of weight 60 kg, 80 kg and 110 kg. Fig 7.14 shows the battery supply profile of the Heavyweight Rider (110 kg rider); Fig 7.15 shows the battery supply profile for the Middleweight Rider (80 kg rider); Fig 7.16 shows the battery supply profile of the Lightweight Rider (60 kg rider); Fig 7.17 shows the comparative battery power analysis of all 3 riders; Fig 7.18 shows the comparative load power analysis of all 3 riders.

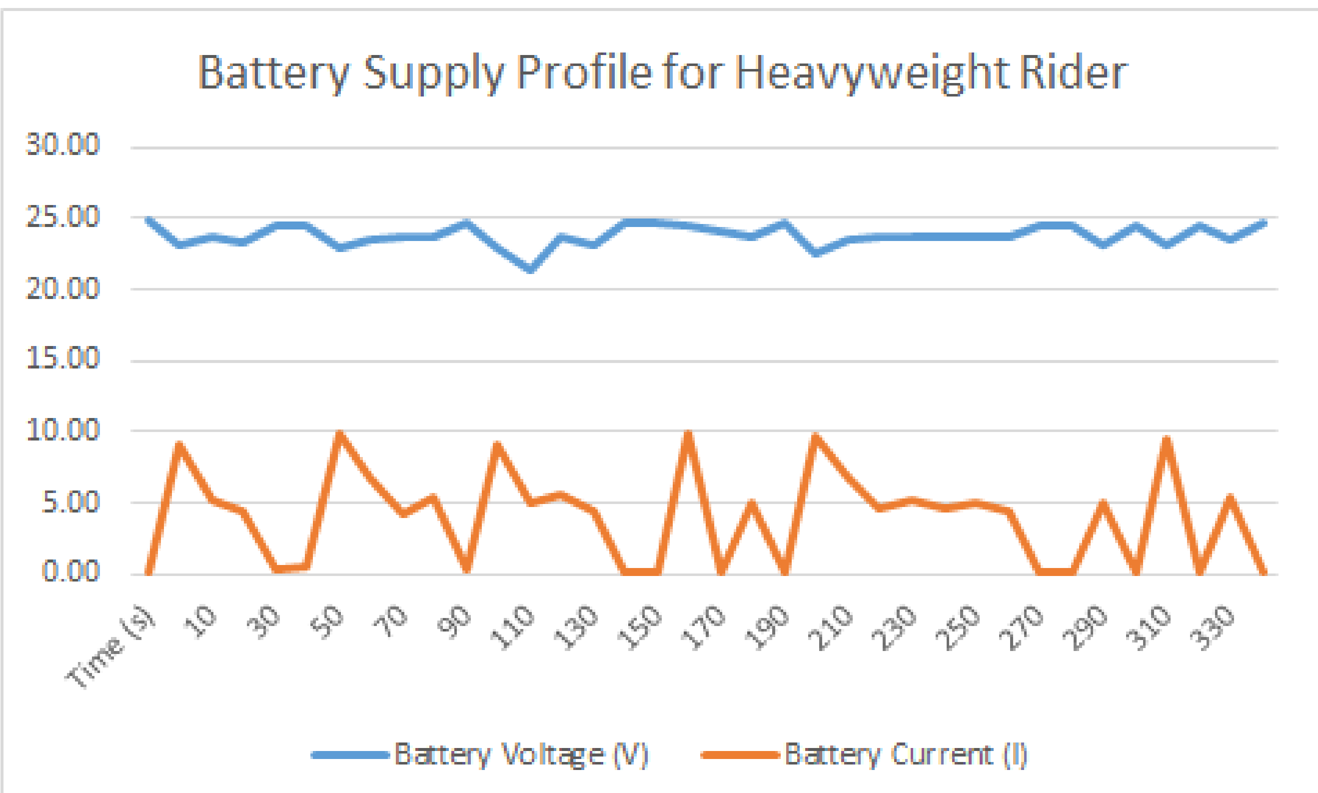

Fig 7.14: Battery Supply Profile for Heavyweight Rider

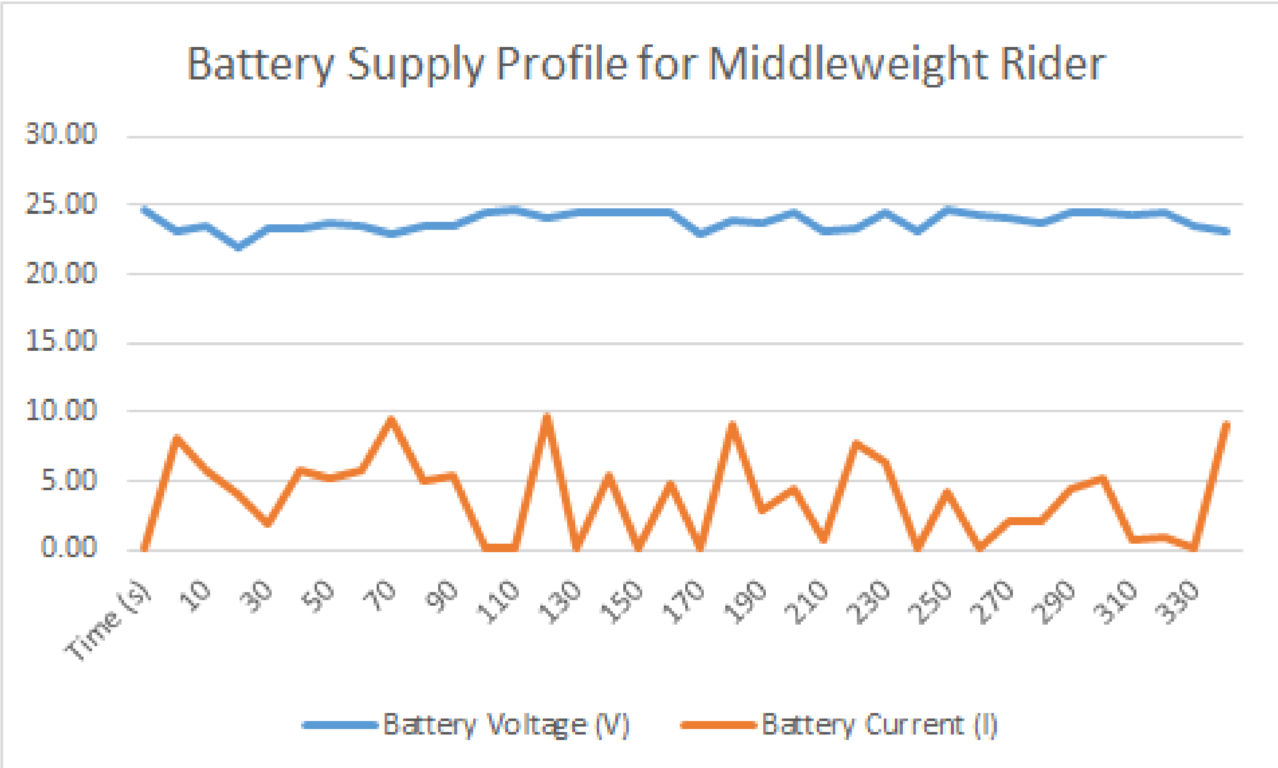

Fig 7.15: Battery Supply Profile for Middleweight Rider

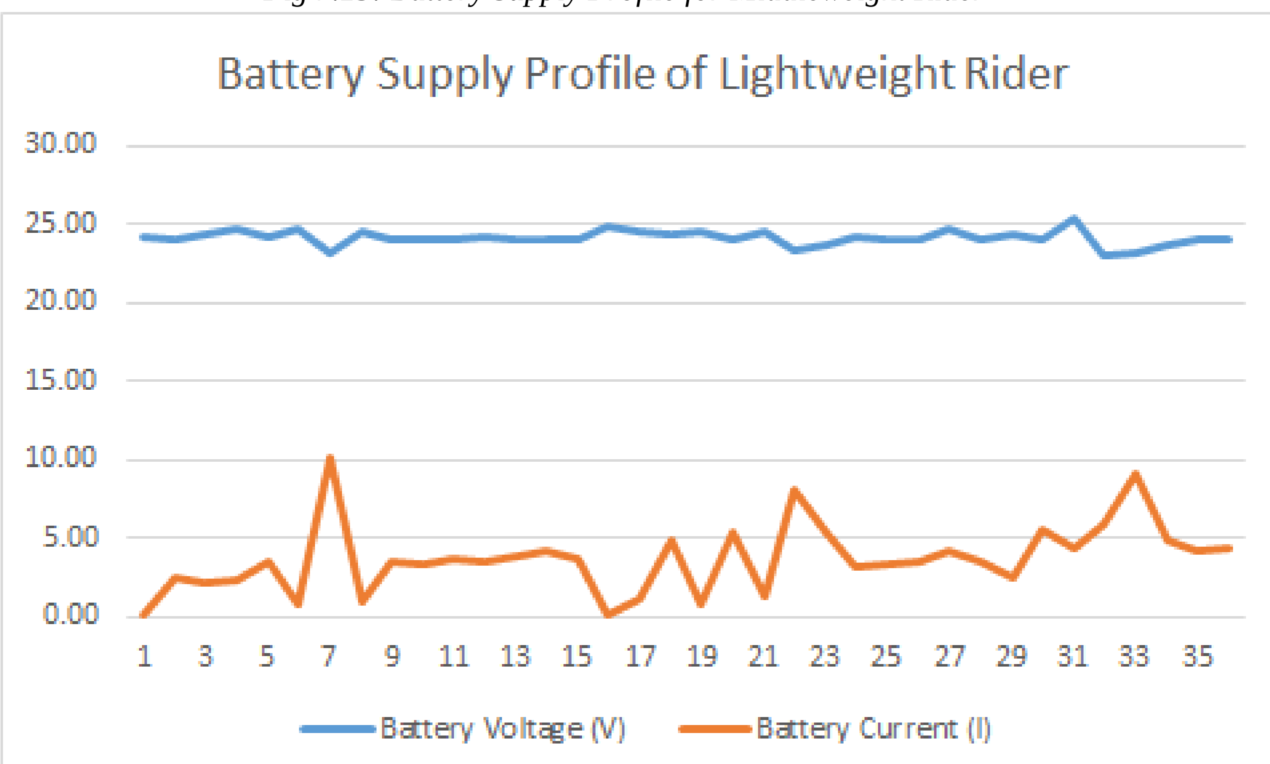

Fig 7.16: Battery Supply Profile for Lightweight Rider

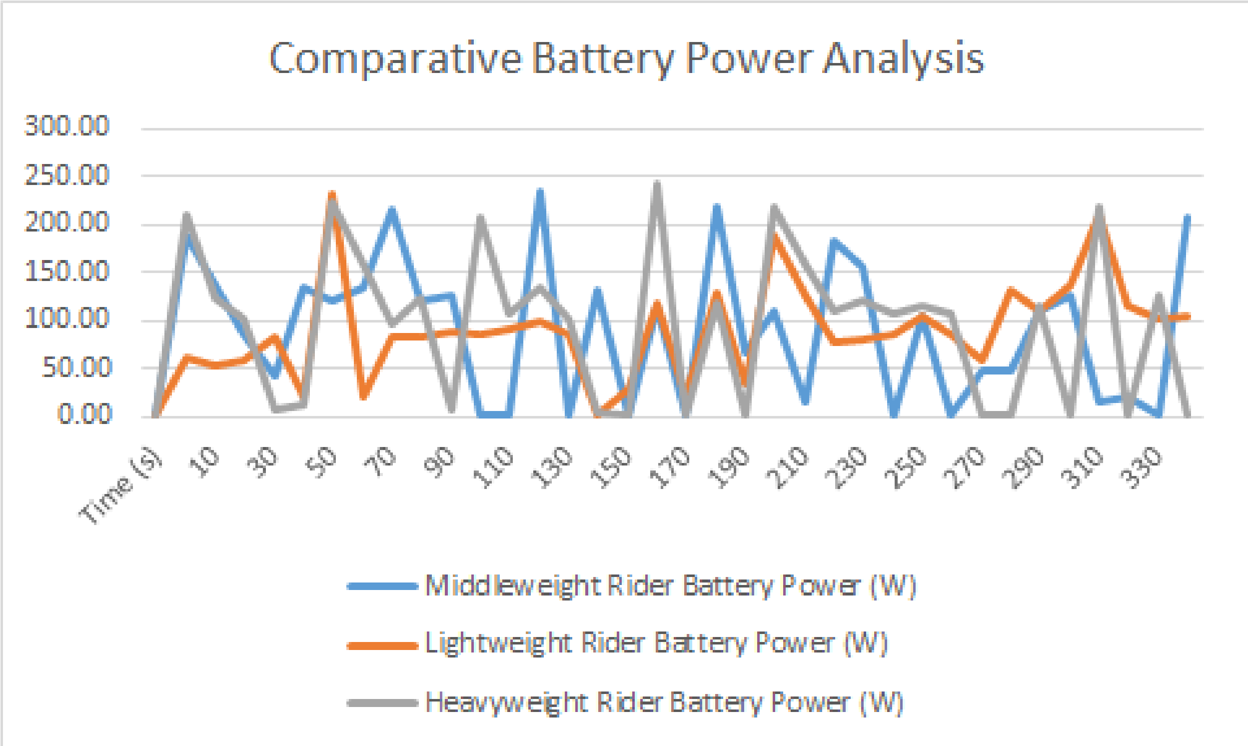

Fig 7.17: Comparative Battery Power Analysis

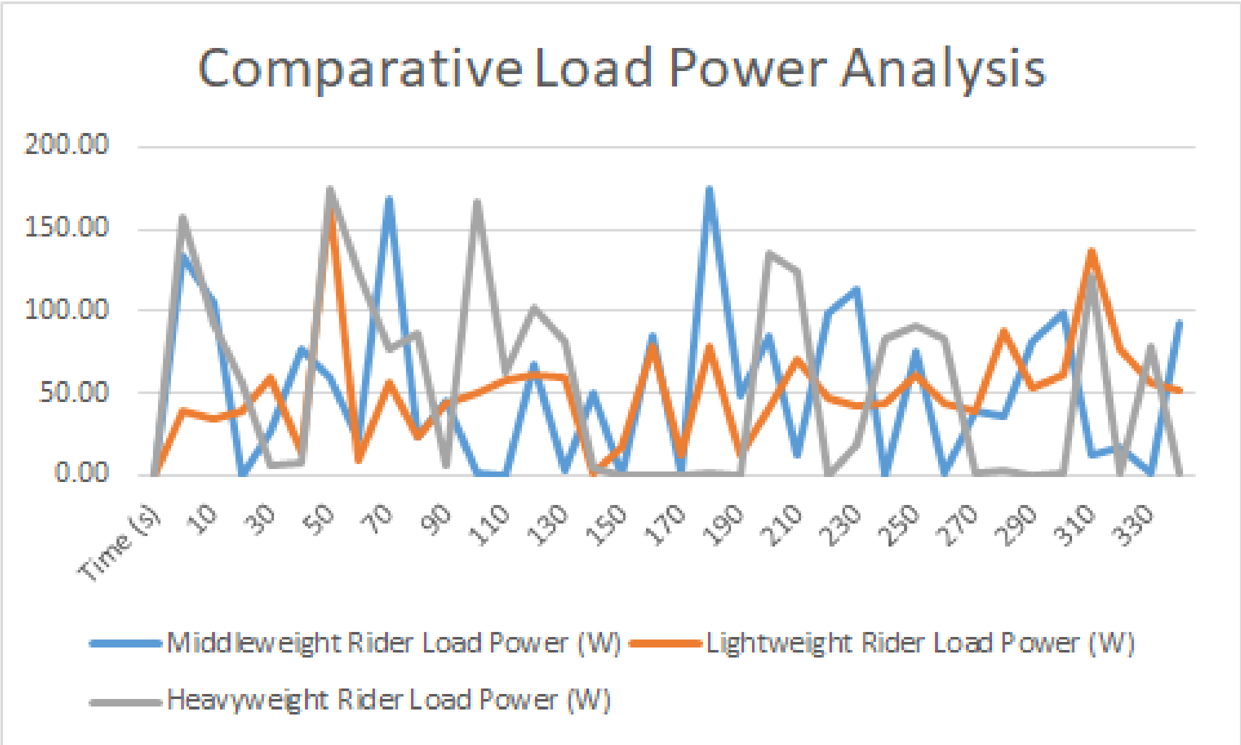

Fig 7.18: Comparative Load Power Analysis

By analysis of these graphs we can determine that there really isn’t much difference that the higher weight groups made from riding the e-bike to the motor consumption. By taking the area under the graphs and finding the energy used, the Lightweight uses up 17968.76 J of energy, the Middleweight uses up 18073.94 J of energy and the Heavyweight uses up 19467.45 J of energy. Thus, there really isn’t a significant change in the power consumed from the battery.

7.8 Testing the e-bike on Ramps

The e-bike was taken and tested on three different slopes of elevation 30°, 45° and 60° degrees. When trying to climb the 30°and 45° slopes the e-bike could go about these with relative ease but the bike faced relative difficulty when trying to climb the 60° slope, there was some difficulty just pedaling up it and it took the riders a lot more effort to get up the slope. Afterwards, the gain for the bike was changed to 100% and even then, the riders faced trouble with this slope but eventually managed to get it done this time.

8. Comparative Study and Analysis

8.1 Introduction

For the comparative study of the e-bike, we needed to take into consideration those e-bikes that are currently in the market and who have both pedal and throttle capabilities, i.e. it is similar to the working of our torque sensor e-bike. As such, we managed to find quite a few parameters from which we can extrapolate information from.

Fig 8.1: Akij Eagle

Fig 8.2: Avon E-Lite

Fig 8.3: DP Durbar Electric Bike

Fig 8.4: Torque Sensor Based e-bike

8.2 Price Comparison

Most e-bikes have relatively high prices ranging from BDT 70,000 to the lowest being BDT 35,000. The following are the prices of some of the e-bikes, varying over a wide range of amounts.

Akij Eagle Price: BDT 49,500
Avon E Lite: BDT 57,000
DP Durbar Electric Bike: BDT 35,000
Electromechanical Bike: BDT 32,520

8.3 Distance Comparison

In the distance test, our e-bike performed far better than any of the commercially available e-bikes in the market.

Akij Eagle Range: 45-50 KM/charge
Avon E Lite: 50 KM/charge
DP Durbar Electric Bike: 50 KM/charge
Electromechanical Bike: 70 KM/charge

8.4 Speed Comparison

When comparing the speeds, we found that our e-bike has the following observed speed.
Akij Eagle Range Speed: 38 KM/H
Avon E Lite: 24 KM/H
DP Durbar Electric Bike: 50 KM/H
Electromechanical Bike: 25.6 KM/H

8.5 Safety Features

Akij Eagle
Front brake: Disc
Rear brake: Drum

Avon E Lite
Front brake: Drum
Rear brake: Drum

DP Durbar Electric Bike

Front brake: NA
Rear brake: NA

Electromechanical Bike
Front brake: V Brake
Rear brake: V Brake

8.6 Charging Time

Akij Eagle Charging Time: 4-8 hrs.
Avon E Lite Charging Time: 6-8 hrs.
DP Durbar Electric Bike Charging Time: 3-6 hrs.
Electromechanical Bike: 5-6 hrs.

8.7 Weight of the e-bike

Akij Eagle Range: 70 KG
Avon E Lite: 56 KG
DP Durbar Electric Bike: 150 KG
Electromechanical Bike: 40 KG

9. Conclusion

9.1 Conclusion

After one year of extensive research, the electrical and electronic implementation of the project was a great success. The key objective of this project was to accomplish an efficient e-bike which will change the people's way of transportation and it ends up with a great significance. The control system and other supporting modernizations made the whole system a complete one. For conserving power, the introduction of a torque sensor pedal and battery swapping technique make the system as an off-grid solution. Also, this technique substantiated to be an efficient one for its sustainable refueling infrastructure. After doing several types of field test our project proved its enormous efficiency over all other comparable models. This efficiency leads us to think about further growing and enhancing our project.

9.2 Future Goals

In the future there are plans to improve on our model of the e-bike further. We could provide a training manual that would talk about safety features and how to actually use the e-bike in the best possible way. We could also use solar deep-cycle batteries instead of the lead-acid batteries we have already used because those can be discharged to 20% SOC and therefore can give better performance. Alongside that we can perhaps implement some IoT techniques into the e-bike for traffic monitoring and the like. Adding a first aid kit, having the ability to personalize the bike and refining the overall project are all things in our agenda.

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APPENDIX

Tabular Data from the Field Tests

Table 1: Field Test Data when using only the Motor, without the Torque Sensor

Battery Voltage (V)	**Battery Current (I)**	**Torque Sensor Voltage (V)**	**Motor Voltage (V)**
24.67	0.07	0.74	0.00
24.23	1.58	1.50	9.59
24.18	2.89	1.44	9.50
24.39	9.80	0.75	6.30
24.46	12.80	1.40	7.29
24.52	4.10	1.34	4.31
23.49	5.72	1.48	16.62
23.24	4.47	1.43	13.42
23.08	7.11	1.53	17.23
24.51	0.07	1.42	19.19
24.54	9.70	1.47	13.44
24.23	9.70	1.41	15.02
22.77	10.17	1.43	15.95

23.15	5.59	1.53	18.79
23.49	0.07	1.42	13.65
24.27	8.58	1.41	8.54
22.99	4.71	1.43	16.44
24.06	7.40	1.43	12.48
22.93	9.11	1.37	15.94
23.67	1.57	1.40	15.39
24.13	8.91	0.74	16.61
24.33	4.19	1.45	8.88
22.87	13.90	0.74	8.53
24.00	24.90	1.45	15.86
23.38	7.44	1.39	8.30
22.77	2.48	1.49	15.90
22.88	5.17	1.42	16.69
24.36	9.59	1.43	14.62
24.36	7.57	1.40	15.45
24.27	0.07	1.40	5.95
24.26	1.10	1.45	12.75

22.82	1.00	0.74	12.45
24.37	6.20	1.46	6.02
22.93	7.17	1.55	7.14
24.43	1.10	1.42	16.62
22.76	23.50	1.51	17.47
24.29	1.95	1.45	13.76
22.87	7.34	5.95	14.94
24.18	9.18	1.41	9.02
24.34	2.70	1.40	9.02
24.35	9.18	0.74	15.72
23.64	9.80	0.74	9.95
22.84	19.70	1.51	4.36
24.77	9.70	0.96	10.23
24.23	9.40	1.42	14.53
24.26	3.40	1.53	8.56
22.85	8.97	1.44	3.98
24.28	0.78	1.26	12.45
23.76	8.47	1.49	13.76

24.34	0.78	0.78	16.18
23.02	1.90	1.26	14.64
24.30	3.80	1.49	14.03
22.91	9.32	1.41	2.15
24.19	9.70	1.09	15.97
23.71	3.33	1.48	13.80
24.02	3.79	1.42	9.02
23.04	9.90	1.33	9.89
22.77	7.29	1.43	15.63
22.89	9.70	1.50	6.53
22.34	7.15	1.32	10.63
22.89	1.74	1.01	9.62
22.75	8.24	1.42	13.77
22.40	0.34	1.41	9.80
24.18	1.40	1.41	14.59

Table 2: Field Test Data when using the full system (with Torque Sensor)

Battery Voltage (V)	**Battery Current (I)**	**Torque Sensor Voltage (V)**	**Motor Voltage (V)**
25.03	0.07	0.75	0.00
23.33	10.15	1.45	12.00
24.22	3.33	1.42	6.90
24.83	0.07	1.56	13.70
24.77	0.07	0.89	18.30
23.23	10.03	0.75	8.80
24.66	0.60	1.46	11.11
24.25	2.63	1.42	1.34
23.08	4.59	1.57	13.30
24.67	0.76	1.58	16.10
24.58	1.23	1.60	12.50
24.68	1.08	1.59	13.90
24.73	0.72	1.61	19.30
24.26	2.74	1.62	19.00
23.72	5.30	1.66	14.90
24.66	0.57	1.66	16.40
24.71	0.07	1.55	15.40

23.47	2.59	1.57	16.10
24.59	1.39	1.57	13.50
23.95	3.57	1.59	14.50
24.25	2.30	1.50	11.21
24.11	2.53	1.56	15.30
24.44	2.22	1.56	15.80
24.72	2.42	1.63	16.30
24.15	3.51	1.61	16.80
24.78	0.84	1.69	16.20
23.12	10.08	1.67	16.40
24.61	0.91	1.66	9.60
23.97	3.51	0.79	15.90
24.06	3.45	1.63	6.90
24.09	3.73	0.95	11.71
24.12	3.55	1.44	14.30
24.04	3.82	1.50	15.20
24.01	4.21	1.56	14.60
24.09	3.62	1.63	16.50

24.89	0.07	1.64	16.10
24.54	1.16	1.62	15.00
24.40	4.83	1.62	16.10
24.59	0.88	1.62	13.90
24.10	5.39	1.45	14.50
24.50	1.38	1.52	8.50
23.30	8.06	1.63	5.00
23.66	5.37	1.43	13.10
24.22	3.25	0.81	14.60
24.10	3.35	1.44	12.50
24.02	3.58	1.43	12.30
24.71	4.24	1.58	14.60
24.09	3.54	1.57	12.40
24.43	2.46	1.60	15.60
24.02	5.50	1.63	16.00
25.38	4.36	1.69	12.20
23.07	5.94	1.53	10.20
23.25	9.07	1.53	15.10

23.70	4.86	1.61	15.70
24.04	4.29	1.69	13.20
24.07	4.35	1.47	11.70
24.34	4.24	0.75	5.70
24.10	3.32	1.60	15.30
24.13	3.17	1.62	14.90
24.61	0.93	1.62	16.00
24.69	0.52	1.62	16.20
23.61	10.80	1.69	7.56
23.91	4.11	1.63	14.10
24.01	4.21	1.63	11.80
24.70	0.12	1.56	15.70
23.95	4.42	1.56	6.00
24.78	0.08	1.42	10.70
24.57	1.23	1.54	14.50
24.63	1.01	1.51	12.50
24.89	0.07	1.55	4.40
23.66	6.71	0.79	12.70

23.93	3.86	1.54	16.80
24.37	2.81	1.59	10.90
24.03	1.31	1.50	11.80

Table 3.1: Field Test Data for Full Gain

Battery Voltage (V)	**Battery Current (I)**	**Torque Sensor Voltage (V)**	**Motor Voltage (V)**
24.67	0.07	0.74	0.00
24.23	1.58	1.45	1.95
24.46	12.80	1.45	13.76
24.52	4.10	1.46	14.82
23.08	7.11	1.45	12.89
24.51	0.07	0.93	3.56
24.54	9.70	1.46	13.08
23.15	5.59	1.44	13.16
23.49	0.07	1.44	13.08
24.27	8.58	1.50	13.48
22.99	4.71	1.45	5.94
24.06	7.40	1.58	14.06

23.67	1.57	1.48	16.76
24.13	8.91	1.49	15.10
24.33	4.19	1.57	10.05
24.36	9.59	1.48	16.10
24.36	7.57	0.75	1.15
24.27	0.07	0.83	1.18
24.26	1.10	1.50	4.84
22.93	7.17	0.87	8.62
24.43	1.10	1.57	13.43
22.76	23.50	1.44	5.12
24.29	1.95	1.51	9.31
22.87	7.34	1.48	19.23
24.34	2.70	1.40	4.00
24.35	9.18	0.75	15.87
23.64	9.80	1.44	15.17
22.84	19.70	1.41	14.91
24.77	9.70	0.77	14.83
24.23	9.40	1.52	15.16

24.77	9.70	1.53	14.55
24.23	9.40	1.45	14.90
24.26	3.40	1.32	11.65
22.85	8.97	1.45	15.11
24.28	0.78	1.51	14.18
23.76	8.47	1.45	14.87
24.34	0.78	1.49	14.55
23.02	1.90	1.95	5.88
24.30	3.80	1.47	9.99
22.89	9.70	1.55	4.99
22.34	7.15	1.60	6.81
22.89	1.74	1.35	8.62

Table 3.2: Field Test Data for Half Gain

Battery Voltage (V)	**Battery Current (I)**	**Torque Sensor Voltage (V)**	**Motor Voltage (V)**
25.02	0.07	0.74	0.00
23.24	9.75	1.46	13.90
24.29	5.20	1.46	11.56

24.76	0.07	1.32	7.41
24.27	0.95	0.78	0.00
23.40	7.91	0.71	0.20
23.46	9.60	1.47	15.02
24.67	4.20	1.53	11.62
24.87	0.08	1.00	1.73
23.80	9.67	1.54	12.38
24.29	2.32	0.74	3.68
23.41	8.22	1.48	15.02
23.38	8.66	1.48	11.62
23.38	9.71	0.76	1.73
23.54	9.64	1.77	2.58
24.65	0.05	1.33	3.68
24.72	2.80	1.61	15.01
24.67	5.04	1.48	4.66
24.05	1.30	0.75	4.30
24.67	0.07	1.46	1.08
24.80	0.07	1.55	12.64

24.70	1.33	1.27	15.09
23.58	6.67	1.47	8.04
23.67	9.53	1.49	15.09
24.21	9.17	1.48	12.08
23.31	1.21	1.41	3.50
23.25	1.21	1.39	14.09
24.65	1.08	1.46	15.46
24.64	0.07	0.74	12.88
24.81	0.80	1.51	14.46
24.25	1.13	1.54	3.75
23.26	3.45	1.48	16.76
23.22	7.76	1.30	8.78
24.33	3.71	1.44	10.47
23.54	9.19	0.74	13.75
23.17	0.07	1.48	14.61
23.17	3.93	1.41	5.13
24.22	8.71	1.47	22.99
24.24	7.12	1.45	14.56

24.59	2.90	1.59	16.16
24.05	0.07	1.47	15.70
23.46	5.80	1.51	15.68

Table 3.3: Field Test Data for Quarter Gain

Battery Voltage (V)	**Battery Current (I)**	**Torque Sensor Voltage (V)**	**Motor Voltage (V)**
25.10	0.07	0.74	0.00
23.46	9.24	1.39	17.50
24.78	4.30	1.44	7.51
24.78	9.70	0.74	3.61
24.78	0.70	1.40	10.95
23.58	9.69	1.38	3.61
24.14	4.40	0.74	10.95
24.29	9.70	1.48	4.90
24.71	5.40	1.47	4.30
23.33	1.38	0.83	7.30
24.13	9.24	1.48	7.85
24.67	9.10	1.32	0.95

23.44	1.00	1.31	9.68
23.25	8.30	1.34	4.05
24.87	3.73	1.35	4.80
24.30	8.30	1.44	3.67
24.82	3.73	1.40	1.19
24.43	8.70	1.46	9.38
24.82	3.30	1.44	3.52
24.45	3.60	1.42	12.68
23.37	4.10	4.37	6.52
24.82	9.24	0.83	2.04
24.45	1.50	1.42	6.35
23.37	92.00	1.52	7.65
24.85	4.10	1.48	4.12
23.78	9.24	1.50	9.41
23.35	1.50	1.50	10.01
24.95	9.70	1.47	12.12
23.32	2.10	0.91	4.32
23.34	2.90	0.74	9.91

23.51	0.07	1.48	4.66
24.78	4.00	1.49	8.00
24.74	9.24	1.44	9.04
23.32	1.50	1.46	8.00
23.44	9.70	1.48	8.72
24.87	2.00	1.45	11.08
23.61	0.07	1.23	10.02
23.96	4.70	1.48	11.38
24.88	5.81	1.23	13.46
23.96	5.44	1.37	3.61
24.88	3.73	1.33	8.52
23.25	4.80	1.44	4.32

Table 4.1: Field Test Data for Heavyweight Rider

Battery Voltage (V)	**Battery Current (I)**	**Torque Sensor Voltage (V)**	**Motor Voltage (V)**
24.90	0.07	0.74	0.00
23.11	9.11	1.27	17.22
23.73	5.20	1.29	17.75

23.31	4.41	1.26	12.62
24.52	0.36	1.43	14.72
24.47	0.58	1.45	11.92
22.95	9.79	1.46	17.82
23.43	6.81	1.28	18.21
23.67	4.13	1.20	18.67
23.64	5.30	1.29	16.27
24.64	0.36	1.28	18.57
23.01	9.07	1.37	18.43
21.39	5.06	1.46	12.44
23.67	5.65	1.22	18.08
23.14	4.47	1.26	18.33
24.65	0.21	1.28	18.19
24.71	0.07	1.41	1.21
24.48	9.91	0.78	0.00
24.14	0.07	1.86	0.28
23.71	5.03	1.37	0.38
24.62	0.06	1.24	5.68

22.55	9.74	1.25	13.85
23.55	6.80	1.24	18.16
23.71	4.70	0.72	0.00
23.62	5.11	1.23	3.62
23.76	4.59	1.22	18.29
23.69	4.94	1.29	18.56
23.73	4.51	1.20	18.40
24.51	0.08	1.26	18.59
24.55	0.14	1.65	17.31
23.14	5.02	1.46	0.00
24.49	0.07	1.27	13.71
23.07	9.52	1.21	12.65
24.51	0.08	1.28	17.19
23.60	5.38	0.47	14.52
24.67	0.06	1.42	18.16

Table 4.2: Field Test Data for Middleweight Rider

Battery Voltage (V)	**Battery Current (I)**	**Torque Sensor Voltage (V)**	**Motor Voltage (V)**

24.78	0.07	0.72	0.00
23.05	8.16	1.46	16.32
23.43	5.85	1.23	18.00
22.05	3.94	0.72	0.00
23.26	1.83	1.46	14.75
23.40	5.73	1.47	13.51
23.74	5.16	1.16	11.55
23.46	5.76	1.28	3.88
23.01	9.42	1.24	17.84
23.54	5.10	0.72	4.60
23.47	5.43	1.42	8.23
24.53	0.07	1.55	17.28
24.64	0.07	1.00	0.00
24.05	9.73	1.56	6.88
24.52	0.12	1.56	18.10
24.57	5.35	1.56	9.28
24.57	0.07	0.72	5.50
24.57	4.73	1.24	18.03

23.02	0.07	1.28	18.50
23.94	9.13	0.75	19.08
23.63	2.86	0.72	17.03
24.59	4.49	1.56	18.89
23.15	0.68	0.72	18.18
23.38	7.82	1.24	12.56
24.55	6.42	1.28	17.61
23.17	0.07	0.75	4.74
24.60	4.32	0.72	17.26
24.21	0.07	1.56	18.68
24.20	2.02	1.58	19.01
23.71	2.07	1.58	17.28
24.51	4.51	1.68	18.10
24.59	5.21	1.62	19.08
24.38	0.70	1.55	18.10
24.40	0.86	1.47	19.24
23.50	0.07	1.24	18.74
23.05	9.02	1.55	10.23

Table 4.3: Field Test Data for Lightweight Rider

Battery Voltage (V)	**Battery Current (I)**	**Torque Sensor Voltage (V)**	**Motor Voltage (V)**
24.25	2.30	1.50	11.21
24.11	2.53	1.56	15.30
24.44	2.22	1.56	15.80
24.72	2.42	1.63	16.30
24.15	3.51	1.61	16.80
24.78	0.84	1.69	16.20
23.12	10.08	1.67	16.40
24.61	0.91	1.66	9.60
23.97	3.51	0.79	15.90
24.06	3.45	1.63	6.90
24.09	3.73	0.95	11.71
24.12	3.55	1.44	14.30
24.04	3.82	1.50	15.20
24.01	4.21	1.56	14.60
24.09	3.62	1.63	16.50

24.89	0.07	1.64	16.10
24.54	1.16	1.62	15.00
24.40	4.83	1.62	16.10
24.59	0.88	1.62	13.90
24.10	5.39	1.45	14.50
24.50	1.38	1.52	8.50
23.30	8.06	1.63	5.00
23.66	5.37	1.43	13.10
24.22	3.25	0.81	14.60
24.10	3.35	1.44	12.50
24.02	3.58	1.43	12.30
24.71	4.24	1.58	14.60
24.09	3.54	1.57	12.40
24.43	2.46	1.60	15.60
24.02	5.50	1.63	16.00
25.38	4.36	1.69	12.20
23.07	5.94	1.53	10.20
23.25	9.07	1.53	15.10

23.70	4.86	1.61	15.70
24.04	4.29	1.69	13.20
24.07	4.35	1.47	11.70