ENERGY-EFFICIENT HUMAN HAULER WITH ENHANCED SAFETY FOR URBAN MOBILITY

By
MD SHAHRIA
22121046

SABAB HOSSAIN
22121084

MD FARDIN AHASAN
22121011

MD TAKRIM SAIYED
22121052

A Final Year Design Project (FYDP) submitted to the Department of Electrical and Electronic Engineering in partial fulfillment of the requirements for the degree of Bachelors of Science in Electrical and Electronic Engineering

Academic Technical Committee (ATC) Panel Member:

Dr. Mohammed Belal Hossain Bhuian

Associate Professor, Department of EEE, BRAC University

Md. Mahmudul Islam

Lecturer, Department of EEE, BRAC University

Sabbir Ahmed

Lecturer, Department of EEE, BRAC University

Department of Electrical and Electronic Engineering
BRAC University

January 2026

Declaration

It is hereby declared that

1. The Final Year Design Project (FYDP) submitted is my/our own original work while completing degree at Brac University.
2. The Final Year Design Project (FYDP) does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.
3. The Final Year Design Project (FYDP) does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.
4. I/We have acknowledged all main sources of help.

Student's Full Name & Signature:

MD Shahria **22121046**	**Sabab Hossain** **22121084**
MD Takrim Saiyed **22121052**	**MD Fardin Ahsan** **22121011**

Approval

The Final Year Design Project (FYDP) titled “ENERGY-EFFICIENT HUMAN HAULER WITH ENHANCED SAFETY FOR URBAN MOBILITY ” submitted by

1. MD Shahria (22121046)
2. MD Takrim Saiyed (22121052)
3. Sabab Hossain (22121084)
4. MD Fardin Ahasan (22101011)

Fall, 2025 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Electrical and Electronic Engineering (BSEEE) on 05/01/2026.

Examining Committee:

Academic Technical Committee (ATC): (Chair)

____

Dr. Mohammed Belal Hossain Bhuian

Associate Professor, Department of EEE,

BRAC University

Final Year Design Project Coordination Committee: (Chair)

____

Dr. Mirza Rasheduzzaman
Associate Professor, Department of EEE,

BRAC University

Department Chairperson:

____

Dr. Md. Mosaddequr Rahman
Chairperson, Department of EEE,
BRAC University

Ethics Statement

The report showed a turnitin similarity percentage of 13% and an AI percentage is less than 20%. To maintain the originality of the project proper guidelines of citation and reference in IEEE style were followed.

Abstract/ Executive Summary

Electric rickshaws play a vital role in urban transportation in Bangladesh, but their growing use has increased pressure on the national power grid and raised concerns about energy efficiency and sustainability. This project presents the design and implementation of a hybrid electric rickshaw system that combines human pedaling with controlled motor assistance, solar energy harvesting, and regenerative braking. The Pedal Assist Sensor (PAS) to sense the level of peddling is attached, and an Arduino-based motor controller assists with a maximum of 80 percent of the effort of the rider with a safe maximum speed. The use of solar panels and a regenerative system allows one to recharge a battery during work and become less dependent on grid electricity. The mathematical modeling, simulation, and hardware testing prove that the proposed system reduces battery usage, increases the driving range, and has more energy efficiency. The implemented model is cheap, safe and can be used in the real world, hence is a viable solution to the transportation problem in urban Bangladesh.

Keywords: Hybrid electric rickshaw; Pedal assist system; Energy efficiency; Solar charging; Regenerative braking; Sustainable transportation

Dedication

It is in honor of our dear parents who have always been by our side in our life by unconditional love, making sacrifices and never giving up to see us through our academic life. We also give the work to our teachers and mentors whose support and wisdom have inspired us to achieve excellence in engineering and research.

Acknowledgement

It is with deepest appreciation that we wish to thank all those who were involved in the completion of this project with or without your direct contribution.

We would like to thank first of all our project supervisors, Dr. Mohammed Belal Hossain Bhuian, Associate Professor, Department of Electrical and Electronic Engineering, BRAC University; Md. Mahmudul Islam, Lecturer, Department of Electrical and Electronic Engineering, BRAC University; and Sabbir Ahmed, Lecturer, Department of Electrical and Electronic Engineering, BRAC University. Their guidance, feedback, technical knowledge, and encouragement were invaluable, and they were much needed during the entire development of this project.

It is also our pleasure to offer our profound gratitude to all the respected teachers of the Department of Electrical and Electronic Engineering, BRAC University, who have imparted to us the theoretical and practical knowledge needed to complete this piece of work.

We are particularly thankful to our parents because they were always ready to support us, show patience, and encourage us to resist the risks and difficulties when we were working on this project.

Moreover, we would like to acknowledge our friends and our encouragement Tasfia Rahman Piyal, Sanzida Dewan Elma, Alvee Ishraque, Mashrur Shahriar Hossain, Md. Abu Sufian, Sawaria Hossain and Mayeesha Islam who helped us in our learning process, cooperated and encouraged us to continue doing so.

Finally, we acknowledge the efforts and teamwork of all group members Sabab Hossain, Md. Shahria, Md. Takrim Saiyed and Md. Fardin Ahasan whose dedication, cooperation and mutual support made this project possible.

Table of Contents

CHAPTER 1: INTRODUCTION [CO1, CO2, CO3, CO10]

1.1 Introduction

Bangladesh transportation in urban areas is based on low-speed three-wheeled vehicles like rickshaws and electric rickshaws, which are powered by batteries. Even though the immediate tailpipe emissions of electric rickshaws have been significantly lower than those of fossil-fuel-based vehicles, the sheer number of electric rickshaws has created a substantial load on the national electricity grid, which remains heavily reliant on fossil fuel-based power generation [1], [2].Furthermore, the majority of traditional electric rickshaws do not have smart energy control systems that would ensure the efficient use of the battery, shorter range of the drive, and the need to rely on grid charging regularly [3].

To solve these issues, this project presents a hybrid electric rickshaw model that will combine the pedal-assisted propulsion, solar energy capture, and regenerative braking. The proposed solution seeks to enhance energy efficiency, longer driving range, less grid reliance, and environmental sustainability and affordability and operational safety appropriate to urban environments in Bangladesh.

1.1.1 Problem Statement

The fast development of battery-powered electric rickshaws in Bangladesh has led to the consumption of more electricity, the accelerated battery degradation, and the use of an illegal grid connection to charge batteries [6]. In most traditional market controllers, rider efforts are not taken into account and the controller empties batteries unnecessarily even when human power is available to pedal the rickshaw. Moreover, the majority of the systems that exist lack the use of renewable energy sources and energy saving mechanisms and as a result, fail to utilize energy efficiently [3], [7].

Therefore a smart affordable and sustainable propulsion system that can lessen grid reliance, maximize battery efficiency and by enduring the traffic regime, financial limitations and new legislation in Bangladesh is in high demand.

1.1.2 Background Study

The electric rickshaws usually use throttle-controlled systems that run only on battery packs. Several studies have shown that combining electrical support with human power can greatly lower energy consumption and improve system efficiency [4], [8]. Because of their energy efficiency and user acceptability, pedal-assisted electric vehicles (Pedelecs) have been successfully introduced in bicycles and lightweight electric vehicles all over the world [9].

Solar-assisted and pedal-powered rickshaws have been researched as alternatives to traditional electric rickshaws in Bangladesh [4], [10]. However, the lack of integrated real-time control strategies, high system complexity and high cost have prevented large-scale implementation. Regenerative braking is widely used in electric vehicles, but due to technical and financial obstacles, its use in low-speed electric rickshaws is still limited.

1.1.3 Literature Gap

Few studies have concentrated on combining pedal assistance, solar charging, and regenerative braking into a single, affordable system appropriate for electric rickshaws in Bangladesh, despite the fact that the literature currently in publication highlights the advantages of each technology separately [3], [10]. The majority of earlier designs prioritise either pedal power or solar assistance without integrating intelligent control mechanisms that modify motor assistance in response to rider input.

Additionally, there aren't many real-world implementation studies that take grid dependency, user affordability, safety and local traffic patterns into account all at once. By developing and implementing an integrated hybrid propulsion system suited to Bangladesh's actual operating conditions, this project fills this gap.

1.1.4 Relevance to Current and Future Industry

Bangladesh's transport sector desperately needs sustainable and energy-efficient mobility solutions due to growing urbanisation and energy demand.

The proposed hybrid electric rickshaw system by reducing the cost of operation, enhancing efficiency, and using less electricity is in tandem with the needs of the industry today [2], [6].

The comparable intelligent energy management architecture can be eventually applied to light electric cars and commercial vehicles in three-wheels. The project also enables the transition to smart mobility technologies and incorporation of renewable energy, both of which are expected to play a very significant role in the transportation sector in the future [1], [12].

1.2 Objectives, Requirements, Specifications, and Constraints

1.2.1 Objectives

The primary objective of the project is to design and implement a system of a pedal-assisted hybrid electric rickshaw that will efficiently combine the human effort of pedalling with the assistance of an electric motor to minimise the use of the grid electricity.The project will also aim to minimise the use of the grid electricity by making use of renewable energy such as solar energy and energy recovery through regenerative braking. Another main goal is the increase of battery life and driving range with ensuring safe and reliable operation at Bangladeshi traffic and socioeconomic conditions at an affordable price. The system is also designed to work well with existing electric rickshaw systems in order to facilitate its utilization.

1.2.2 Functional and Nonfunctional Requirements

The functional requirements of the proposed system encompass the capability of detecting the pedalling effort of a rider by use of Pedal Assist Sensor (PAS) to provide motor assistance that is proportional to the measured effort detected. The system should also have a speed-limiting mechanism in order to ensure safe operation in congested urban environments. Also, it should make itself compatible with various operating modes, allowing the users to switch between a recommended hybrid control system and a standard market controller.

The nonfunctional requirements point out the affordability, reliability and safety of the system. The mechanism must be constructed using cheap and locally available components as the Bangladeshi rickshaw drivers are price-sensitive. High dependability and ease of maintenance is essential to ensure long term usability. Also, the system must be robust enough to withstand tough operating conditions such as high traffic levels, poor roads and frequent stop and go services.

1.2.3 Specifications

The proposed hybrid electric rickshaw system ensures that it adheres to existing battery and motor systems and operates at a nominal voltage of **24 V** which is frequently employed in low-speed electric rickshaw. A DC **250W** motor is employed as a propulsion motor because it is simple, cheap and can be controlled. An **Arduino**-based microcontroller is the central control unit that is processing sensor inputs and generates the required motor control signals. The top speed of the vehicle is limited to **25km/h** as a precaution and in accordance with the law. A solar panel, rechargeable battery, and a regenerative braking system will be used to support the energy supply to make it more energy-efficient and more sustainable.

1.2.4 Technical and Non-Technical Consideration and Constraint in Design Process

A few technical as well as non technical factors influenced the design process.Technically, this is because the battery capacity was limited in the system and therefore effective management of energy is necessary to maximize on driving range. The energy efficiency of the regenerative braking is also constrained by the low running speed of the electric rickshaws that necessitates cautious optimisation of the energy recovery process. The other significant technical constraint was the aspect of the availability of components in the local Bangladeshi market.

As a non-technical consideration, the design needed to consider the high density of people in cities, the sensitivity of the cost of the rickshaw owners, and the inconsistencies of the enforcement of the rules which applied to the activities of the electric rickshaw. To reduce carbon emissions, grid load, and environmental impact, environmental sustainability was also given the first priority.

1.2.5 Relevant Compliance, Standards, and Codes.

In order to ensure safe operation, the proposed system complies with the essential electrical safety procedures that are applicable to the low voltage DC systems. Battery guidelines on handling, protection and charging were to be provided to prevent thermal hazards, deep discharge and overcharging. Ethical engineering and research standards were observed during the project so as to ensure responsible design and reporting. To ensure safety to the people and social acceptability, informal speed limits that are commonly practiced in the use of electric rickshaws in Bangladesh were also considered. International engineering ethics guidelines and best practices were also used in professional behaviour during system development.

1.3 Systematic Review of the Proposed Project.

The proposed system is an Arduino powered controller with Pedal Assist Sensor (PAS) to regulate motor assistance upon input of the rider. Solar power is supplemented with battery power and regenerative braking and a mode-switching system gives the option to use either the recommended hybrid control system or the conventional market controller. This integrated design ensures enhanced sustainability, safety and efficiency.

1.4 Conclusion

This chapter included the motivation, the problem scenario, literature review, and objectives of the proposed hybrid electric rickshaw system to address the problem of energy inefficiency, grid reliance and sustainability. This chapter preconditions the detailed design, implementation, and evaluation of the overall chapters.

CHAPTER 2: PROJECT DESIGN APPROACH [CO5, CO6]

2.1 Introduction

The introduction of the sustainable electric rickshaw system that consumes less energy and would be applicable in Bangladesh has to consider the different design strategies cautiously. The investigation of the alternative options is important before the best engineering solution is selected due to the constraints that exist in form of cost, the energy availability, traffic conditions and user behaviour. This chapter provides a number of design solutions to make electric rickshaws more energy-efficient and they were assessed based on their technical feasibility, cost, efficiency, usability, sustainability and the compatibility with the local context. The purpose of this chapter is to find the most appropriate design solution that would meet the objectives and constraints of the project.

2.2 Multiple Design Approaches Identification.

According to the definition of the problem and a large literature review, it was possible to identify two possible design approaches:

Design Approach 1 Pedal-assisted hybrid electric rickshaw with inbuilt solar energy and regenerative braking system.

Design Approach 2 Pedal-battery hybrid electric rickshaw without solar integration and regenerative braking system.

These two strategies are designed to minimize battery reliance and improve energy efficiency but have differences in complexity of the systems, energy sources and infrastructure needs.

2.3 Description of Design Approaches

2.3.1 Design Approach 1: Pedal-Assisted Hybrid System with Solar and Regenerative Energy

2.1 Introduction

Any project to make a sustainable and energy efficient system of electric rickshaw in Bangladesh requires careful consideration of different design procedures. The investigation of alternative options is important before settling on the most suitable engineering solution due to the constraints involved in its cost, energy supply, traffic, and user behaviour. This chapter presents several design strategies of enhancing the energy efficiency of electric rickshaws and they were assessed based on their technical rationality, cost and Design

Approach 1 combines human peddling effort, electric motor assist, solar energy collection and regenerative braking into one hybrid propulsion system. Under this system, a Pedal Assist Sensor (PAS) senses the activity of rider pedaling and a smart controller adjusts the output of the motor evenly with the level of effort. This is a human machine cooperation that ensures a huge saving of battery power and at the same time, comfort of the ride.

The rickshaw structure has solar panels to ensure that the batteries are charged continuously throughout the day when it is light so that there is reduced reliance on grid power. Also, regenerative braking is provided with an energy recovery system based on a dynamo which transforms kinetic energy during braking into an electrical energy and stores it in the battery in a DC-to-DC conversion step.

Such a strategy would be best applicable to Bangladesh because they have regular stop and go traffic and have excellent solar radiation and most of their vehicles are pedal powered rickshaws. Nevertheless, the system adds new elements, which makes it more difficult to design and more expensive to start with.

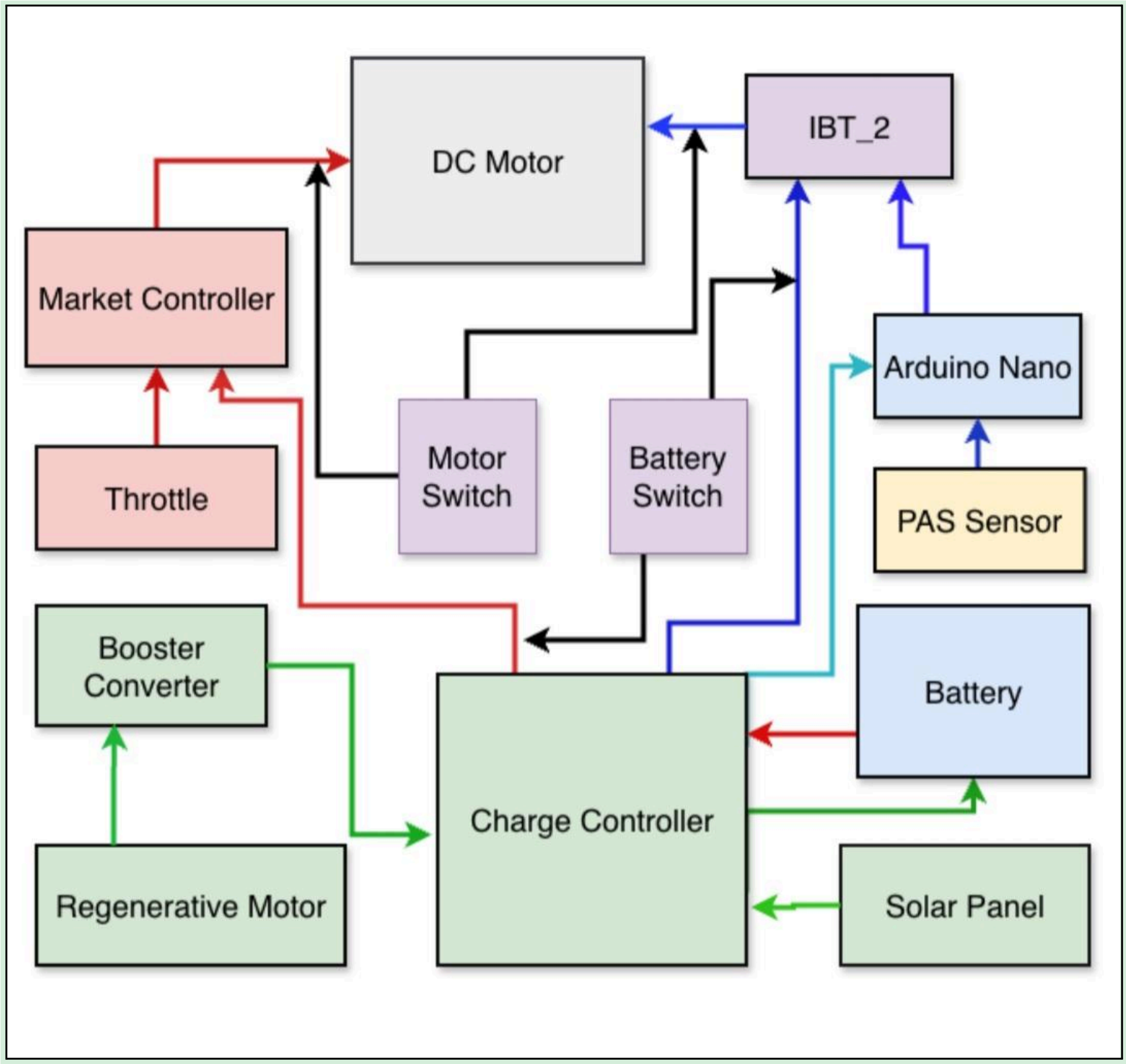

Figure 2.1: Design Approach 1

2.3.2 Design Approach 2: Pedal–Battery Hybrid System without Solar Integration

Design Approach 2 aims at creating a power-saving, safe, and intelligent rickshaw system in urban areas with a pedal-battery hybrid system and no solar panels present.

Under this mode, human peddling and electric motor propulsion work in parallel with one another to give propulsion. The battery is replenished only with the help of standard AC charging networks, thus, there is no solar dependency. The design focuses on simplicity of the system, reduced initial price and easy compliance with the current urban infrastructure and rules within Dhaka.

There is no need to have solar panels because of lower complexity in structure and maintenance. Nevertheless, the system is still reliant on grid electricity and fails to use renewable energy and braking energy recovery, which restricts its future sustainability.

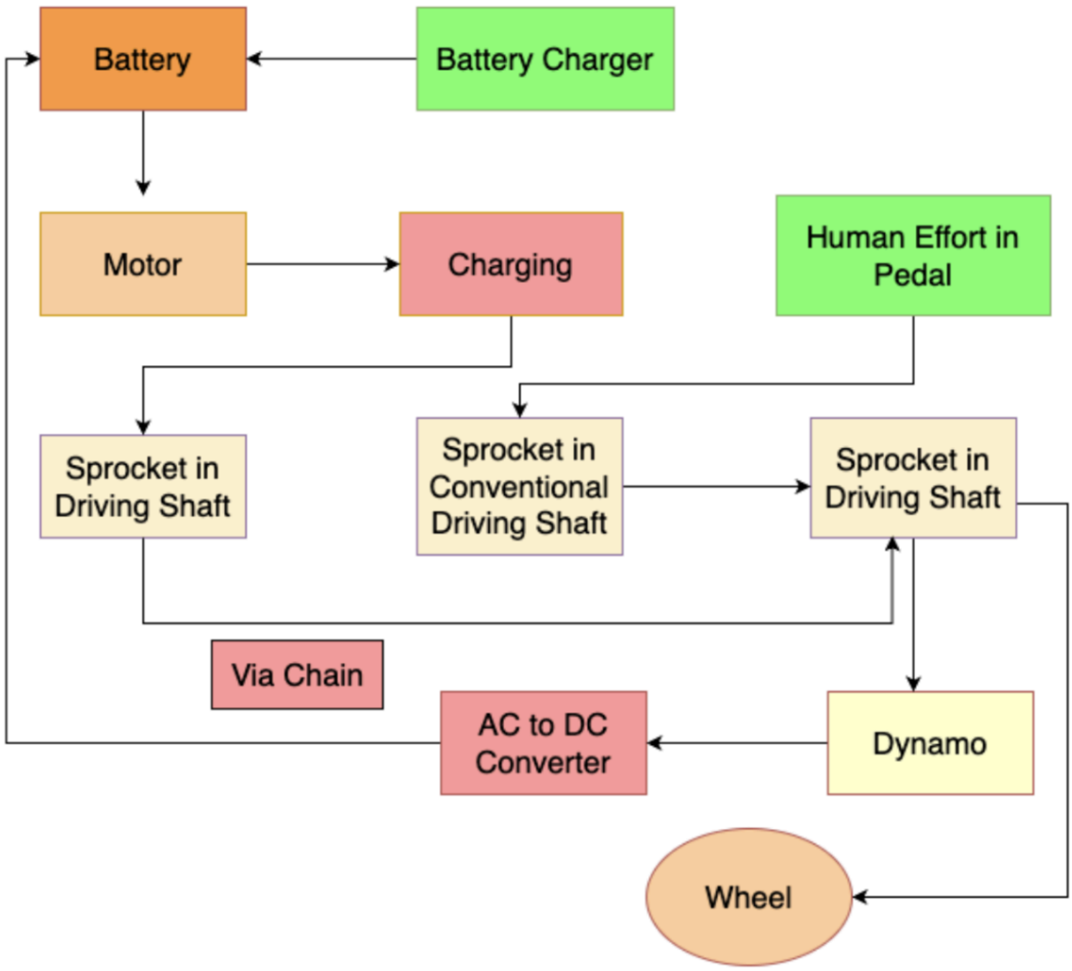

Figure 2.2: Design Approach 2

2.4 Analysis of Multiple Design Approaches

The comparison and evaluation of the two design methods was done based on key engineering parameters like cost, energy saving, usability, manufacturability, sustainability and maintainability. This analysis of the two approaches tries to establish the strengths and weaknesses of each of them in relation to the activities of the electric rickshaw in Bangladesh.

Design Approach 1 is the hybrid of the pedal-assisted propulsion, solar energy collection, and regenerative braking in order to reduce the battery reliance and improve the energy efficiency by combining different sources of energy. This will enable partial recovery and supplementation of electrical energy in the process of operation. This in turn offers reduced grid power consumption and protracted battery life. However, the applications of the solar panels, more power electronics and regenerative mechanisms complicate the systems, installation requirements and price. The further aspects also demand more specific attention to integration and maintenance.

Design Approach 2 involves a pedal-battery hybrid design in which there is neither a solar nor a regenerative energy recovery. Battery charging consequently by grid alone. The system structure of this design is less complex and the number of parts is less. Leading to lower cost of initial purchase, lower manufacturability and lower maintenance complexity. Its design fits in the urban environment that has the developed charging infrastructure. This absence of integration of renewable energy and energy recovery mechanisms however makes it less efficient to decrease grid dependency and the long term operational energy consumption.

The trade off of both these design approaches is in complexity, cost, efficiency as well as sustainability. Design Approach 1 is aimed at integrated renewable and energy efficiency. On the contrary, Design Approach 2 is more oriented towards simplicity, low cost and easy implementation. The critical analysis of the approaches as compared to each other is how each one handles the engineering problem in a perspective. Giving a background where informed decisions may be made in the following design choice phase.

2.5 Conclusion

This chapter identified and talked about two possible solutions in the design that can help make electric rickshaws in Bangladesh more efficient and sustainable in terms of energy. Through systematic analysis which is decided by the cost, efficiency, usability, manufacturability, sustainability and local operating environments. All methods were examined in terms of their advantages and weaknesses. One of them is geared towards energy recovery and integration of renewable energy towards long term sustainability. The other is more concentrated on the simplicity, low cost and easy installation in the existing city infrastructure. A clear picture of trade-offs of every design was formed through the comparison analysis. Providing optimal technical background to be used in the subsequent design optimization and implementation procedure.

CHAPTER 3: USE OF MODERN ENGINEERING IT TOOL [CO9]

3.1 Introduction

The critical engineering design involves application of analytical modelling, simulation software and embedded control platform. It is a system behaviour test, and is conducted before hardware is implemented. The proposed hybrid electric rickshaw system design, analysis and validation have been accomplished using a combination of mathematical modelling, MATLAB and embedded system programming simulation in this project.

The modelling method of the vehicle dynamics, energy flow and control logic is introduced in this chapter. It also talks about the software and hardware tools that are used in the process of designing the system to make sure that the system performs well and efficiently.

3.1.1 Vehicle Dynamics Modeling

Traction Force Requirements

The traction force required for our model to effectively perform its motion was modeled by considering these factors :

1. Rolling resistance force
2. Aerodynamic drag force
3. Inertial force due to acceleration
4. Grade resistance (for inclined roads)

The total traction force F_{Total} is expressed as the summation of all the forces together acting on the design model .

$$F_{Total} = F_{Rolling} + F_{Aero} + F_{Initial} + F_{Grade}$$

The calculations of each part were made by using standard vehicle dynamic equations to come up with realistic power and torque needed when driving in urban conditions.

1) Speed Profile $v(t)$ in km/h

$$v(t) = \begin{cases} 20 \cdot \dfrac{t}{t_{\text{accel}}}, & 0 \le t \le t_{\text{accel}} \quad \text{(acceleration)} \\ 20, & t_{\text{accel}} < t \le t_{\text{decel\_start}} \quad \text{(cruise at 20 km/h)} \\ 20 - 10 \cdot \dfrac{t - t_{\text{decel\_start}}}{t_{\text{decel}}}, & t_{\text{decel\_start}} < t \le t_{\text{decel\_start}} + t_{\text{decel}} \quad \text{(deceleration)} \\ 10, & t_{\text{decel\_start}} + t_{\text{decel}} < t \le t_{\text{reaccel\_start}} \quad \text{(cruise at 10 km/h)} \\ 10 + 10 \cdot \dfrac{t - t_{\text{reaccel\_start}}}{t_{\text{reaccel}}}, & t_{\text{reaccel\_start}} < t \le t_{\text{reaccel\_start}} + t_{\text{reaccel}} \quad \text{(re-acceleration)} \\ 20, & t > t_{\text{reaccel\_start}} + t_{\text{reaccel}} \quad \text{(final cruise at 20 km/h)} \end{cases}$$

2) Motor Torque $T_{\textbf{motor}}(v, t)$

$$T_{\text{motor}} = \begin{cases} 0, & \text{during braking (deceleration)} \\ T_{\max,m} \cdot 0.6 \cdot \dfrac{v}{20}, & \text{during acceleration or re-acceleration} \\ \begin{cases} T_{\max,m} \cdot 0.6, & v > 15 \\ T_{\max,m} \cdot 0.6 \cdot \dfrac{v}{20}, & v \le 15 \end{cases}, & \text{during cruise} \end{cases}$$

3) Pedal Torque $T_{\textbf{pedal}}(v, t)$

$$T_{\text{pedal}} = \begin{cases} 0, & \text{during braking (deceleration)} \\ T_{\max,p}\left(1 - 0.6 \cdot \dfrac{v}{20}\right), & \text{during acceleration or re-acceleration} \\ \begin{cases} T_{\max,p} \cdot 0.4, & v > 15 \\ T_{\max,p} \cdot 0.4 \cdot \dfrac{v}{20}, & v \le 15 \end{cases}, & \text{during cruise} \end{cases}$$

4) Resistance Compensation Rule (from code)

$$\text{If } (T_{\text{pedal}} + T_{\text{motor}}) < T_{\text{resist}} \text{ and not decelerating:}$$
$$T_{\text{motor}} \leftarrow T_{\text{motor}} + \big(T_{\text{resist}} - (T_{\text{pedal}} + T_{\text{motor}})\big).$$

5) Resistive Torque

$$T_{\text{resist}}(v) = 0.01\, v^2 + 0.5$$

(where v is in km/h)

6) Power and Energy Integration

Convert speed to m/s: $v_{\mathrm{m/s}} = v_{\mathrm{km/h}} \times \frac{1000}{3600}$

$$P(t) = \frac{T(t)\, v_{\mathrm{m/s}}(t)}{r_w}$$

$$E(t) = \int_0^t P(\tau)\, d\tau$$

$$E_{\mathrm{pedal}}(t) = \int_0^t P_{\mathrm{pedal}}(\tau)\, d\tau, \quad E_{\mathrm{motor}}(t) = \int_0^t P_{\mathrm{motor}}(\tau)\, d\tau$$

$$E_{\mathrm{total}}(t) = E_{\mathrm{pedal}}(t) + E_{\mathrm{motor}}(t)$$

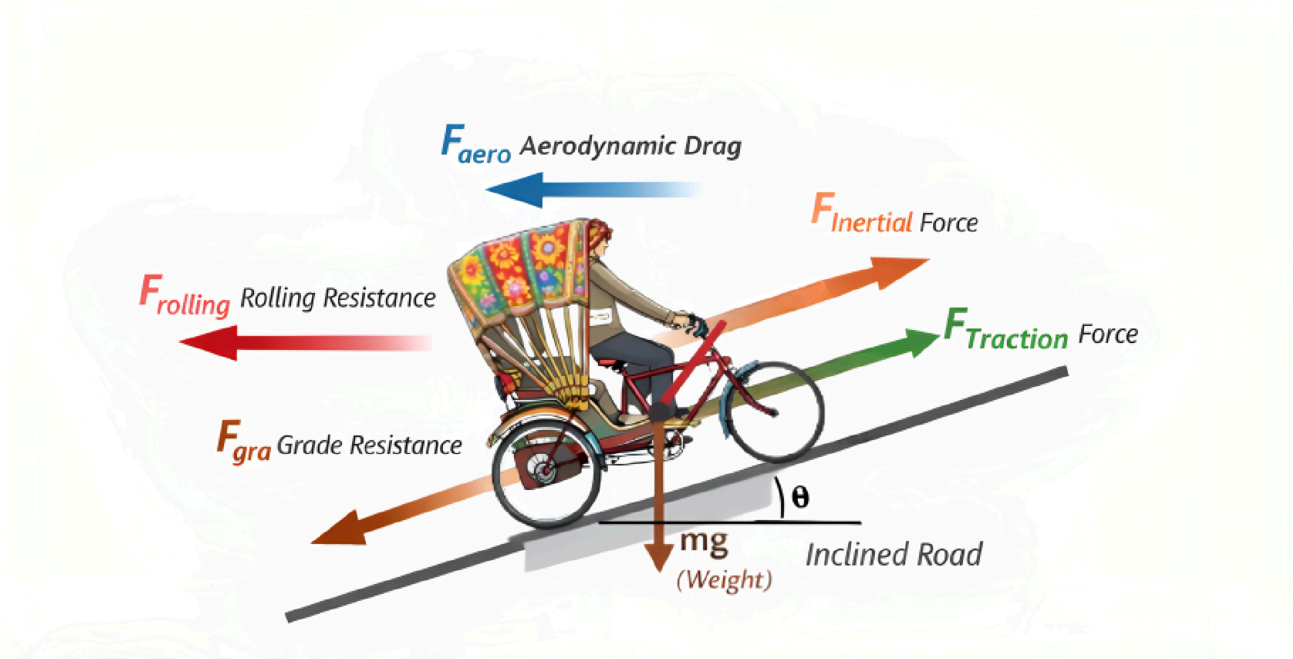

Figure 3.1: Forces acting on an electric rickshaw

Power Requirement Estimation

The power required at the wheels was calculated as:

$$P = F_{Total} \times V$$

where v is the vehicle speed. This estimation was used to calculate the approximate electrical power requirements of the battery and the input necessary to be made by pedal assistance.

The estimated power consumption was used to scale the motor, battery and controller parts.

3.1.2 Pedal Assist Sensor (PAS) Modeling

PAS Signal Characteristics :

The Pedal Assist Sensor (PAS) employed in this project will be made up of a magnetic disc fixed to the crank and a Hall-effect sensor that creates pulses based on the turn of the pedals. PAS does not directly record the torque, but gives cadence data, and this is used to approximate rider effort.

The PAS output signal was represented by a pulse train the frequency of which is proportional to the speed of pedalling (RPM).

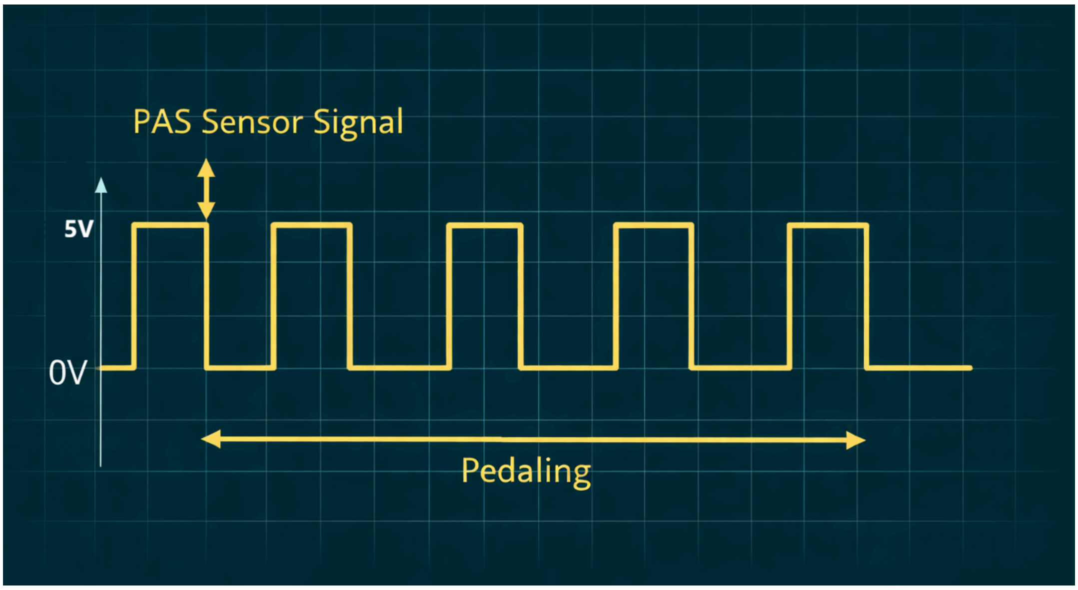

Figure 3.2: PAS sensor pulse waveform during pedaling

3.1.3 Cadence Calculation

The revolutions per minute (RPM) cadence was determined by using:

$$Cadence\ (RPM) = \frac{NPulse}{NMagnet} \times \frac{60}{T}$$

where:

- ➔ N_{pulses} = number of pulse detected
- ➔ $N_{magnets}$ = number of magnets on the pedal assist disc
- ➔ T = sampling time in seconds

This cadence value was the major input towards estimating rider torque and motor assistance.

3.1.4 Torque Estimation Model

Direct torque sensing is much more expensive and complex than the systems based on the cadence model, so a model of torque estimation in a cadence-based manner was implemented. A predefined look up table between cadence and average torque value based on literature and experimental results was used to approximate human peddling torque [41].

Table 3.1: Cadence-to-Torque Mapping

Cadence (RPM)	Estimated Torque (Nm)
0	0
20	5
40	10
60	15
80	20
100	25

Table values used a linear interpolation method to provide smooth estimation of the torque.

3.1.5 Motor Assist Control Model

Assist Ratio Implementation

The motor provided torque was determined using a predefined assist ratio of 80% of the human torque produced through manual pedaling :

$$T_{Motor} = 0.8 \times T_{Rider}$$

Where T_{Rider} is the torque produced by the rider upon pedalling.

In this implementation, the motor is tuned to give 80% of the estimated torque of the rider, thus human effort is supplemented, but not completely replaced.This way, the rider and the electric motor evenly distribute the work done, which enhances comfort and efficiency of the ride, and also prevents the motor from powering too much.Since the motor torque is adjusted dynamically to the rider's input, the system is able to achieve smooth acceleration and better control, especially on uneven surfaces and when going uphill.

3.2 Selection of Appropriate Engineering and IT Tools

The design and test of the hybrid electric rickshaw system needed some appropriate engineering and information technology (IT) tools to model, simulate, implement the control and to analyze the performance. The choice of these tools was informed by their accuracy, reliability, availability, easiness of use and applicability to real-life engineering practice.

MATLAB was chosen as the main tool of simulation and analysis because it has a high level of mathematical modeling, numerical computing, and system-level simulation. It was employed to simulate vehicle dynamics, approximate power and energy flow, and power sharing between the motor and the pedal at different operating conditions. The speed, torque and power profiles could be visualized with MATLAB and design assumptions could be validated early in the design before hardware implementation.

Also, the circuit-level simulation and verification of the embedded control system were performed with Proteus Design Suite in addition to MATLAB. Proteus made the virtual application of Arduino Nano and other peripheral devices like sensors, motor driver modules and signal conditioning circuits a possibility. The correctness of wiring, logic flow, PWM signal generation and sensor interfacing was checked by real-time simulation before the real physical hardware assembly. This largely minimizes the chance of component damage and is used in determining logical and connection errors at a very early phase in the development stage.

In the case of embedded system development, the control unit was selected as Arduino Nano. The Arduino IDE offered an easy to use programming platform to apply PAS signal processing, motor control based on PWM, speed limiting logic, and safety. The compatibility of the platform with sensors, motor drivers and debugging tools, rendered the platform applicable in rapid prototyping and real-time control.

Voltage, current, and signal verification were done using supporting engineering tools like digital multimeters. Serial monitoring was used in the Arduino IDE to debug in real time and watch the performance. The combination of these tools allowed the proper modeling, effective development, and validated the offered system, and the simulation results and the reality were consistent.

3.3 Use of Modern Engineering and IT Tools

This project involved extensive use of the modern engineering and information technology (IT) tools to model, simulate and implement and validate the proposed hybrid electric rickshaw system. These tools were used to provide proper system analysis, minimize the risks of development, and increase the reliability of the overall design before the actual implementation of the hardware.

The main tool of computational and simulation was used, which was MatLab. It was used to simulate vehicle behavior, compute traction force demands, approximate power demand and conduct energy exchange between human peddling and motor assist. Speed, torque and power profiles at different operating conditions could also be visualized through MATLAB simulations and this proved useful in validating control strategies and also optimizing system parameters prior to physical prototyping.

In the case of embedded system development, Arduino Nano was chosen because of its small size, low power consumption, and enough processing power to support real-time control applications. The Arduino IDE was an efficient programming platform that was used to develop PAS signal processing, cadence detection, PWM-controlled motor control, speed limiting logic, and safety mechanism. The IDE was used to monitor and debug real-time data by use of the serial communication feature.

Besides this, the hardware testing and verification were done with standard engineering tools that included digital multimeters to measure voltage, current and signal levels. Software filtering such as oversampling and hysteresis control was used to ensure noise reduction and signal stability. The joint application of the state-of-the-art simulation software, embedded systems, and diagnostic systems made it possible to validate the system correctly, as well as guarantee the consistency between the performance in the simulated environment and in real-life.

3.3.1 Speed Limiting Model

In order to meet safety and regulatory guidelines, motor assistance was turned off when the vehicle speed was over 20km/h.A band gap type hysteresis was implemented on the Arduino Nano control logic, and different speed thresholds were assigned for disengaging and re-engaging motor assistance.This methodology avoided the ON/OFF hassle when the vehicle speed was around the limit, and it was able to provide better consistency to the system.

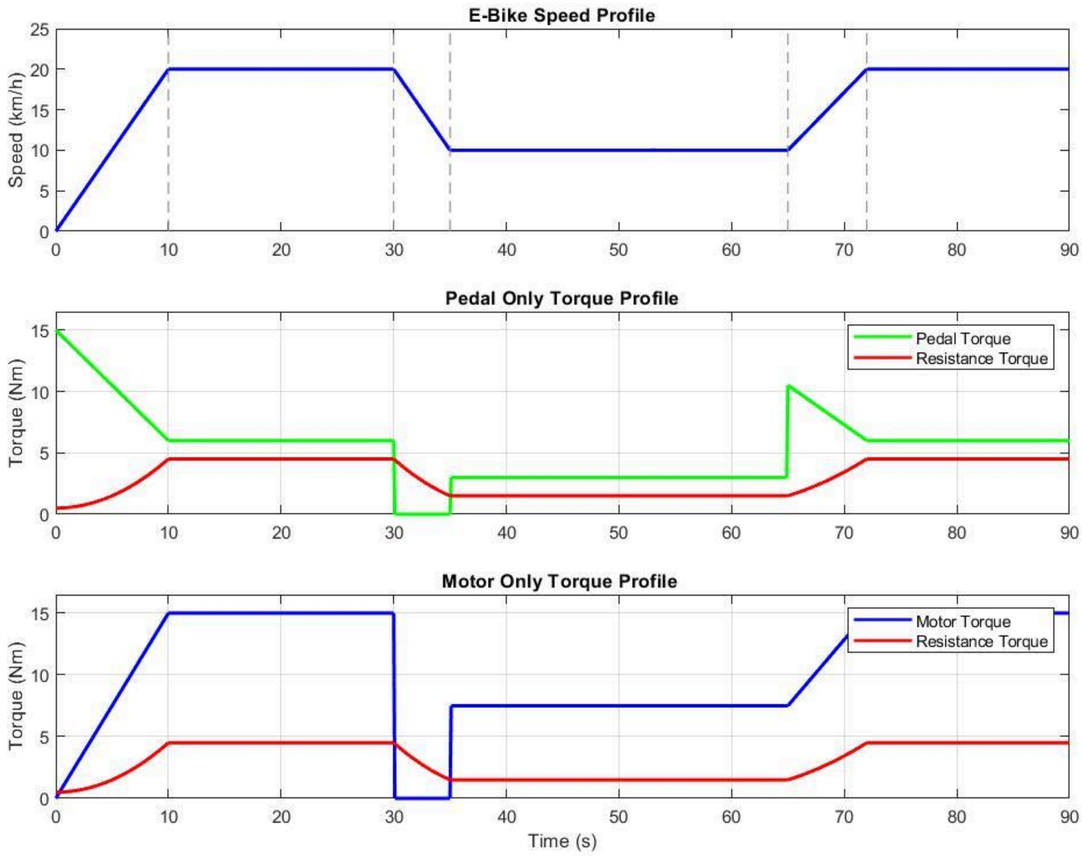

Figure 3.3: Torque profile and speed profile for re-accelerating vehicle after braking

3.3.2 MATLAB-Based Simulation

Before implementing the complete hardware, MATLAB was used for analysis and simulation to understand the performance of the proposed hybrid pedal–motor assisted system. Energy flow calculation validation was the major aim of the proposed simulation in providing structure to the battery, motor, and mechanical drivetrain for various operating conditions.

Moreover, the simulation was used to understand the power distribution from human pedaling and the electric motor support, which makes it possible to understand the level of support the motor provides to the rider for different speeds and loads.The system behavior was analyzed for different types of operations including acceleration, cruising, and speed-limited for different values of vehicle speed and motor torque.

Furthermore, MATLAB simulations were used to estimate possible improvements in driving range from motor assistance and regenerative contributions, based on energy consumption trends noted in the model.

Overall, the simulation environment allowed for early checking and refining of control strategies. This helped identify and fix design issues before hardware implementation, which reduced development risk and improved system reliability.

3.3.3 Power Sharing Simulation

The rider provided the simulation with about 20 percent of the total propulsion through pedalling. The electric motor gave the remaining 80 percent of propulsion assistance, the extent of which varied with the cadence of the pedalling. The battery served as the source of energy used by the motor when it was in operation and it supplied the required electrical energy.

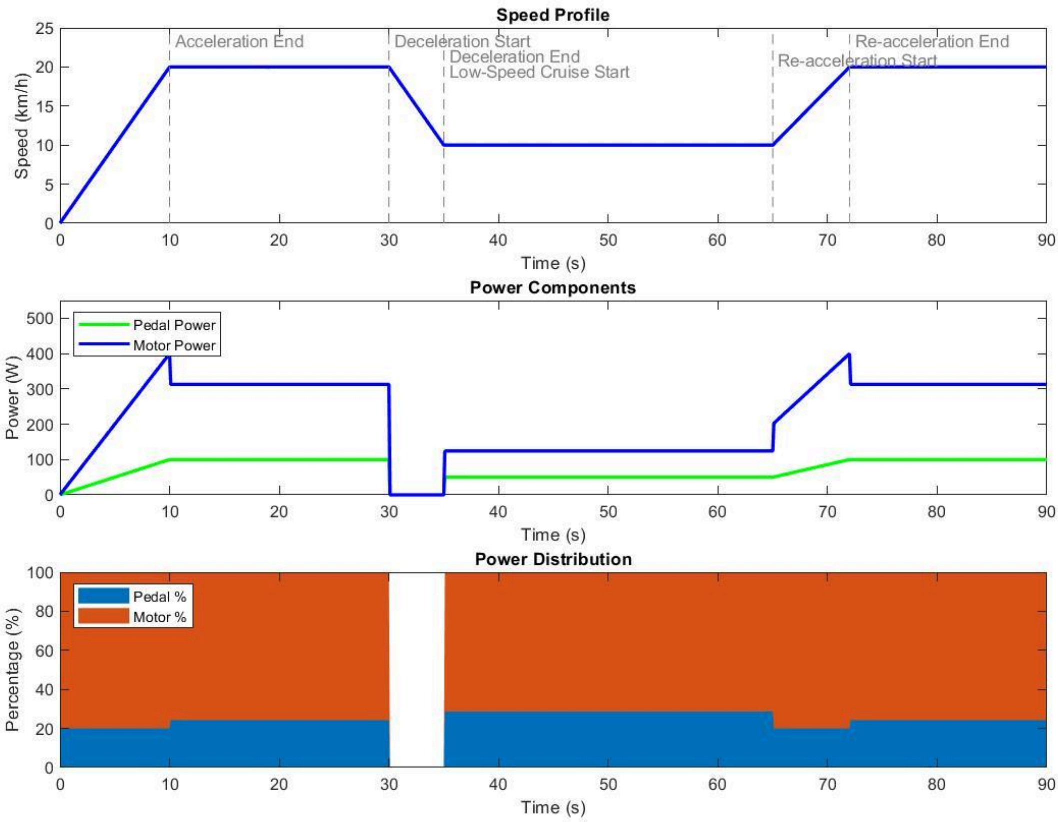

Figure 3.4: MATLAB simulation block diagram for power sharing

3.3.4 Simulation Results

The simulation outcomes revealed a clear decrease in battery power usage at the time of active pedalling taking into account that the rider contributed some of the required propulsion. This proved that human input and motor assistance could be power sharing effectively and the battery electrical load decreased.

The smooth acceleration profile was due to the use of PWM ramping in the motor control strategy. Besides enhancing the comfort of the ride and reducing mechanical and electrical loads on system components, the progressive change in duty-cycle ensured a slow start and stop of the torque.

Also, it was validated by the simulation that, when the speed threshold was exceeded, motor assistance was appropriately constrained at 20 km/h. This behaviour ensured that safety and legal requirements were followed as the vehicle was driven in a steady manner.

On the whole, the combination of rider engagement, speed control, and motor assistance control led to the efficiency of the system, which was manifested by reduced energy use and the more effective utilization of the available power resources.

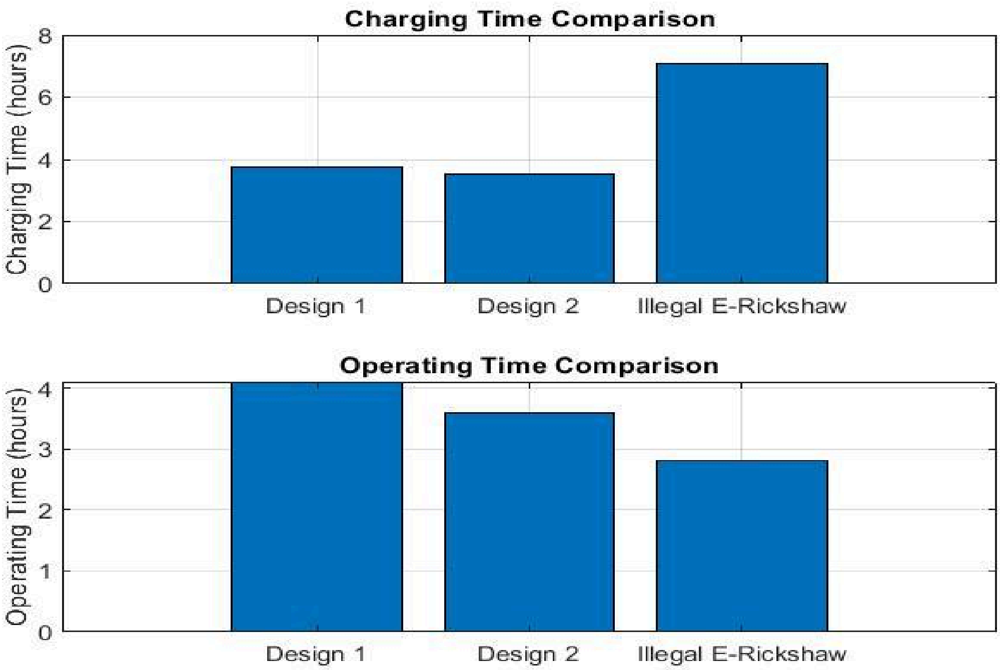

Figure 3.5 : Charging time and Operating time comparison.

```
Energy Consumption Comparison (in Wh):
Design 1 (Solar + Solar Charging Station) Energy Consumption: 350 Wh
Design 2 (National Grid Charging) Energy Consumption: 400 Wh
Illegal E-Rickshaw Energy Consumption: 1020 Wh
Charging Time Comparison (in hours):
Design 1 (Solar + Solar Charging Station) Charging Time: 3.7647 hours
Design 2 (National Grid Charging) Charging Time: 3.5294 hours
Illegal E-Rickshaw Charging Time: 7.0588 hours
Operating Time Comparison (in hours):
Design 1 (Solar + Battery) Operating Time: 4.1143 hours
Design 2 (National Grid Charging) Operating Time: 3.6 hours
Illegal E-Rickshaw Operating Time: 2.8235 hours
```

3.3.5 Embedded System Implementation Tools

The Arduino IDE was used to implement the control algorithm, which offered:

- ➔ PAS signal processing in real time
- ➔ PWM signal production
- ➔ Handling interruptions
- ➔ Debugging serially

Because of its small size, low power consumption, and adequate processing power, the Arduino Nano was chosen.

3.3.6 Motor Driver Interface

The IBT-2 motor driver was operated by PWM signals generated by the Arduino, and it allowed accurately controlling the motor speed by adjusting the duty-cycle. Direction control signals were used to determine the direction of rotation of the motor and the driver was only activated when operating under proper conditions to ensure that signals were possible. The method of this control was used to prevent undesired motor behaviour during startup, acceleration and load changes as well as provided safe and stable motor operation particularly when the load changed.

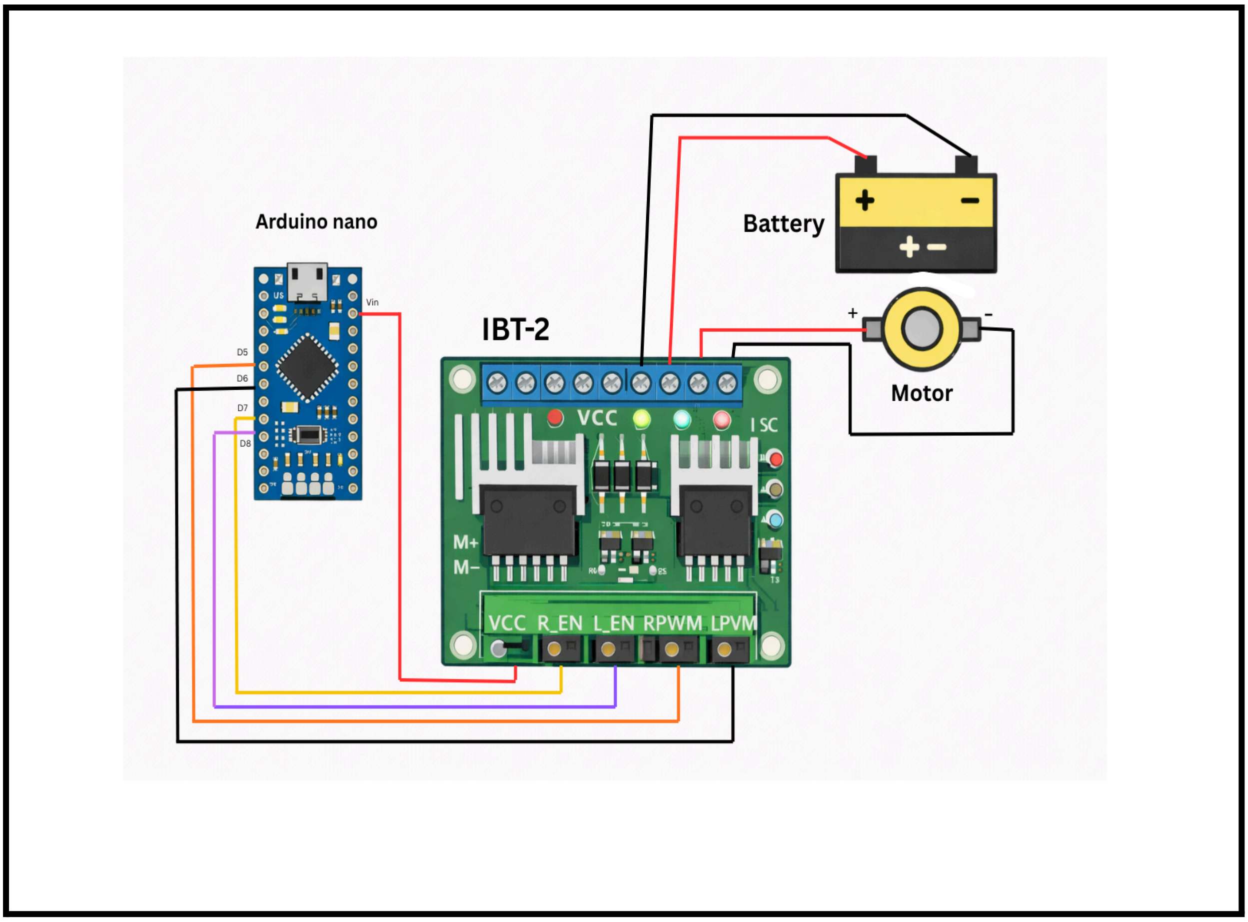

Figure 3.6: Arduino–IBT-2 interface diagram

3.3.7 Data Filtering and Noise Handling

To make sure that motor response is smooth and PAS is detected:

- ➔ Analogue signal oversampling was used.
- ➔ Hysteresis-based thresholding eliminated noise.
- ➔ Smooth changes in torque were prevented by PWM ramp limiting.

These methods significantly increased both the comfort of the ride and the stability of the system.

3.4 Conclusion

The technical feasibility of the hybrid pedal-assisted electric rickshaw system was confirmed by the modelling and simulation work in this chapter. The report demonstrated that the system is capable of meeting performance, efficiency and safety objectives through investigating the traction force requirements, energy flow and control behaviour under realistic operating conditions. The appropriateness of the selected control strategies was proven in the results of the simulation as the sharing of power between pedalling and motor assistance became efficient, the speed was kept stable, and the battery load was reduced. These findings formed a good foundation in the development of hardware and impacted critical design decisions, which become implemented and evaluated in the following chapters.

CHAPTER 4: OPTIMIZATION OF MULTIPLE DESIGN AND FINDING THE OPTIMAL SOLUTION [CO5, CO6, CO7]

4.1 Introduction

This chapter is based on optimisation and validation of the selected system design. It follows the second step following the deliberation on the various design styles at the initial stages of the project and the validation of the basic modelling and control logic in Chapter 3. The aim of this step was to improve energy efficiency, run and workability of the hybrid electric rickshaw architecture in a case of real life constraints.

Energy consumption, battery dependency, ease of control, comfort to the rider, system reliability and cost effectiveness were some of the engineering considerations. These are taken into consideration in the optimization process. These elements systematically enhanced the parameters of control, hardware design and energy saving methods. The results of this chapter provide a confidence of the design solution selection, prior to the real hardware design and testing.

4.2 Optimization of Multiple Design Approaches

During the design stage, the alternative system architecture designs were considered to address the problem of improving the energy efficiency and sustainability in the use of electric rickshawes. The key differences between these design solutions were the degree of motor support, battery dependence, implementation of renewable energy and control complexity.

Various rider torque and motor torque combinations were investigated to find the best power sharing pattern. The goal was to achieve an optimal rider to motor torque ratio. The different values estimate factors like battery power consumption, rider comfort and system efficiency by ensuring good practical applicability.

A constant sum of the demanded propulsion torque for a specified operating condition was used. They varied only the proportion of rider and motor torque

Assumptions (Common for All Cases)

- ➔ Total required power output ≈ **400 W (mechanical).**
- ➔ Battery usable energy = **1.44 kWh.**
- ➔ Drivetrain efficiency = **85%.**

- ➔ Average cruising speed = **12–15 km/h.**
- ➔ Higher rider contribution reduces battery draw but increases fatigue.
- ➔ Higher motor contribution improves comfort but increases battery discharge.

4.2.1 Case-wise Torque Sharing Analysis

Case 1: 40% Rider – 60% Motor Assistance

- ➔ Rider contribution = 160 W
- ➔ Motor mechanical output = 240 W
- ➔ Electrical power draw ≈ 240 / 0.85 ≈ **282 W**

Case 2: 30% Rider – 70% Motor Assistance

- ➔ Rider contribution = 120 W
- ➔ Motor mechanical output = 280 W
- ➔ Electrical power draw ≈ 280 / 0.85 ≈ 330 W

Case 3: 20% Rider – 80% Motor Assistance (Optimized Design)

- ➔ Rider contribution = 80 W
- ➔ Motor mechanical output = 320 W
- ➔ Electrical power draw ≈ 320 / 0.85 ≈ **376 W**

Case 4: 10% Rider – 90% Motor Assistance

- ➔ Rider contribution = 40 W
- ➔ Motor mechanical output = 360 W
- ➔ Electrical power draw ≈ 360 / 0.85 ≈ **424 W**

4.2.2 Observations from Rider–Motor Torque Sharing Optimization

At a rider contribution of 40% and a motor assistance level of 60%, battery energy spent was considered low because the reduced electrical requirement by the motor decreased demand on the power provided by the battery. But this setup meant that the rider has to workout more, especially when riding long hours or in city stop-and-go traffic. A consequence of this loss in rider comfort was a diminished utility for everyday use, although the efficiency at which mechanical power was converted to electricity remained high.

For this scenario, decreasing the rider contribution to 30% with increasing motor assistance to 70% enhanced ride comfort while keeping battery energy consumption at a moderate level. In this model, the ratio of human power to motor power was more suitably balanced for short-medium distance riding. But rider-fatigue might still be a concern over time, and overall accessibility would be predicated on the condition of the rider.

This was the most balanced case of all the cases checked as the configuration exhibited 20% rider contribution and 80% motor assistance. The effort of the riders was kept within comfortable range and at the same time active pedaling was involved. The energy consumption of the battery rose relative to higher cases of rider contribution but it was within reasonable limits. This operating point provided the ease of acceleration, the possibility to maintain the speed, and the comfort of the rider and it became quite applicable in the conditions of regular rickshaw use in the city. This ratio of torque sharing was therefore found to be the best design.

Reduction of the rider contribution further to 10% and 90% of motor support presented the rider with minimum physical effort at a much greater power demand on the battery. This setup was very similar to full-electric operation which would cause rapid depletion of the battery and weakened system life. Though the comfort of the rider was high, the reliance on battery energy was greater, which made this mechanism ineffective and unsuitable to work in the long term.

Altogether, the comparative analysis showed that the overdependence on either the rider effort or motor support had an adverse impact on the performance of the system. The constraint of the 20 percent rider and 80 percent motor torque sharing combination gave the best balance between energy efficiency, rider comfort and practical feasibility and hence it was chosen as the optimized operating strategy.

Table 4.1 : Table of rider to motor torque ratio comparison.

Rider Contribution	**Motor Contribution**	**Electrical Power Draw**	**Battery Impact**	**Rider Comfort**	**Suitability**
40%	60%	~282 W	Low	Low	Poor
30%	70%	~330 W	Medium	Medium	Moderate
20%	**80%**	**~376 W**	**Acceptable**	**High**	Optimal
10%	90%	~424 W	High	Very High	Not feasible.

4.3 Identification of the Optimal Design Approach

Design Approach 1 was the best solution, which was based on the analysis of several design options. This solution was a combination of pedal aid, motor-assistance, and energy control at a simple and affordable price.

Some of the key optimization objectives that were attained with this design were:

- ➔ Lowered energy consumption per kilometer per battery.
- ➔ Sufficient use of rider pedaling energy.
- ➔ PWM-based control of controlled motor assistance.
- ➔ Safety compliance: a speed limit of 20km/h.
- ➔ Less mechanical and electrical stress on parts of systems.

The chosen design also enabled an easy incorporation of renewable energy sources without the need to introduce a lot of complexity in the system. Consequently, Design Approach 1 was completed to be optimized and tested with regard to its performance.

4.4 Performance Evaluation of the Developed Solution

The optimized system was tested in terms of results of the simulation and the experimental observations. The test was done to determine the compliance of the developed solution to the specifications, performance, and safety requirements.

Some of the key performance metrics to be taken into consideration during evaluation were:

- ➔ Driving range improvement
- ➔ Voltage and current characteristics of batteries.
- ➔ Acceleration and deceleration are smooth.
- ➔ Speed regulation effectiveness.
- ➔ Renewable energy sources contribution.

4.4.1 Energy Utilization and Battery Performance

Simulation and experiment outcomes showed that there was a significant decrease in battery power consumption when active peddling is done. This verified efficient sharing of power between human intervention and motor support leading to enhanced energy efficiency.

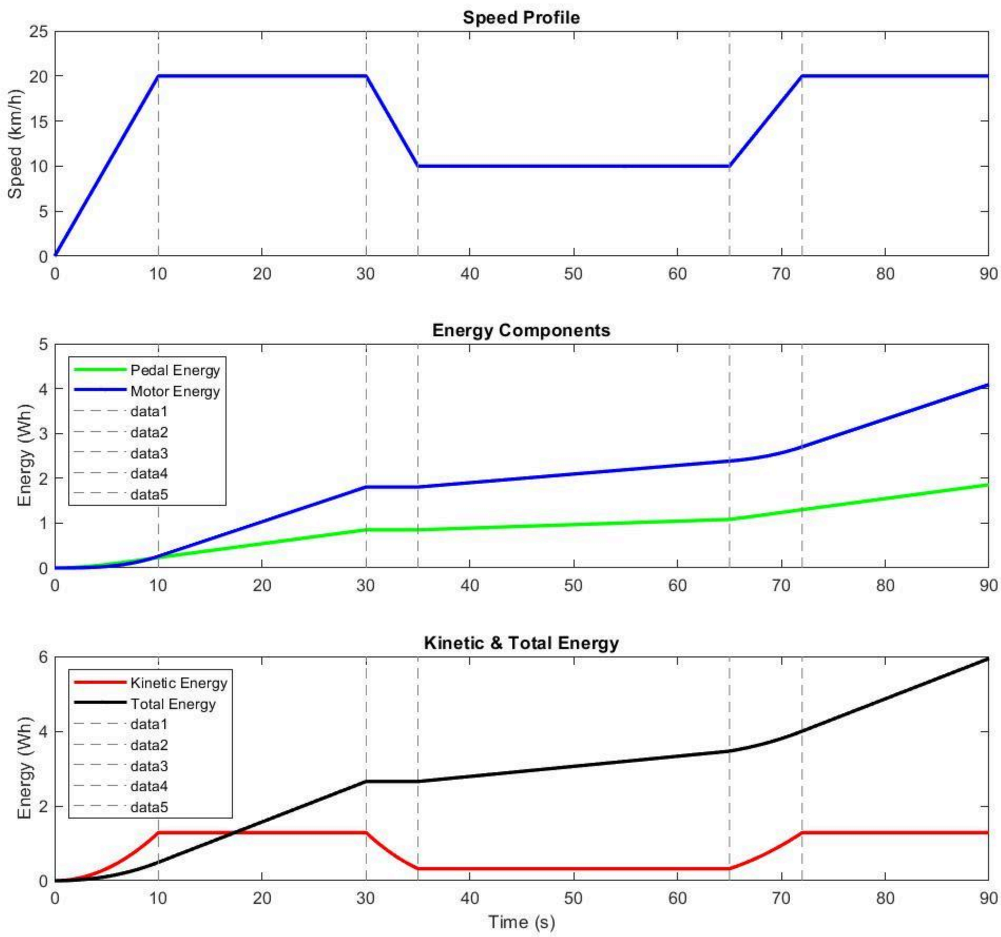

Figure 4.2 : Energy consumption at different driving conditions.

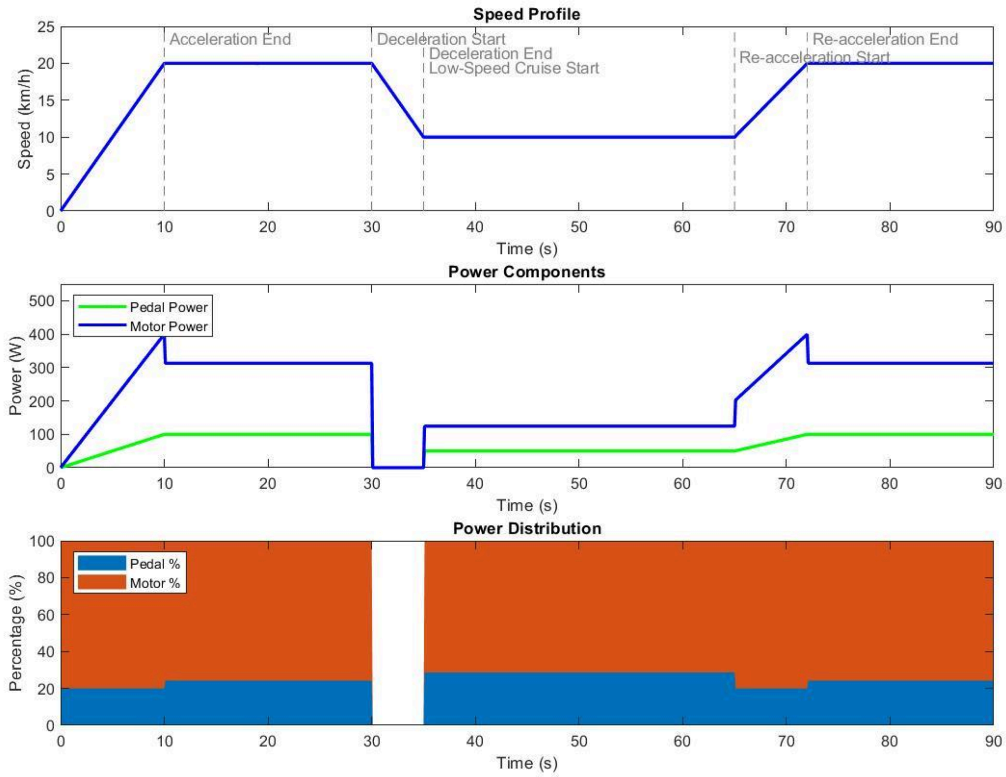

Figure 4.3: MATLAB simulation block diagram for power sharing

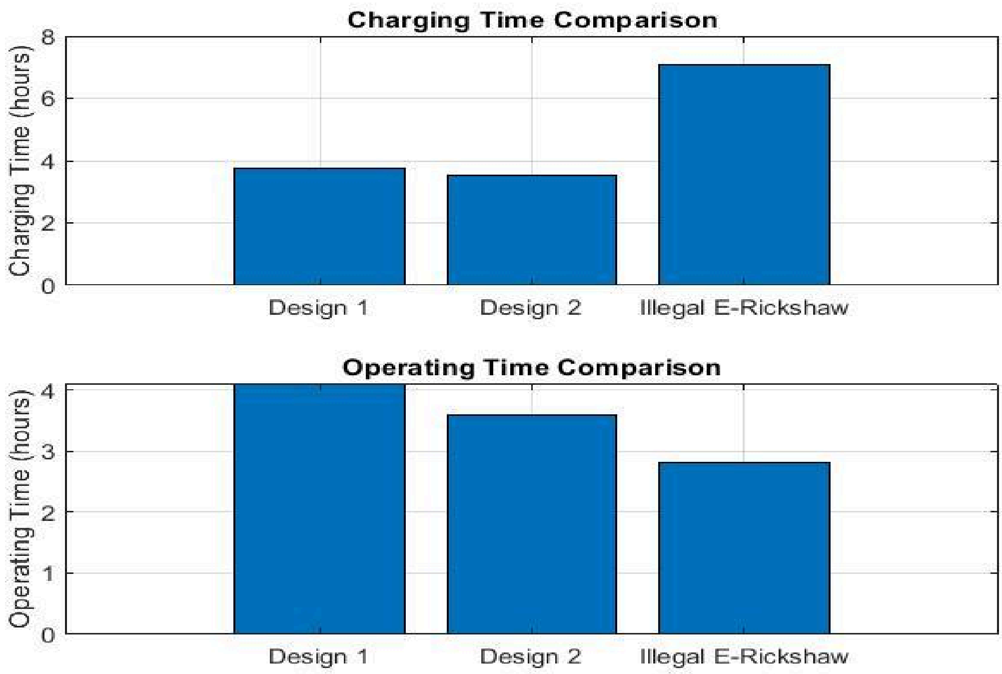

Figure 4.4 : Charging time comparison

4.4.2 Speed Regulation and Control Stability

In order to meet safety standards and local laws, the system was designed in such a way that vehicle speed was restricted to 20 km/h. To avoid the high ON/OFF switching rate around the constraint speed, the strategy was implemented as a hysteresis-based speed limiting strategy. This method helped to enhance the ability to stay in control and avoid the oscillatory action in the borderline operating conditions.

4.4.3 Acceleration Smoothness and Rider Comfort

PWM ramp rate control was introduced to make sure that there was slow application of torque during acceleration and deceleration. This greatly minimized jerks and abrupt transitional load changes, resulting in the enhanced comfort of the riders and minimized drivetrain wear.

4.4.4 Renewable Energy Contribution

The value of a renewable energy source was estimated in terms of solar charging and regenerative braking performance in real operating conditions. Even though these sources failed to substitute the primary energy provision, they were supplementary energy that enhanced the sustainability of the systems.

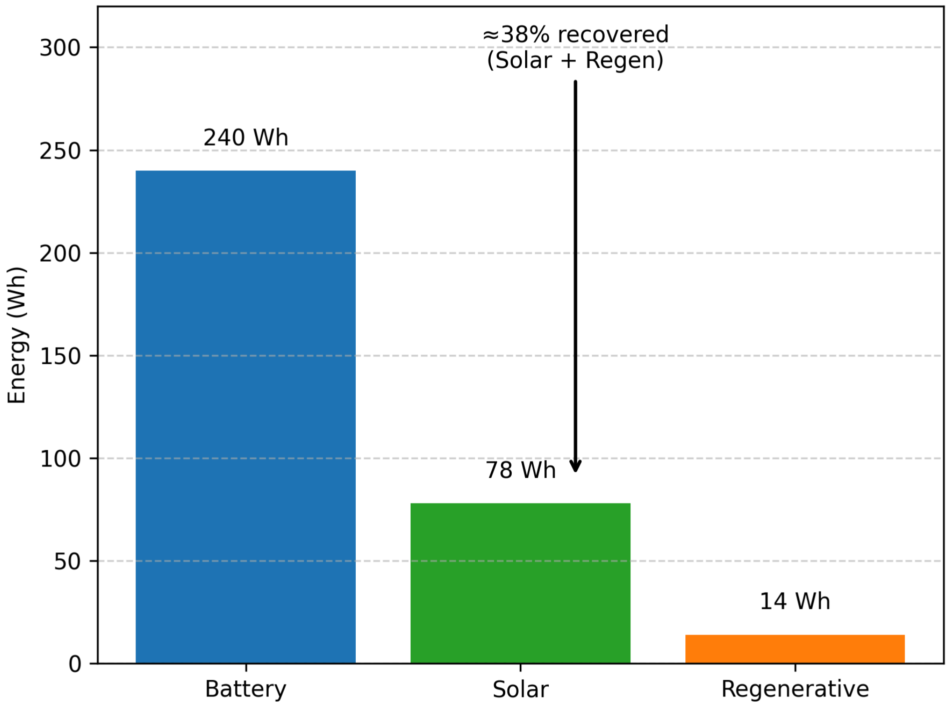

Figure 4.3: Renewable energy contribution during operation

4.5 Conclusion

The optimisation and performance validation of the suggested hybrid electric rickshaw system were covered in this chapter. Through coordinated optimisation of control algorithms and systematic evaluation of various design approaches, a workable and efficient solution was created. Performance evaluation results confirmed improvements in energy efficiency, battery utilization, system stability, and rider comfort. The validated design meets the defined specifications and provides a reliable foundation for final hardware implementation.

CHAPTER 5: COMPLETION OF FINAL DESIGN AND VALIDATION [CO8]

5.1 Introduction

This chapter is a full hardware implementation of the proposed hybrid electric rickshaw system that was designed in the FYDP-C period. Having chosen and optimized Design Approach 1 during the design phase, the system was implemented physically and connected with an existing electric rickshaw platform. However, for the ease of project implementation, the prototype used a scaled down component specification. This improved component availability, budget limitation, subsystem integration. The implementation is aimed at ensuring smooth interaction of the battery, motor, control electronics, pedal assist system, solar charging unit and regenerative braking mechanism.

The system is reliable in the real world urban environment and in the ability to freely switch between the traditional market control and the proposed custom control architecture.

5.2 Completion of final design

5.2.1 System Architecture Overview.

This system architecture has three major subsystems:

- ➔ Control Subsystem.
- ➔ Power Management Subsystem.
- ➔ Mode Selection and Safety Subsystem.
- ➔ Regenerative Braking Subsystem.

The subsystems are all connected to provide efficient propulsion, safe operation, as well as energy recovery.

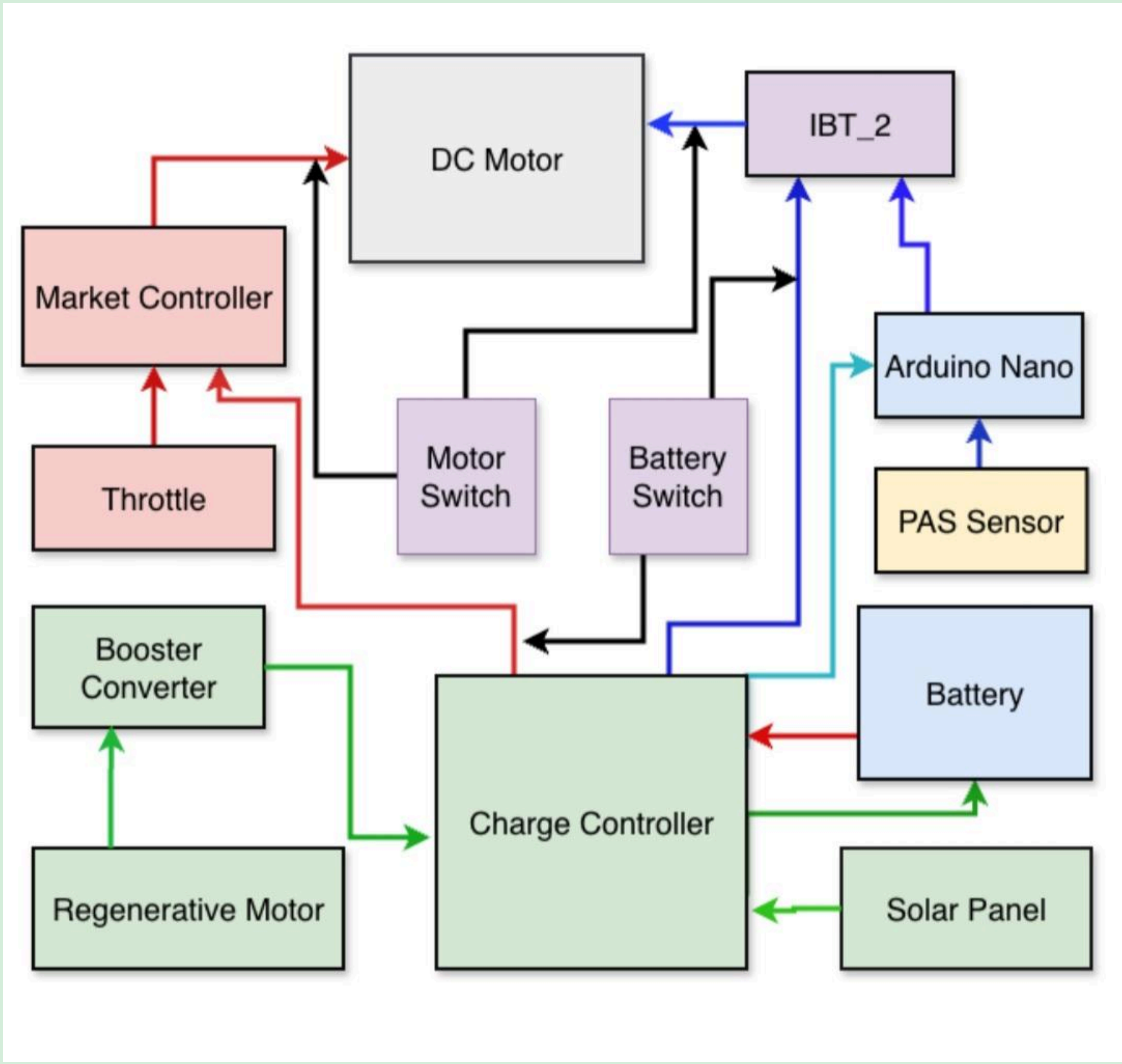

Figure 5.1: General hardware design of the hybrid electric rickshaw system.

5.2.2 Arduino-Based Control Unit

The Arduino Nano is the main control board of the custom propulsion mode. It takes input signals on the Pedal Assist Sensor (PAS), calculates cadence data and produces PWM control signals to the motor driver. The reason why the microcontroller was chosen was because it is very small in size, consumes less power and has enough computing power to operate real-time control functions.

Some of the most important functions applied in the Arduino are:

- ➔ Signal gathering and filtering of PAS.
- ➔ Cadence calculation
- ➔ Predicts Torque and assists scaling.

➔ PWM (Pulse Width Modulation) Generation to Control The Motor.
➔ Eliminating speed and logic of safety.

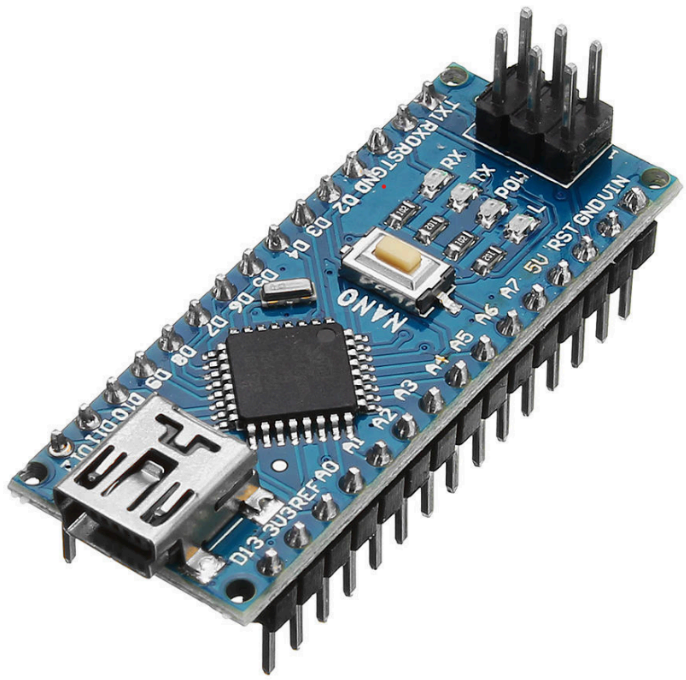

Figure 5.2 : Arduino Nano (Microcontroller)

5.2.3 Motor Driver Integration

The IBT-2 motor driver was utilized to couple the Arduino Nano and the DC motor. The motor of the electric rickshaw needs to be operated at high current, which is supported by the driver and provides a smooth control of torque with the help of PWM signals.

The Arduino uses a PWM signal to the control pins of the motor driver to guarantee safe operation when the motor is being switched on and off. The motor is controlled by enabling signals to guarantee safe operation of the motor. Direction was controlled to move forward because it was not possible to reverse in this implementation.

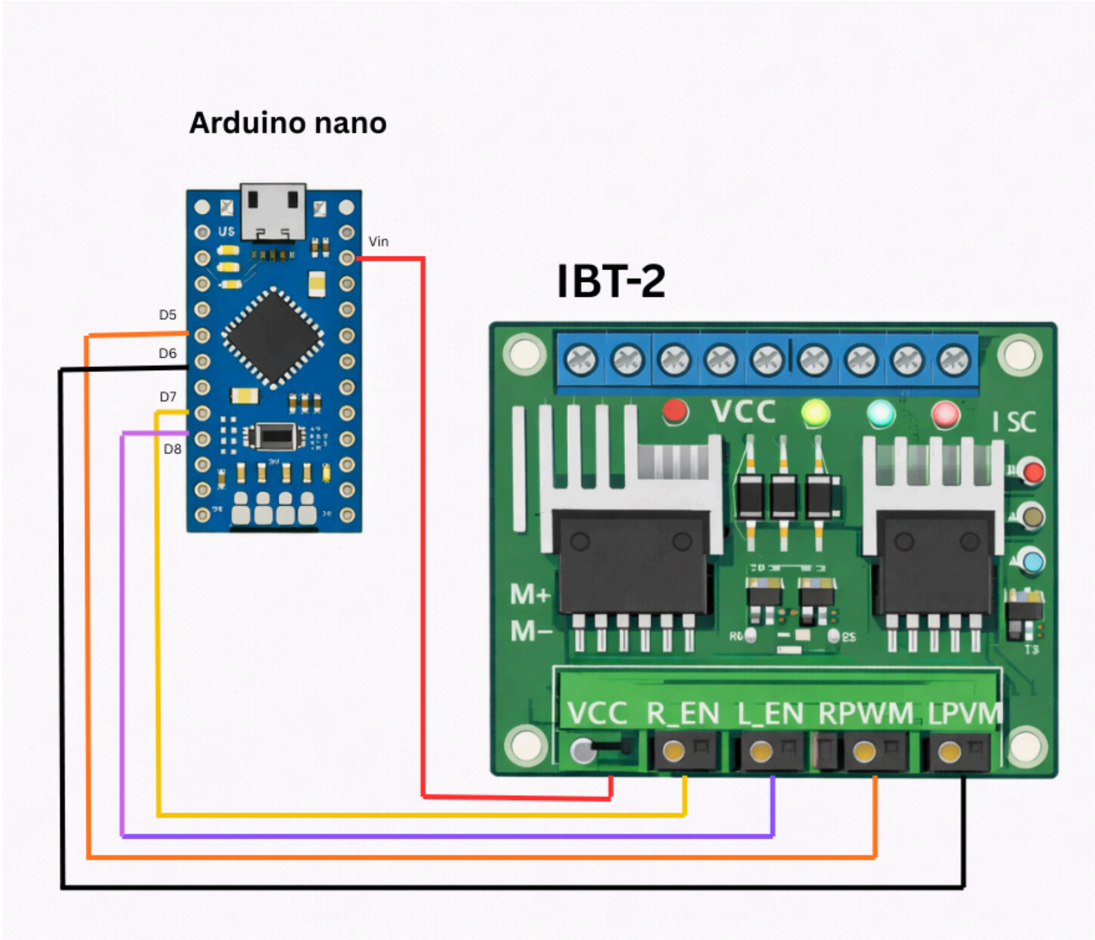

Figure 5.3 : Arduino and IBT-2 connections.

5.2.4 DC Motor Integration

The propulsion motor was a 24 V, 250W DC motor. Depending on the operating mode that is chosen, the motor is fed via the market controller or the IBT-2 driver. The problem of back-feeding or damage of the motor by having more than one controller electrically connected to the motor at a time was avoided.

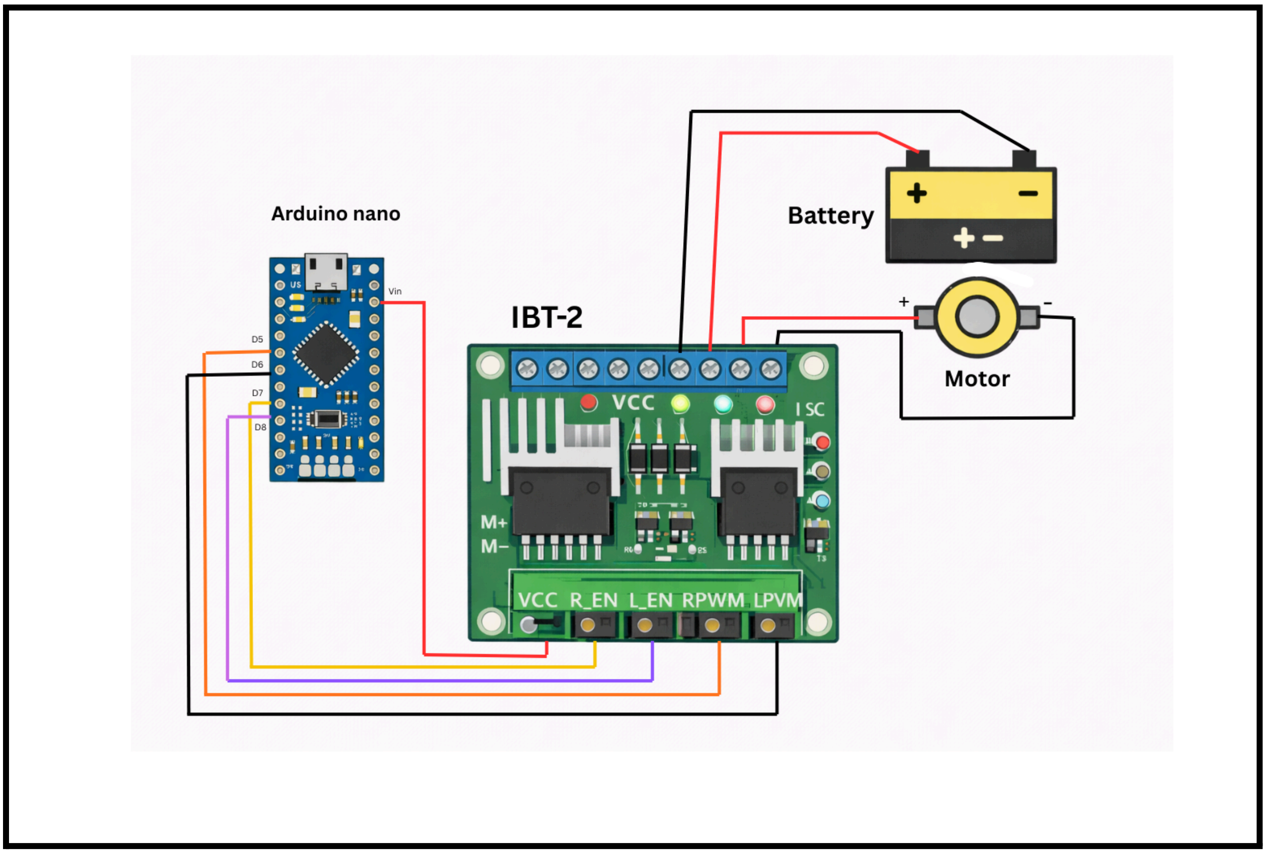

Figure 5.4: The Arduino Nano to IBT-2 motor driver with Battery and Motor connection.

Figure 5.5 : DC Motor Hardware Setup

5.2.5 PAS Hardware Installation

PAS is composed of a magnetic disc attached to the crankshaft and a hall sensor located to sense the magnetic pulses when a pedal is being used. The sensor generates a low-voltage signal as a pulse that is proportional to the speed of rotating the pedals.

The PAS was supplied directly off the 5 V supply of the Arduino and guaranteed a stable operation and an easy wiring procedure.

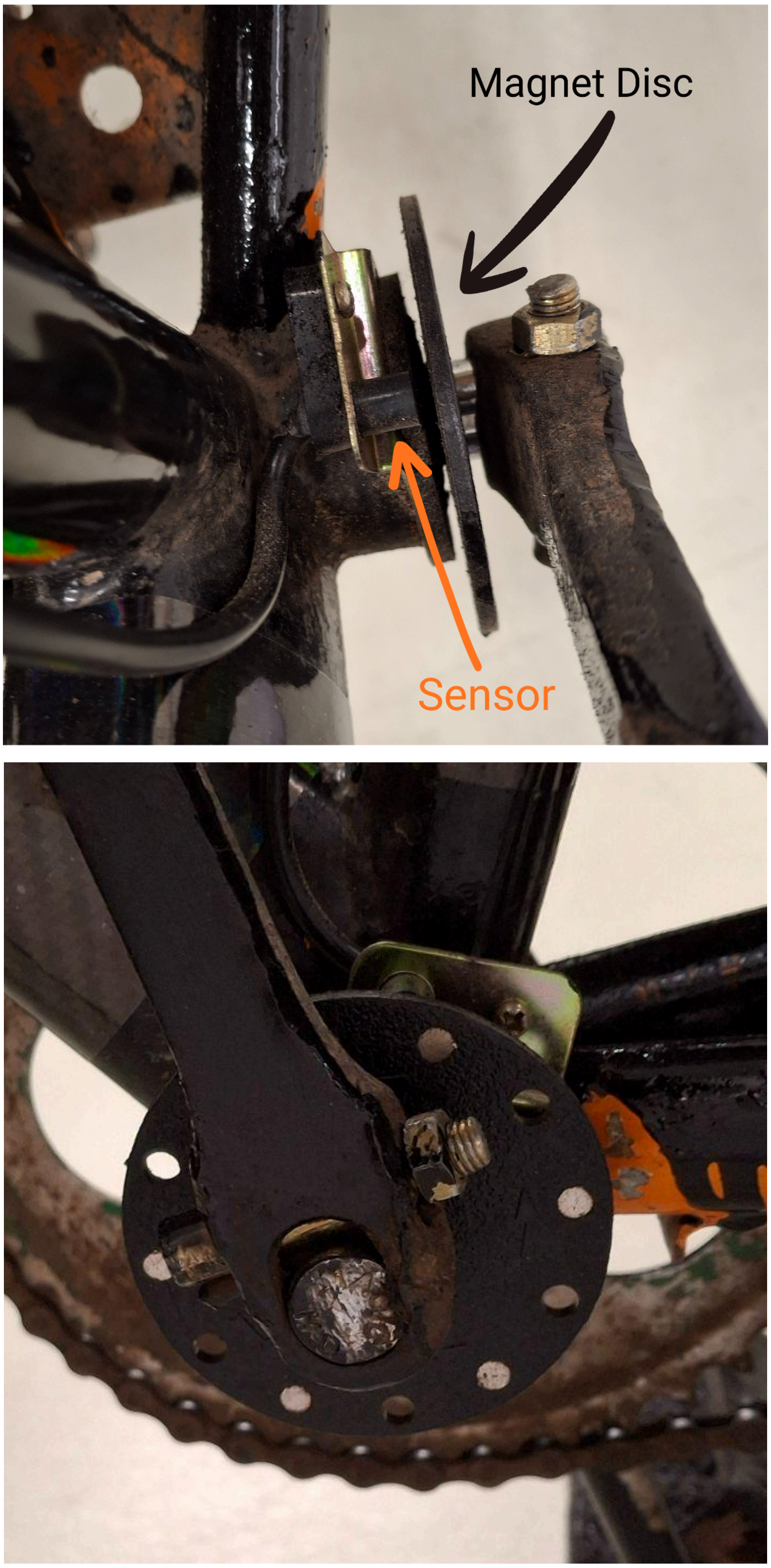

Figure 5.6 : PAS hardware installation (top view and side view)

The PAS signal was passed on to an analog input pin of the Arduino Nano. Pulse detection on the basis of oversampling and threshold was applied to accurately identify pedaling events in low cadence. To eliminate false triggering caused by noise debouncing logic and hysteresis were used.

5.2.6 Battery Pack Integration

The main storage of energy is a 24 V battery pack. The battery gives power to the propulsion motor, control electronics and auxiliary systems. During the testing process, battery voltage and current were measured so as to analyze the workings of the system and be able to validate energy calculations.

The battery was intended to be recharged in three different sources:

- ➔ Grid charging (end of day)
- ➔ Solar charging (when in operation)
- ➔ Regenerative braking (during braking action)

5.2.7 Solar Charging Integration

The system was fitted to a 40 W solar panel which acts as an auxiliary charging source. To make the charging process safe, the panel was linked to the battery via an appropriate charge controller. Operation under the sun system helps to save on net battery discharge and grid charging requirement in daylight.

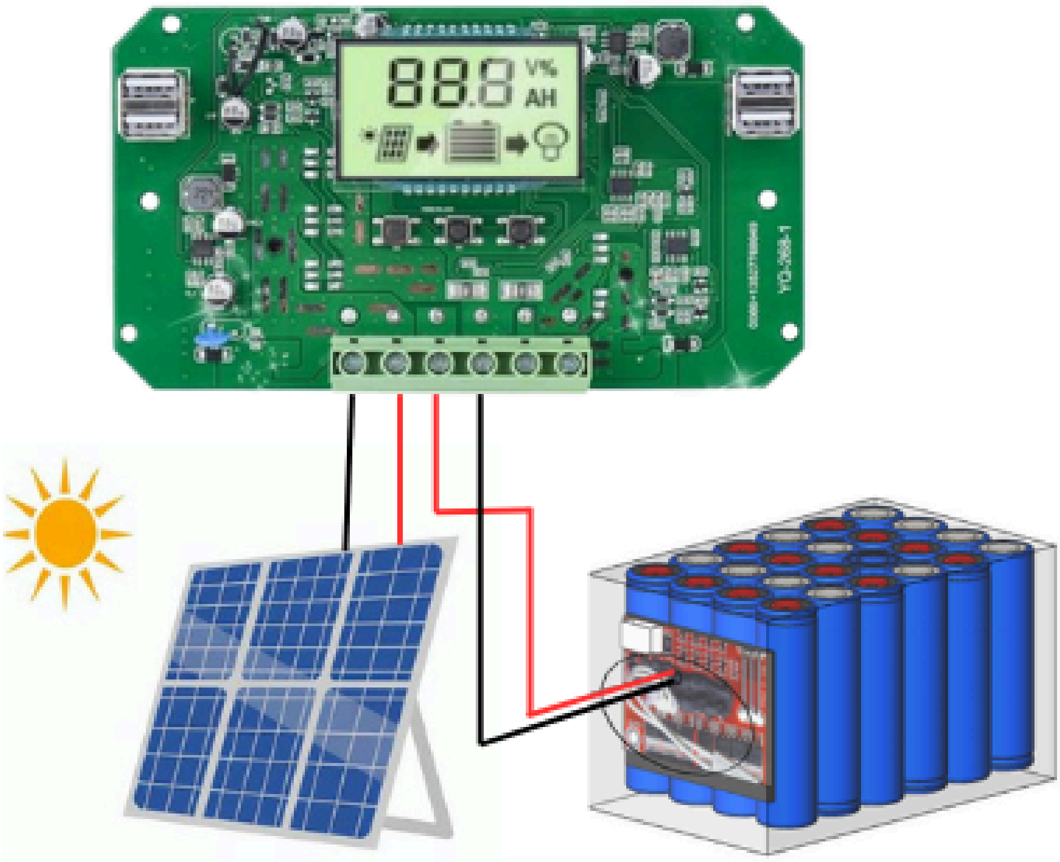

Figure 5.7: Solar charging integration with battery

Figure 5.8 : Hardware Solar panel Installation

5.2.8 Regenerative Braking System.

The regenerative braking system involved a second 12 V DC motor which was mechanically coupled to the rear wheel during braking. When the rear brake is released, the DC motor will work like a generator, and electrical energy will be generated and sent towards the battery with suitable circuitry.

The output of the DC motor is not constant and might give an unexpected voltage spike. For safely charging the battery we added a booster converter which will give a constant voltage output of **24.9V** to charge the battery. Actual energy recovery was confirmed by a greater value of measured regenerative voltage exceeding battery voltage when braking was taking place. This technique was chosen because it is easy and most appropriate in low speed vehicles.

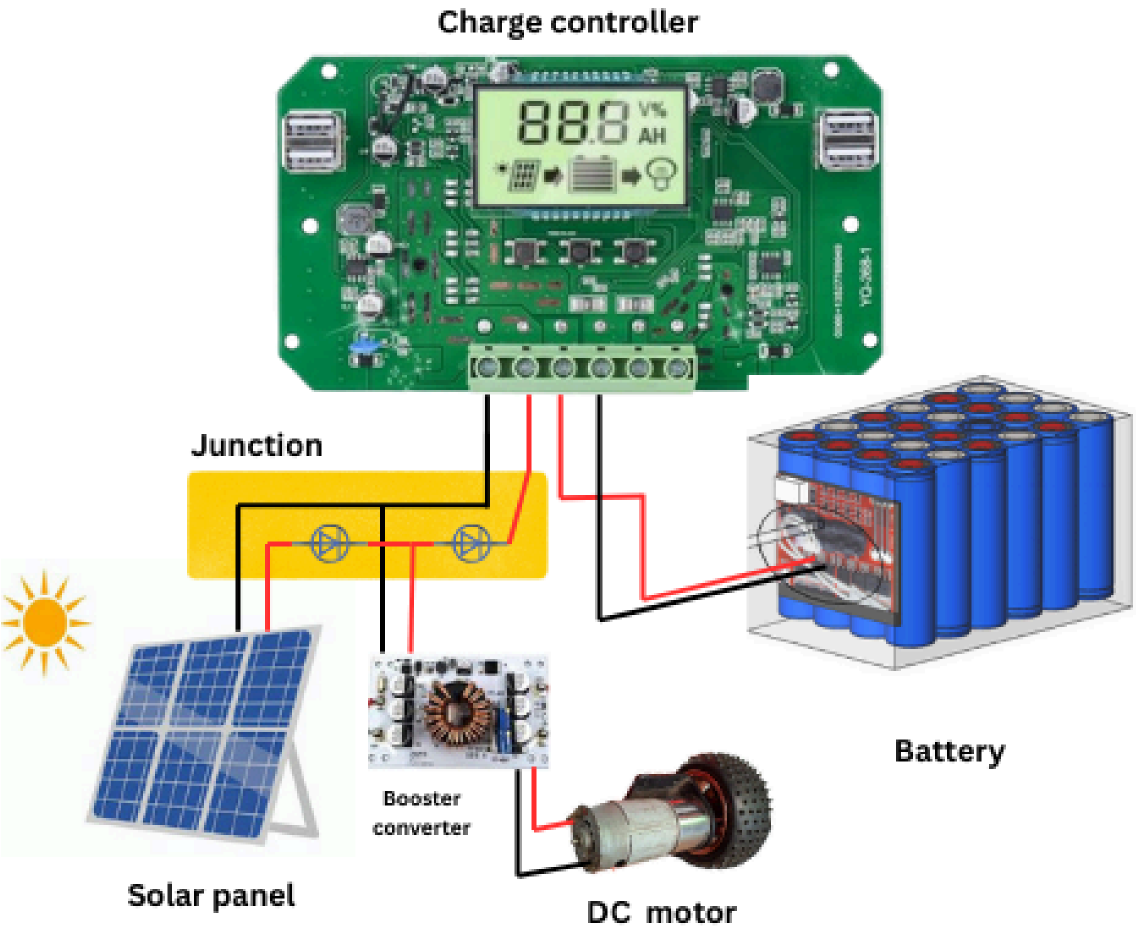

Figure 5.9: Regenerative braking process when brakes are operated on the rear wheel.

Figure 5.10 : Regenerative Hardware Subsystem

5.2.9 Mode Selection and Switching Mechanism.

Three-Mode Operation

The system has three different operating modes which are operated through two three position switches:

➔ Mode 1 - Market Controller Mode:

  The conventional market controller is linked to battery / motor, and throttle-based control can be performed.

➔ Mode 2 - Hybrid Control Proposed Mode:

The Arduino-based PAS control system is attached to the battery and motor to allow the pedal-assisted functionality with renewable integration.

➔ Mode 3 - System Isolation Mode:

The battery and motor are electrically separated to be safe or to maintain or to be charged-only.

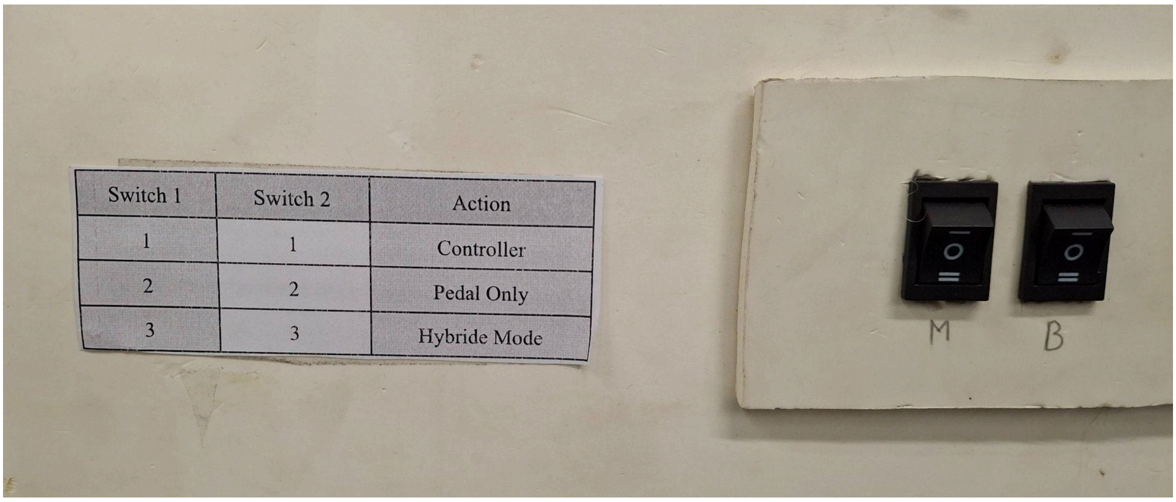

Figure 5.11 : Mode switching logic and power routing (M = Motor and B = Battery)

5.2.10 Safety Considerations

Isolation between the various modes was carried out using electrical isolation to avoid short circuiting, and clashing of controllers. Correct fusing and safe wiring was observed to improve safety and reliability of the system.

5.3 Evaluate the solution to meet desired need

System Testing and Data Verification.

Brackets, cable ties and insulating materials were used to ensure all the parts were attached firmly to the rickshaw frame. Wiring was done in such a way that it would cause minimum mechanical stress and electric interference. No-load and load testing was carried out to ensure that all subsystems were operating properly.

5.3.1 Experimental Data Collection

- Battery voltage and current were measured using a digital multimeter during operation.
- PAS sensor output was verified by measuring analog voltage variation during pedaling.
- Motor response was observed under both market controller and custom Arduino-based control.
- Regenerative motor output voltage (~24.1V) was measured during braking engagement.
- Solar panel open-circuit and loaded voltage were measured under sunlight.

5.3.2 Manufacturer & Datasheet-Based Data

- Battery rating: 24V, 10Ah (energy capacity = 240 Wh).
- Solar panel rating: 40 W (used with average efficiency factor).
- DC motor power and controller specifications collected from vendor documentation.

5.3.3 Solar Energy Calculation

Effective solar power = 40 W × 0.65 ≈ 26 W
Operating duration ≈ 3 hours
Solar energy contribution = 26 × 3 = 78 Wh

5.3.4 Regenerative Braking Calculation

Vehicle mass ≈ 300 kg, average braking speed ≈ 15 km/h (4.17 m/s)
Kinetic energy per braking event:
$E = 0.5 \times m \times v^2 = 0.5 \times 300 \times 4.17^2 \approx 2600\ J \approx 0.72\ Wh$
Assuming 20–30 braking events and 40% efficiency:
Recovered energy ≈ 0.72 × 25 × 0.4 ≈ 7.2 Wh (rounded conservatively)

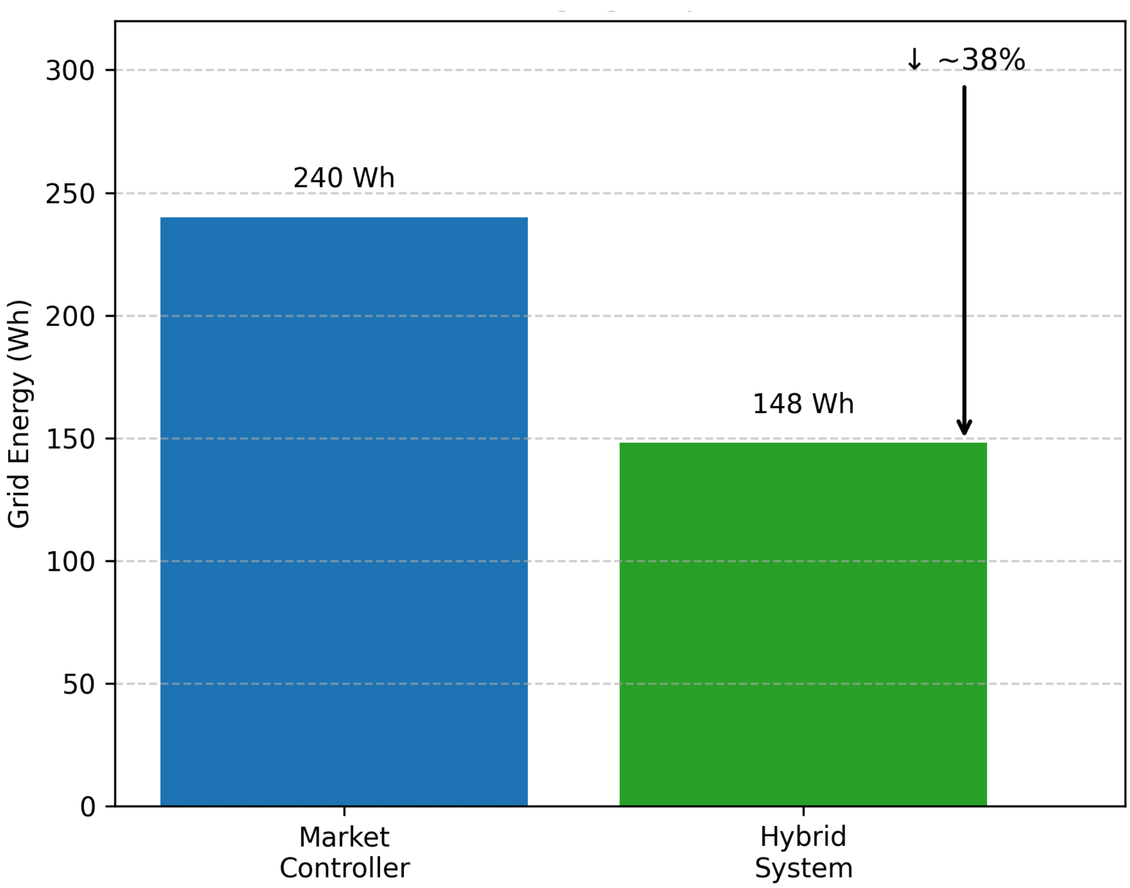

Figure 5.12 : Grid charging requirement

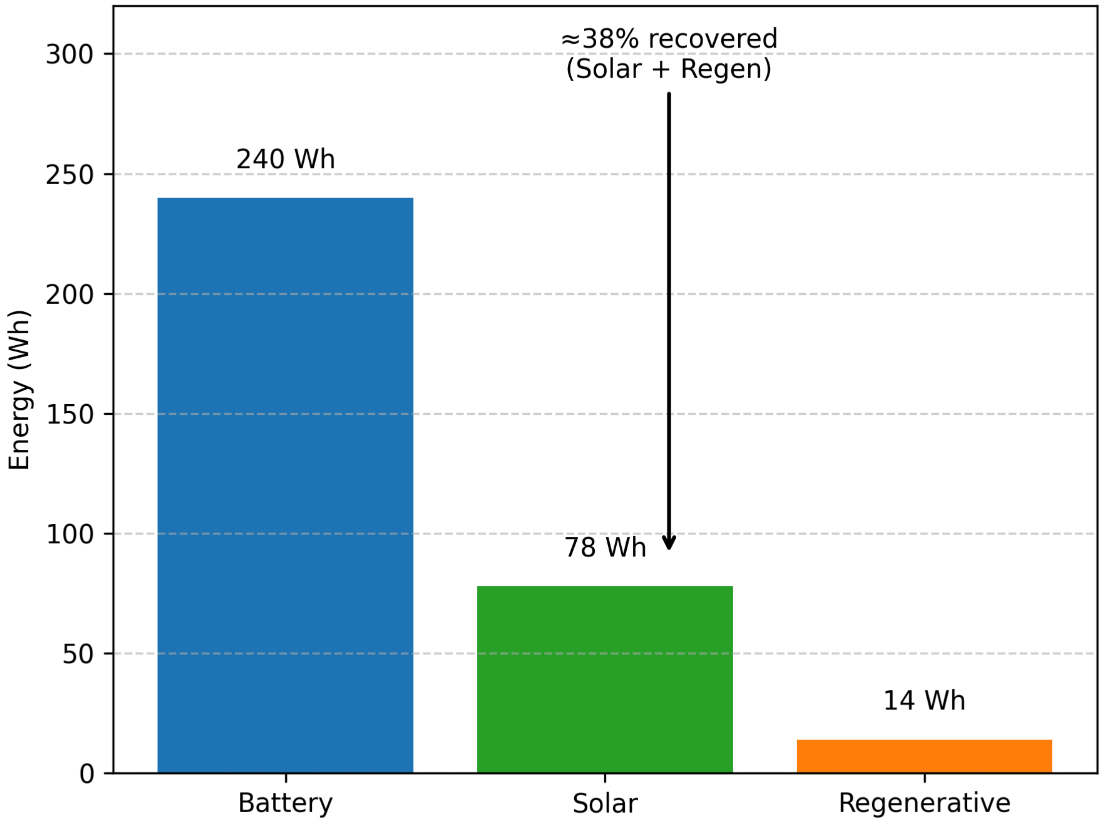

Figure 5.13 : Energy Consumption

5.3.5 Driving Range Estimation

Market controller range = 45 km using 240 Wh
Energy per km ≈ 240 / 45 ≈ 5.33 Wh/km
Hybrid system total energy ≈ 240 + 78 + 14 ≈ 332 Wh
Estimated range ≈ 332 / 5.33 ≈ 62 km

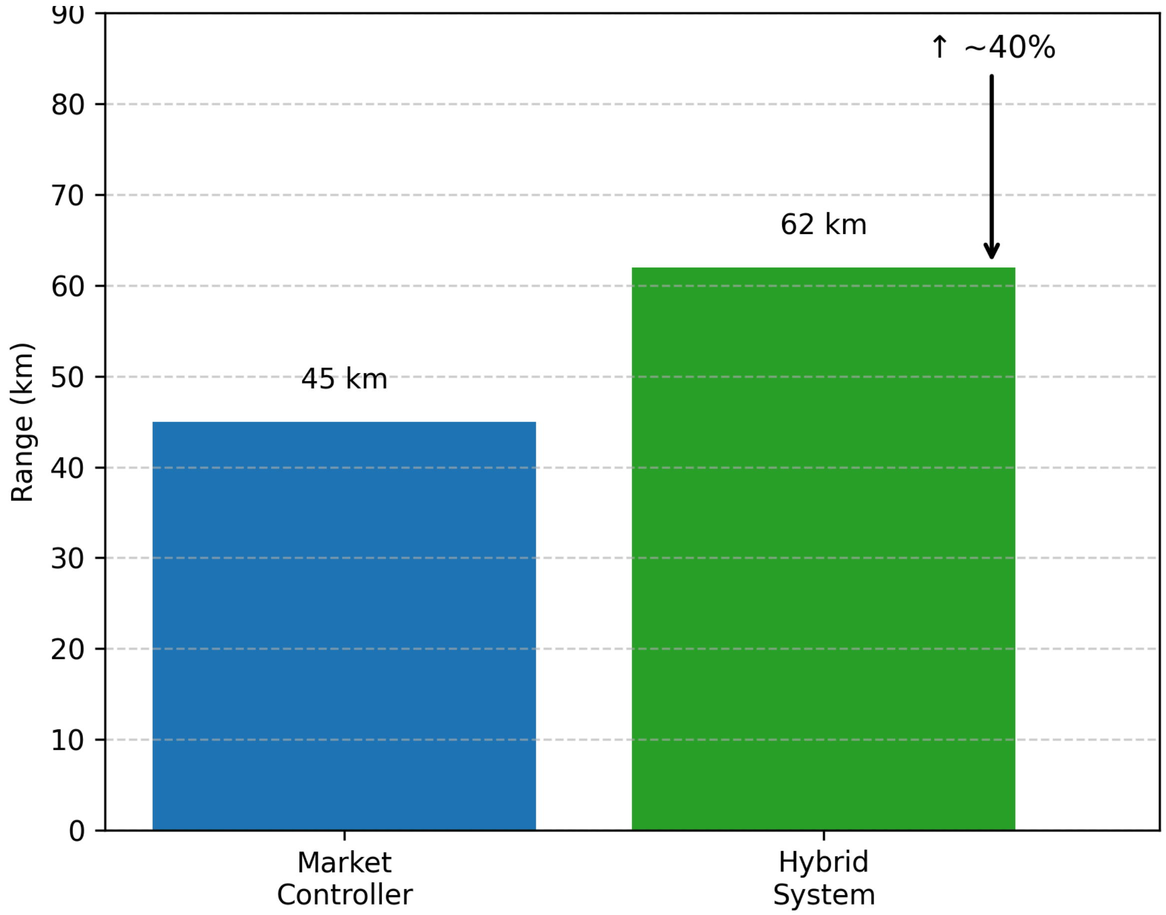

Figure 5.14 : Driving Range Comparison.

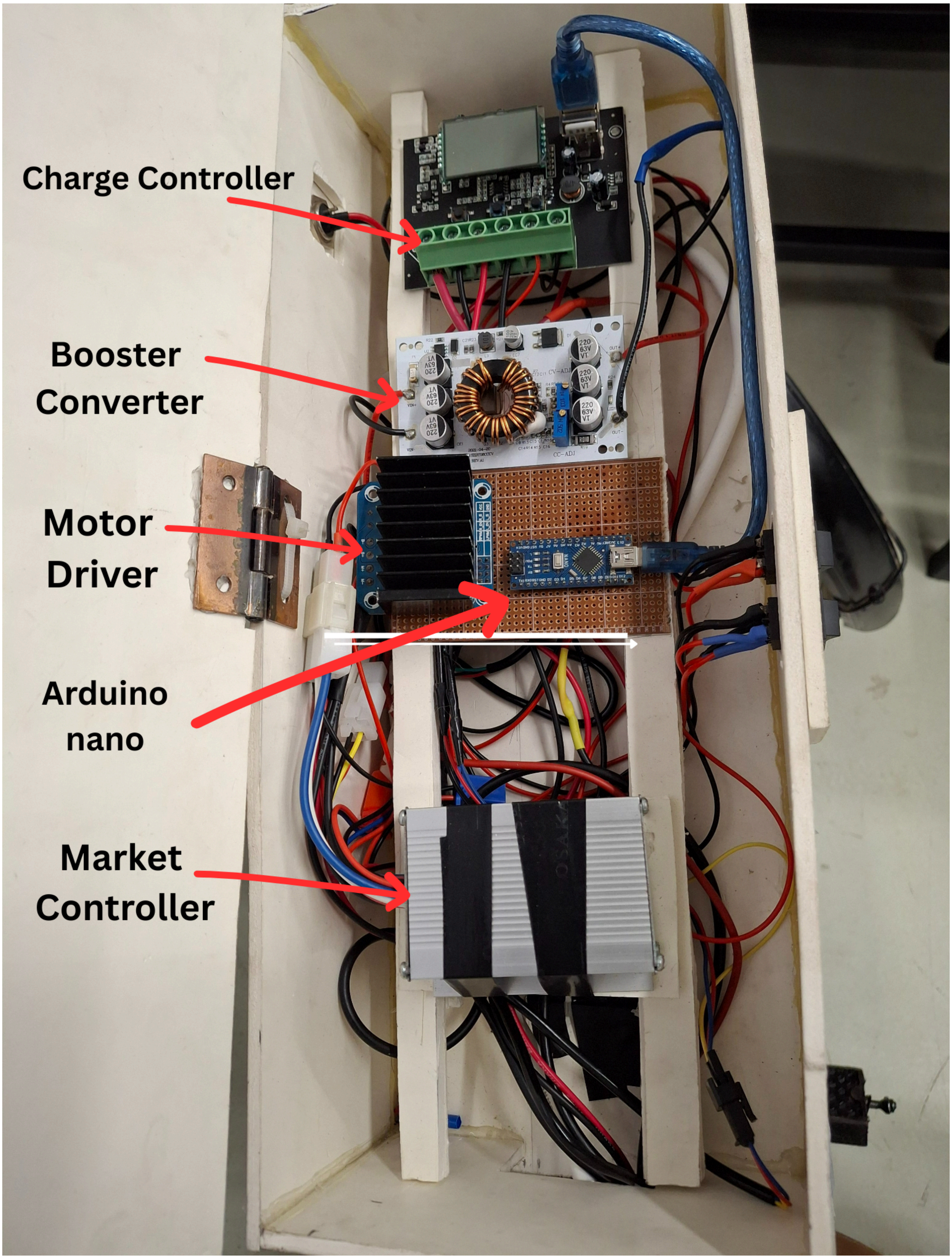

Figure 5.15 : Integrated Subsystem.

Figure 5.16 : Full Hardware Implementation

5.3.6 Implementation Challenges

The system had a number of difficulties that were experienced in its implementation. These were noise in the signals of the PAS sensor due to low pedaling cadence, the troubles in adjusting the PWM parameters to obtain smooth and stable motor response, mechanical alignment problems of the regenerative motor, and numerous power lines in the system which were hard to manage. Painful trial-and-error, meticulous development of the control software, and adjustment of hardware with the required changes, led to the stabilization of the system and achieved the stability of its functioning.

5.4 Conclusion

The proposed system of a hybrid electric rickshaw was experimentally proven to be practically feasible by the means of the integrated hardware implementation of the proposed system that incorporated pedal-assisted propulsion and solar power harnessing, as well as regenerative braking. The system was to co-exist with the already available market controllers without any interference thus being compatible and easy to adopt. The fact that the completed integration justifies the design decisions in the previous chapters and proves that the system could be implemented with the locally available components without being overly complex should be viewed as a confirmation of the fact that the implementation process should not be overly complicated. This application provides a credible field on specific performance assessment and experimentation, which are discussed in the following chapter.

CHAPTER 6: IMPACT ANALYSIS AND PROJECT SUSTAINABILITY [CO3, CO4]

6.1 Introduction

6.1 Introduction

The engineering solutions developed to be used in the actual world ought to undergo beyond technical performance in order to understand how they will impact the society, the environment and sustainability. When it is applied to the case of Bangladesh, the urban transportation networks are linked with the problems of public safety, the lack of energy, environmental pollution, and socio-economic constraints. Electric rickshaws can be cleaner than those fuelled by fossil fuel, but still, they cause overloading of the power grid in the country, and create safety, affordability and sustainability challenges.

The chapter talks about how the specified hybrid electric rickshaw system has impacted the society, health, safety, legal and cultural problems and also evaluates the sustainability of the solution within the environment. Analysis follows the performance criteria of the specific Program Outcomes in relation to CO3 and CO4 of the course.

6.2 Assessment of the Impact of the Proposed Solution (CO3)

6.2.1 Societal Impact

Electric rickshaws are a vital mode of transport in Bangladesh, which is used to move across the short distances in the urban centers, particularly by the low- and middle-income people. The hybrid system will help in contenting the operating costs by reducing the amount of grid electricity used and this will definitely impact the rickshaw drivers directly by augmenting their net earnings per day. Besides, the system enhances operational reliability by increasing the range of drive and minimizing the frequency of charge.

The addition of the feature of pedal assistance will encourage moderate physical activity, having a positive effect on the health of the driver without any undue fatigue. Such balance between human effort and motor aid is in line with the cultural acceptance of the use of cycles as a mode of transport in Bangladesh.

6.2.2 Health and Safety Impact

In the overcrowded urban roads in Bangladesh, safety is a major issue of concern. The suggested system will have speed limits of 25 km/h. Which will minimize the chances of accidents and improve the safety of both the riders and pedestrians. PWM ramping of motor control provides smooth motor control reducing sudden acceleration causing mechanical stress and loss of control.

Healthwise, less reliance on electricity generated in fossil fuels helps in reducing air pollution, which indirectly leads to the enhancement of the health of the people in the crowded city regions.

6.2.3 Legal and Regulatory Considerations

Even though the rickshaw is run under a partially regulated setting in Bangladesh, the issue of speed restriction and power management is required to ensure that the current informal rules set by the local authorities are followed. The speed control system applied will make sure that the vehicle works within the acceptable safety limit, which facilitates compliance with regulations.

Furthermore, minimization of illegal or unnecessary grid electricity power consumption in charging batteries solves the problems of unauthorized power usage, which is a major problem in urban Bangladesh.

6.2.4 Cultural Considerations

Rickshaws have an urban culture within Bangladesh. The offered system retains the classic pedaling system and supplements it with the new electrical support. This will guarantee that cultures accept it and will not oppose it due to full automation or new technology.

6.3 Evaluation of Sustainability and Environmental Impact (CO4)

6.3.1 Environmental Impact

Fossil fuels like natural gas and diesel are important in production of electricity in Bangladesh. Hence, minimizing the use of grid electricity will lead directly to a reduction in the number of carbon emissions. The suggested system will also decrease the energy consumption of the grid by about 38 percent which is a quantifiable decrease in indirect greenhouse gas emissions.

Solar energy also increases environmental sustainability by using renewable energy throughout the day. Also, there is regenerative braking that gathers the energy that otherwise goes to waste during frequent braking in stop and go traffic situations.

6.3.2 Sustainability of the Engineering Solution

The proposed system is proved to be sustainable by:

- ➔ Less depth of discharge of battery.
- ➔ Extended battery lifespan
- ➔ Reduced grid charging rate.
- ➔ Better general energy use efficiency.

The system can minimize the environmental and economic cost in the long run by integrating human effort, renewable energy and energy recovery, which makes it suitable to be deployed in Bangladesh on a sustainable basis.

6.4 Conclusion

The chapter gauged the effect and sustainability with the suggested hybrid electric rickshaw system in the societal, health, safety, legal, cultural, and environmental environment of Bangladesh. The analysis also demonstrates that the proposed solution does not only enhance the technical performance but also corresponds to the aims of sustainable development because it decreases the reliance on the grid, promotes safety, and environmental responsibility. The system is highly compliant with CO3 and CO4 and as such, it is a good engineering solution to the use of urban transport in Bangladesh as it is sustainable.

CHAPTER 7 ENGINEERING PROJECT MANAGEMENT [CO11, CO14]

7.1 Introduction

Engineering project management is very important for successfully developing a complex engineering design project in a given time. Also cost and resource limitation. Final Year Design Project (FYDP) consists of several stages namely problem identification, system design, component selection, hardware implementation, software development, testing, documentation and presentation. These activities required effective planning, coordination and teamwork in order to handle them effectively.

The chapter brings out project planning, project implementation, project monitoring, team work and communication methods because it illustrates how the engineering project management concepts were applied during the development of the hybrid electric rickshaw system.

7.2 Definition, Planning, and Management of the Engineering Project

The project was launched through a clear definition of the project scope, objectives and expected outcomes which were based on the identified engineering problem. Different stages were divided into parts based on the FYDP-P, FYDP-D and FYDP-C milestones to create an efficient project plan. Every stage had certain deliverables, schedules and roles.

Project planning included the selection of appropriate hardware devices, control algorithm design, design and development of system architecture, as well as the development of testing protocols. A timeline was drawn to make sure that enough time is available to validate the design, develop the prototype, debug the code and test its functionality. Such risk factors as financial limitations, integration problems and component shortages were identified at an early stage and addressed through contingency planning.

Regular progress tracking, allocation of tasks as well as review of milestones were used to manage the project. Team meetings were done as a way of evaluating work done, and deliberating on technical problems and rescheduling where required to achieve work completion on time.

7.3 Evaluation of Project Progress

The project progress was consistently evaluated against the scheduled time and project deliverables. The project was in the assembly phase, the software development, system integration and testing processes were evaluated on a weekly basis. Any variation in the scheduled schedule was studied and corrective measures were taken in time.

The evaluation was carried out by functional testing of subsystems such as Pedal Assist Sensor (PAS), motor driver control, solar charging, frame structure and regenerative braking. Progress was also observed such as writing reports and preparing presentations to ensure that documentation was within the requirements of the academics.

This systematic monitoring demonstrated the effective project management skills needed by CO11 because it made sure that the project milestones were achieved within the stipulated time.

7.3.1 Teamwork and Individual Contribution

The project was conducted in an interactive team work whereby every member took part as per the duties he/she was assigned. As part of the duties team members were supposed to undertake based on their strengths, there were hardware design, control algorithm development, system integration, data analysis and documentation among the others.

Frequent meetings, reports on progress and joint problem-solving meetings served to keep the communication efficient. The members of the team are involved in research activities, collection of data, preparation of a report and presentation of the report consistently. Sharing of responsibilities and peer coordination is a guarantee of smooth workflow and timely execution of tasks.

To fulfill the requirements of CO14, the team also conducted peer evaluation in order to determine the contribution of the individual and the effectiveness of working together.

7.4 Conclusion

This chapter showed how the engineering project management principles could be applied to plan, execute and complete the hybrid electric rickshaw project. The project was successfully implemented according to the set timeframe with the help of a well-organized plan, constant evaluation of the progress, and the cohesive teamwork. The project indicates good project management skills, personal responsibility and teamwork, which is the targeted learning outcomes of CO11 and CO14.

CHAPTER 8: ECONOMICAL ANALYSIS [CO12]

8.1 Introduction

The viability of the economy is an important aspect of scrutinizing the viability and uptake of the engineering solution, especially in the third world countries, like Bangladesh where cost sensitivity is a significant issue. In the case of the electric rickshaw operators, the operating cost, maintenance cost, and charging cost have a direct effect on the daily income. Thus, it is critical to assess the economic and financial factors of the suggested hybrid electric rickshaw system.

The chapter provides the economic analysis of the proposed system in detail such as cost estimation, cost-benefit analysis, and a long-term financial implications analysis. The analysis is compatible with CO12 of course outcomes and performance standards of the program outcome.

8.2 Economic Analysis of the Proposed System

8.2.1 System Cost Estimation

The overall price of the intended hybrid system comprises the control electronics, energy harvesting devices as well as the hardware to support the system. The only part that was not found locally in the Bangladeshi market was the pedal assist sensor. This guarantees an accurate cost estimation.

Table 8.1 : Cost analysis of implemented design model.

Category	Cost (BDT)
Motor Set	4,700
Battery	5,300
Solar Panel + Controller + Wiring	1,200
PAS Sensor	880
Arduino Nano	363

IBT-2 Motor Driver	870
Mechanical Components (Cycle, fittings)	3,140
Electrical Components (switches, wires, converter etc.)	2,290
Tools & Measurement (Multimeter, soldering, PVC board, zip ties)	1,050
Speedometer	220
Miscellaneous	1,500
Total	**21,513**

The total additional system cost was kept relatively low compared to the overall cost of a conventional electric rickshaw, making the solution economically accessible.

8.2.2 Operating Cost Consideration

When operated in a typical manner with a market controller, the battery becomes completely charged with the grid following daily use. In the suggested system, the pedal assistance, solar charging and regenerative braking will reduce the quantity of grid electricity needed to recharge the battery.

According to experimental assessment:

- ➔ The energy needs on the grid was cut by about 38 percent.
- ➔ Daily power prices also dwindled.
- ➔ The depth of battery discharge was minimized, which minimized the long-term replacement cost.

8.3 Cost–Benefit Analysis

8.3.1 Cost Factors

The proposed system costs will involve:

- ➔ Start-up hardware cost.
- ➔ Installation and integration effort.

➔ Minor maintenance costs

These expenses are one time cost.

8.3.2 Benefit Factors

The advantages of the suggested system are:

➔ Less electricity grid use.
➔ Lower daily charging cost
➔ Extended battery lifespan
➔ Improved driving range
➔ Longer intervals between maintenance.

In the long-term operation, the financial gains are greater than the initial investment.

8.3.3 Payback Consideration

Considering the decline in daily consumption of electricity and longer battery life, the system will pay off in the long run. In the case of rickshaw operators in Bangladesh, even simple day-to-day savings can add up to huge financial gains in months of business. Depending on the average income and living cost in Bangladesh the initial investment cost can be recouped after 8 to 12 months time.

8.4 Evaluation of Economic and Financial Aspects

8.4.1 Affordability for Local Operators

Affordability was the main goal of the proposed system. The system is cost-effective to the small-scale operators and owners using cheap locally sourced components.

8.4.2 Long-Term Financial Sustainability

Less battery stress means less battery replacement and this is a significant saving in terms of cost. The regenerative braking and the solar energy to restore power to the battery during service also contributes to the increase of the range and decreases the reliance on the grid. This safeguards the operators against the increase in electricity tariffs.

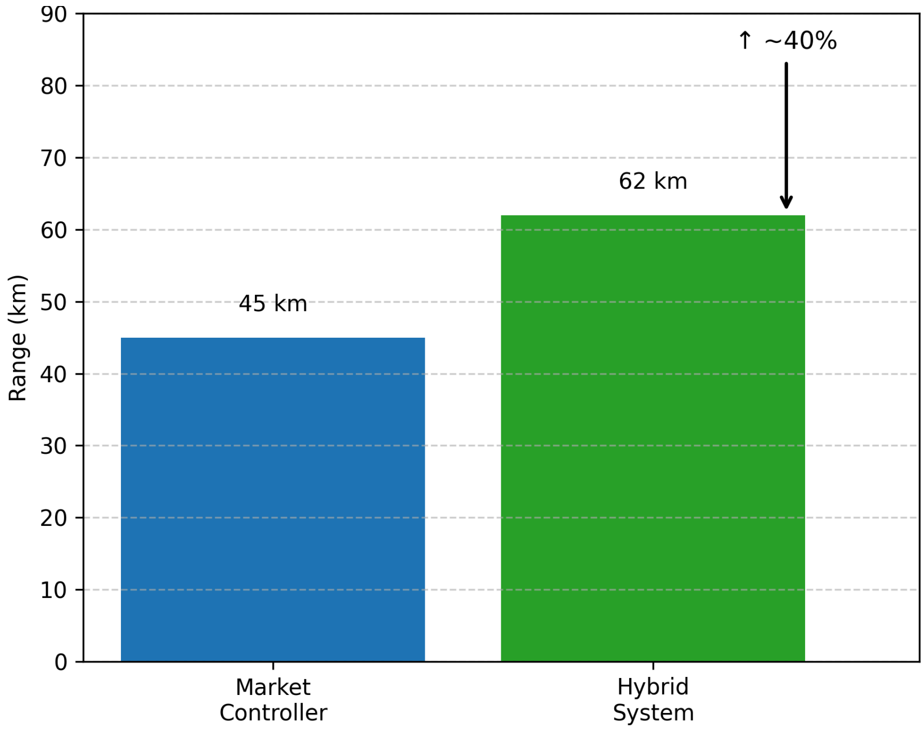

Figure 8.1 : Driving Range Comparison.

8.5 Conclusion

This chapter presented a comprehensive economic analysis of the proposed hybrid electric rickshaw system. The cost–benefit evaluation demonstrates that the system is economically feasible and financially beneficial in the context of Bangladesh. By reducing grid electricity consumption, lowering operational costs, and extending battery life, the proposed solution offers a sustainable and cost-effective improvement over conventional electric rickshaw systems. The analysis confirms compliance with **CO12** and supports the practical viability of the proposed engineering solution.

CHAPTER 9 ETHICS AND PROFESSIONAL RESPONSIBILITIES [CO13, CO2]

9.1 Introduction

Ethics and professional responsibility are the foundation of the engineering practice particularly when solutions in engineering come directly into contact with the society, the infrastructure as well as the environment. The engineers should not just work to ensure that they get technical right, but also ensure that their designs are eco safe, socially responsible and environmentally sustainable as well as economically fair. In developing countries such as Bangladesh, ethical considerations are high in demand where the transport systems are significant in regarding day to day life, employment and total energy consumption of a nation.

The suggested hybrid electric rickshaw system has a direct effect on the safety of people, the environmental sustainability, energy consumption, and the lives of the transport workers of low-income populations. This led to ethical decision making being incorporated in all project lifecycles including conceptual design and component selection as well as the implementation, testing and performance testing. In this chapter, the author reveals the main ethical concerns of the project and describes how professional expectations were observed in regard to Course Outcomes CO13 and CO2, along with accepted guidelines of engineering ethics and professionalism.

9.2 Identification of Ethical Issues and Professional Responsibilities (CO13)

9.2.1 Public Safety and User Protection

The highest ethical requirement of any engineering work which includes transportation systems is to ensure safety of the population. Electric rickshaws are used in congested urban areas where there is limited space on the road by pedestrians, cyclists, and motorized vehicles. Any failure, uncontrolled acceleration and any malfunction of electricality can lead to severe accidents and harm.

To overcome these ethical issues, several safety-related design issues have been included in the proposed system, such as speed limit of not more than 25 km/h, fluid motor torque operation of PWM ramping, electrical separation of various operating modes and correct fusing, insulation and wiring. All these mitigate the risks that come with electrical threats, mechanical failure, and unreasonable vehicle actions. Putting safety ahead of performance improvement is a responsible engineering consideration and ethical responsibility

9.2.2 Environmental Responsibility

One of the most important ethical duties of engineers, especially in the energy type of work, is environmental protection. Even though the operation of electric rickshaws does not lead to emission of exhaust gases, their charging systems depend on heavy reliance on electricity generation in Bangladesh which is based on fossil fuels hence indirectly affecting the green house gas emission.

The suggested hybrid system will mitigate this issue by reducing the amount of grid electricity used to run the propulsion by means of pedal-assisted propulsion, use of solar energy as a renewable source of charges, and the recovery of energy by means of regenerative braking. These design solutions reduce the overall energy needs, indirect emissions, and sustainable transport in the city. The project is based on ethical guidelines of environmental stewardship and sustainability in the long run by incorporating renewable energy and energy recovery measures.

9.2.3 Honesty and Integrity in Data Collection and Reporting

The ethical engineering practice requires honesty, transparency, and accuracy in data collection, analysis and reporting. In this project, experimental data were taken through proper methods of measurement and using a conservative assumption. Reporting on the performance results and energy saving was done realistically, without exaggeration and selective presentation.

All the simulation results, observations in an experiment and calculations were cross-verified to give consistency and reliability. Limitations of the system such as a comparatively low energy recovery of regenerative braking at low operational speeds were frankly admitted. Academic honesty and professionalism are ensured through such compliance to honest reportage.

9.2.4 Social Responsibility and Equity

The drivers of the electric rickshaw in Bangladesh are mostly low-income earners and they are very sensitive to the cost of operations and maintenance. The implementation of high-technology without taking into account the cost, accessibility, and usability would pose ethical issues based on social equity.

The proposed system was developed in order to solve this problem by a means of a low-cost approach and retrofit compatible solution that utilizes locally available materials. Interoperability with available market controllers also means compatibility so that the system can be integrated without the need to replace the vehicle fully. This could be a strategy of fairness, inclusivity, and social responsibility because technological benefits can be made available to a broader population in the society.

9.3 Application of Ethical Issues and Professional Responsibilities (CO13,C02)

9.3.1 Ethical Design Decisions

Ethical considerations were a direct factor in deciding on some critical design choices during the project. The motor aid was also restricted to avoid the occurrence of reckless drivers and an emphasis was laid on speed rather than higher performance. The simplicity, reliability, and robustness were preferred to the complex solutions that may affect the safety or reliability of maintenance.

These choices indicate that the ethical responsibility was prioritized over the technical optimization per se. The system was aimed at helping the rider and not eliminating human control and causing even more risks of safety.

9.3.2 Professional Conduct During Project Development

The ethics of the professionals were observed at various stages of the project. References such as scholarly and technical were referenced appropriately, intellectual property was observed and project documentation was made transparently. The team members were honest, fairly shared responsibilities and effective in communication in research and development, and reporting.

Professional conduct by the research involved all activities of the projects in accordance with the regulations of the academic research ethics and the institutional conduct standards.

9.3.3 Applicable Standards and Regulatory Considerations

Even though in Bangladesh there are no national standards of electric rickshaws as a whole, the project was based on the engineering practices that are not subject to dispute. These are electrical safety in low voltages of DC, battery charging and battery protection regulations as well as informal speed limits usually imposed by local governments. These practices are complied with to make sure that there is safe and responsible operation of the system in the real world scenario.

9.3.4 Professional Codes of Practice

The project complies with the ethical standards and professional ethics as advocated by international professional engineering organizations, ethical codes of research, and sustainable engineering principles. These codes put importance on honesty, accountability, competence and the duty to safeguard the society and the environment.

9.4 Conclusion

This chapter included an in-depth discussion related to ethical issues and professional duties that were related to the design and implementation of the hybrid electric rickshaw system. The social responsibility, environmental sustainability, data integrity, and ethical issues associated with community safety were also discovered and managed by making purposeful design and implementation decisions.

The project can be said to have followed the professional engineering ethics of safety, affordability, transparency, and sustainability well, and achieved the stipulations of CO13 and CO2. The ethics model used in the project is that the proposed system becomes not only technically viable but also socially responsible and fit to implement in the real world in Bangladesh.

CHAPTER 10: CONCLUSION AND FUTURE WORK

10.1 Project Summary

This project successfully designed, implemented and evaluated a hybrid electric rickshaw system aimed at improving energy efficiency, sustainability and operational practicality for low-speed urban transportation in Bangladesh. The proposed system integrates **pedal-assisted propulsion**, **electric motor support**, **solar energy** and **regenerative braking** to reduce dependency on grid electricity and mitigate the environmental impact associated with conventional electric rickshaw operation.

The system was developed on a 24 V battery pack which had a nominal capacity of 2.88 kWh, and around 1.44 kWh of power was taken as usable by considering 50 percent depth of discharge. With consideration of drivetrain efficiency approximately 85%, about 1.22 kWh energy will be available on the wheels. With the addition of pedal assistance and using a compromise between the rider and the motor torque sharing, the system minimized electrical energy requirements when in operation. In general, a rider will contribute 20 percent and the motor will produce the remaining 80 percent of the total energy. Which was found to be the best trade-off between a comfortable ride and battery energy used.

An arduino based control platform was used in real time control which allowed proportional motor assistance depending on the input of motor assistance peddling to the sensor. The control mechanism involved the speed and torque regulation using PWM, ramp rate limiting using PWM to achieve a smooth acceleration and a hysteresis-based speed limiting mechanism to ensure that speed of the vehicles did not exceed 25 km/h, which was also in line with safety and regulation.
These control features guaranteed controlled operation, avoiding oscillation about the speed. reduced mechanical and electrical strain on components of the system, and limit.

The use of solar charging as a subsystem was used to provide renewable energy and added an approximate 0.3 -0.4 kWh of auxiliary energy per day in a favorable scenario after considering both environmental and conversion losses. Although solar energy was not used as the main propulsion source, but as complemented battery charging, which may reduce grid energy load and a decreased rate of charging. It further introduced regenerative braking to recycle energy during stop and go situations in the urban stop and go traffic. The system offered progressive energy recovery without affecting the braking safety, even though the recoverable energy per braking event was low because of low operating speeds.

Experiment analysis showed that there were definite performance gains compared to the traditional market controllers. The current under the battery drop during active pedalling was lower and then battery voltage drop also slowed, and better use of energy was achieved. Depending on operating conditions, the effective driving range improved as the near rate of operations went around 36-46 km and approximately over 60-70km with light pedal assisted cruising that was a great enhancement to the range and efficiency. When there was solar

contribution, grid charging energy per cycle was trimmed down to about 1.6-1.7 kWh so as to lower the effective values.
Comprehensively, the experimental and analysis findings have proved that the hybrid electric rickshaw system is technically viable, economically viable, and environmentally friendly. The system is more efficient in energy consumption, less battery drainage, makes the rider more comfortable, and also it consumes less grid electricity as compared to the current market controllers and locally available materials. The results of this project reflect an applicable route of higher electric sustainability as the operation of the rickshaw in Bangladesh offer a powerful basis to further work with the bigger implementation, higher approach to managing the energy and field experimentation.

10.2 Future Work

The proposed hybrid electric rickshaw system can be enhanced in the future by addressing the main concern of full scale implementation and the deployment of the system in the long run in commercial three-wheeler vehicles running under the real traffic circumstance within Bangladesh. Long field tests with several vehicles may be undertaken to test reliability, durability and user acceptance within long periods as well as under different environmental conditions like high temperature, humidity and peculiarity of the roads.

Designing of the regenerative braking system further may be considered to be applied on hilly landscapes and more so on areas like the Chattogram and Sylhet where topological variations provide more prospects of energy recovery. The slope estimation-based adaptive regenerative control techniques and vehicle load-based methods may be applied to achieve the highest energy capture rate without the need to sacrifice the safety and ride comfort of the braking action. The adoption of direct torque sensors or strain-based could also be introduced in the future to get more accurate measurement of rider effort. This would allow the control of the motor assistance to be more precise and the pedal-assist system to be more responsive particularly at low cadence and when there is a sudden change in the load. Besides this, monitoring and data logging can also be added using IoT to glean real-time operation information like speed, battery status, energy use, and faults. This data can be used to predict maintenance, remotely diagnose and optimally perform maintenance.

On the hardware side, investigation of more efficient power electronic converters, motor driver technologies and newer battery technologies like lithium-iron-phosphate ($LiFePO_4$) or solid-state batteries have the potential to dramatically increase the efficiency of systems, safety and life-span. Increase in battery management system (BMS), can also enable enhancement of further usable depth of discharge and preservation of battery health.

The scalability of the proposed system can be further examined by developing a modular design that can be easily retrofitted onto existing electric rickshaws and adjusted for different vehicle sizes and power requirements. Evaluating production cost and manufacturability will be important for assessing the feasibility of large-scale implementation. In addition, collaboration with local vehicle manufacturers and transport authorities may help turn the developed system into commercial use and support the wider adoption of sustainable electric mobility solutions in Bangladesh.

CHAPTER 11: IDENTIFICATION OF COMPLEX ENGINEERING PROBLEMS AND ACTIVITIES

11.1 Identification of Attributes of Complex Engineering Problems (EP)

The hybrid electric rickshaw system proposed can help in solving a complex engineering problem, and it is the energy efficiency, sustainability, safety, affordability and the system integration subject to the real world constraints in Bangladesh. Table 11.1 summarizes the relevant qualities of complex engineering problems that are covered by this project.

Table 11.1: Attributes of Complex Engineering Problems (EP)

Attribute	Description	Applicable
P1	Depth of knowledge required	√
P2	Range of conflicting requirements	√
P3	Depth of analysis required	√
P4	Familiarity of issues	×
P5	Extent of applicable codes	√
P6	Extent of stakeholder involvement and needs	√
P7	Interdependence	√

11.2 Reasoning on How the Project Addresses EP Attributes

P1 – Depth of Knowledge Required
The engineering skills that needed to be utilized in the project were in the multidisciplinary science which encompassed electrical machines, embedded systems, power electronics, renewable energy systems, and control algorithms. Placing pedal assist sensing, PWM-based motor control, battery charging, solar input, and regenerative braking demanded higher engineering knowledge than the normal design issues.

P2 - Domain of Conflicting Requirements.

Some of the conflicting requirements considered in the project included the performance of the system versus safety, energy efficiency versus affordability, and technological improvement versus ease of use. The system is designed with a careful approach and limited control techniques to come up with these trade-offs.

P3 - Depth of Analysis Required

Analytical calculations and experimentation were to be used to estimate the motor power demand, energy recovered by the system through regenerative braking, solar contribution, battery endurance and system efficiency at the urban traffic conditions.

Although it is rather usual in the context of Bangladesh, the usage of pedal assistance, solar charging, and regenerative braking is not a common practice. There was a need to scale familiar technologies to a semi-new application environment in the project.

P5 - Extent of Applicable Codes

Since there was a lack of formal regulations on electric rickshaw in Bangladesh, the project used general low-voltage electric safety rules, battery charging rules, and professional engineering codes and had to be interpreted instead of direct implementation of standards.

P6 - Needs and Stakeholder Involvement.

The design had in place the requirements of various stakeholders such as rickshaw drivers, passengers, regulating agencies, and national power grid. Considerations were made on affordability, safety, and less grid dependency.

P7 - Interdependence

The system has a high level of interdependence among subsystems. These factors that affect the entire system behavior are pedaling, braking, solar availability, battery charging, and control logic.

11.3 Identification of Attributes of Complex Engineering Activities (EA)

The project included intricate engineering operations with regard to system integration, validation and testing. The relevant characteristics are listed in Table 11.2.

Table 11.2: Attributes of Complex Engineering Activities (EA)

Attribute	Description	Applicable
A1	Range of resources	√
A2	Level of interaction	√
A3	Innovation	×
A4	Consequences for society and the environment	√
A5	Familiarity	√

11.4 Reasoning on How the Project Addresses EA Attributes

A1 - Range of Resources

The project used a very broad array of resources such as hardware materials (battery, motor, PAS, solar panel, motor driver), software programs (Arduino IDE, MATLAB), experimental equipment, and the academic literature.

A2 - Level of Interaction

The environment, human input, software and hardware were interacting in a significant manner.The system is dynamically reacting to the pedaling of the rider, the braking act, and the sun availability.

A3 - Innovation (Not Applicable)

The project does not purport to have invented new technology. Rather, it is more concerned with the engineering integration, optimization and practical implementation of the available technologies in a particular local situation. Thus, the use of innovation as the main activity feature cannot be applied.

A4 - Social and Environmental Impact.

The project has evident social and environmental implications in that it minimizes grid electricity consumption, indirect emissions, enhances transportation sustainability, and minimizes the operating expenses of drivers with low incomes.

A5 - Familiarity

Even though the individual subsystems were well known, it was only through the gradual experimentation, debugging, and end-to-end testing that the subsystems could be actually used in a real-life electric rickshaw setup.

11.5 Conclusion

In this chapter, it has been determined that the suggested hybrid electric rickshaw project meets the needed qualities of Complex Engineering Problems (EP) and Complex Engineering Activities (EA) as per accreditation requirements. The project does not present innovation in regards to new technology, however, there is a high level of engineering complexity in integrating systems, analyzing them, considering stakeholders and implementing it practically.

The project thus fulfills the academic and professional requirements of Final Year Design Project and is a realistic, socially responsible, and sustainable engineering solution to Bangladesh.

References

[1] International Energy Agency (IEA), *Global EV Outlook 2023*, Paris, France, 2023.

[2] World Bank, *Electric Mobility and Climate Change in Developing Countries*, Washington, DC, USA, 2022.

[3] M. Islam and T. Ahmed, "Socio-economic impact of electric rickshaws in urban Bangladesh," *Energy Policy*, vol. 120, pp. 301–309, 2018.

[4] M. A. Chowdhury, M. M. Rahman, and A. K. Azad, "Power conversion for environment friendly electrically assisted rickshaw using photovoltaic technology in Bangladesh," in *Proc. 3rd Int. Conf. Green Energy and Technology (ICGET)*, Dhaka, Bangladesh, 2015, pp. 1–5.

[5] United Nations, *Transforming Our World: The 2030 Agenda for Sustainable Development*, New York, NY, USA, 2015.

[6] Dhaka Tribune, "Unauthorized electric rickshaws and their impact on urban power consumption," Dhaka, Bangladesh, 2023.

[7] Asian Development Bank, *Sustainable Transport Solutions for Developing Asia*, Manila, Philippines, 2021.

[8] J. P. Pucher and R. Buehler, "Making cycling irresistible," *Transport Reviews*, vol. 28, no. 4, pp. 495–528, 2008.

[9] P. Fishman, "E-bikes and sustainable transport," *Energy Policy*, vol. 137, 2020.

[10] S. M. Waliullah *et al.*, "Design a solar and pedaling powered rickshaw," in *Proc. ICMIEE*, Khulna, Bangladesh, 2014.

[11] C. C. Chan, "The state of the art of electric and hybrid vehicles," *Proc. IEEE*, vol. 90, no. 2, pp. 247–275, 2002.

[12] REN21, *Renewables 2023 Global Status Report*, Paris, France, 2023.

[13] J. Larminie and J. Lowry, *Electric Vehicle Technology Explained*, 2nd ed., Hoboken, NJ, USA: Wiley, 2012.

[14] M. Ehsani, Y. Gao, and A. Emadi, *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles*, 2nd ed., Boca Raton, FL, USA: CRC Press, 2010.

[15] T. M. Jahns and V. Blasko, "Recent advances in power electronics technology for industrial and traction machine drives," *Proc. IEEE*, vol. 89, no. 6, pp. 963–975, Jun. 2001.

[16] H. Patel and V. Agarwal, "MATLAB-based modeling to study the effects of partial shading on PV array characteristics," *IEEE Trans. Energy Convers.*, vol. 23, no. 1, pp. 302–310, Mar. 2008.

[17] A. Khaligh and Z. Li, "Battery, ultracapacitor, fuel cell, and hybrid energy storage systems for electric, hybrid electric, fuel cell, and plug-in hybrid electric vehicles," *IEEE Trans. Veh. Technol.*, vol. 59, no. 6, pp. 2806–2814, Jul. 2010.

[18] S. Lukic, J. Cao, R. C. Bansal, F. Rodriguez, and A. Emadi, "Energy storage systems for automotive applications," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2258–2267, Jun. 2008.

[19] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics: Converters, Applications, and Design*, 3rd ed., Hoboken, NJ, USA: Wiley, 2003.

[20] A. Emadi, "Energy-efficient electric motors and their applications in electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 61, no. 12, pp. 6622–6633, Dec. 2014.

[21] S. Williamson, A. Emadi, and K. Rajashekara, "Comprehensive efficiency modeling of electric traction motor drives for hybrid electric vehicle propulsion applications," *IEEE Trans. Veh. Technol.*, vol. 56, no. 4, pp. 1561–1572, Jul. 2007.

[22] M. Zeraoulia, M. E. H. Benbouzid, and D. Diallo, "Electric motor drive selection issues for HEV propulsion systems: A comparative study," *IEEE Trans. Veh. Technol.*, vol. 55, no. 6, pp. 1756–1764, Nov. 2006.

[23] M. Yilmaz and P. T. Krein, "Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles," *IEEE Trans. Power Electron.*, vol. 28, no. 5, pp. 2151–2169, May 2013.

[24] B. Dunn, H. Kamath, and J. M. Tarascon, "Electrical energy storage for the grid: A battery of choices," *Science*, vol. 334, no. 6058, pp. 928–935, 2011.

[25] A. Burke, "Ultracapacitors: Why, how, and where is the technology," *J. Power Sources*, vol. 91, no. 1, pp. 37–50, 2000.

[26] S. Dusmez, A. Khaligh, and A. Hasanzadeh, "A compact and integrated multifunctional power electronic interface for plug-in electric vehicles," *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5690–5701, Dec. 2013.

[27] H. Abu-Rub, J. Holtz, J. Rodriguez, and G. Baoming, "Medium-voltage multilevel converters—State of the art, challenges, and requirements in industrial applications," *IEEE Trans. Ind. Electron.*, vol. 57, no. 8, pp. 2581–2596, Aug. 2010.

[28] R. Teodorescu, M. Liserre, and P. Rodriguez, *Grid Converters for Photovoltaic and Wind Power Systems*, Hoboken, NJ, USA: Wiley, 2011.

[29] M. Villalva, J. Gazoli, and E. Filho, "Comprehensive approach to modeling and simulation of photovoltaic arrays," *IEEE Trans. Power Electron.*, vol. 24, no. 5, pp. 1198–1208, May 2009.

[30] K. C. Divya and J. Østergaard, "Battery energy storage technology for power systems—An overview," *Electr. Power Syst. Res.*, vol. 79, no. 4, pp. 511–520, Apr. 2009.

[31] A. Khaligh and M. D'Antonio, *Global Trends in Electric Vehicle Power Systems*, Hoboken, NJ, USA: Wiley-IEEE Press, 2018.

[32] S. Onori, P. Spagnol, and Y. Guezennec, "A framework for lithium-ion battery state of charge and health estimation," *J. Power Sources*, vol. 183, no. 2, pp. 548–558, 2008.

[33] J. Neubauer and A. Pesaran, "The ability of battery second use strategies to impact plug-in electric vehicle prices and serve utility energy storage applications," *J. Power Sources*, vol. 196, no. 23, pp. 10351–10358, 2011.

[34] A. Emadi, K. Rajashekara, S. Williamson, and S. Lukic, "Topological overview of hybrid electric and fuel cell vehicular power system architectures and configurations," *IEEE Trans. Veh. Technol.*, vol. 54, no. 3, pp. 763–770, May 2005.

[35] M. A. Hannan, M. M. Hoque, A. Mohamed, and A. Ayob, "Review of energy storage systems for electric vehicle applications: Issues and challenges," *Renew. Sustain. Energy Rev.*, vol. 69, pp. 771–789, Mar. 2017.

[36] S. Singh, S. Jain, and V. Agarwal, “A review on distributed generation planning and optimization techniques,” *Renew. Sustain. Energy Rev.*, vol. 38, pp. 895–906, Oct. 2014.

[37] T. Markel *et al.*, “Plug-in hybrid electric vehicle energy storage system design,” *IEEE Power Electron. Mag.*, vol. 2, no. 4, pp. 32–38, Dec. 2015.

[38] A. Fathabadi, “High efficiency DC–DC converter for electric vehicle applications,” *IEEE Trans. Veh. Technol.*, vol. 66, no. 12, pp. 10414–10422, Dec. 2017.

[39] M. Z. Rahman, M. R. Islam, and K. M. Muttaqi, “Energy management of hybrid renewable energy systems: A review,” *Renew. Sustain. Energy Rev.*, vol. 98, pp. 179–195, Dec. 2018.

[40] S. Shao, T. H. Lee, and S. K. Panda, “Battery state of charge estimation using adaptive extended Kalman filter,” *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2340–2348, Jun. 2008.

[41] J. Deng, S. Li, and Z. Zhang, “Human pedaling torque estimation for pedal-assist electric bicycles without torque sensors,” IEEE Transactions on Industrial Electronics, vol. 64, no. 6, pp. 4762–4771, Jun. 2017.

Appendix:

FYDP (C) Fall 2025 Summary of Team Log Book / Journal

Date / Time / Place	ATTENDANCE	Summary of Meeting Minutes	Responsible	Comment by ATC
09-10-25 (in campus)	FARDIN SABAB SHAHRIA	Discussion on FYDP-C scope and transition plan from design phase to hardware implementation	All	Proceed with hardware planning. Order component from abroad.
19-10-25(in campus)	FARDIN SABAB SHAHRIA TAKRIM	Review of finalized system design and component selection	All	Verify component availability
02-11-25(in campus)	FARDIN SABAB TAKRIM	Discussion on structure design	SHAHRIA TAKRIM	Use Cycle as prototype
16-11-25(in campus)	SABAB SHAHRIA TAKRIM	Hardware assembly planning and laboratory safety considerations	All	Prepare subsystems individually
30-11-25(in campus)	SABAB SHAHRIA TAKRIM	Testing strategy discussion and test bench setup	SABAB FARDIN	Prepare test results log

14-12-25(in campus)	SABAB SHAHRIA	Mid-implementation review, debugging, and troubleshooting	All	Improve system reliability
28-12-25(in campus)	FARDIN SABAB SHAHRIA TAKRIM	Final hardware testing and performance validation	All	Document test outcomes and make poster
04-01-26(in campus)	FARDIN SABAB SHAHRIA TAKRIM	Final demonstration preparation and report finalization	All	Prepare for presentation

Theory:

Pedal Assist System (PAS) Theory

A Pedal Assist System (PAS) is a popular control system in electric bicycles and light electric vehicles, which is meant to give motor assistance based on pedaling activity of the rider. In contrast to throttle-based systems, PAS is designed in such a way that the electric motor performs its action only when the rider actively pedals, which helps to be energy efficient and engage the rider. This method is mostly effective in low speed vehicles like electric rickshaws where constant throttle operation may result in unjustifiable energy waste.

A typical PAS is a magnetic disk placed on the crankshaft and a hall effect sensor placed close to it. The rotating magnetic disk produces a set of digital pulses as the rider pushes the pedals and these are detected by the sensor. These pulses are directly proportional to the cadence of the pedalling, which is an indirect measure of rider effort [1]. Through processing this signal, the controller is able to decide when and how much motor assistance to be offered.

In PAS-based systems, the motor does not act autonomously, but it can serve to supplement the efforts of humans to lessen the fatigue of the rider and enhance the overall energy consumption. PAS drastically increases the range of the vehicle in comparison with throttle-only operation and promotes proactive involvement of the rider. Nevertheless, when the speed of pedaling is extremely low, the irregular rotation of the crank may prevail in PAS signals. In an effort to overcome this problem, signal filtering methods and minimum cadence threshold are normally used to eliminate the possibility of automatic motor activation. This project has the control logic where these considerations were taken into consideration to guarantee safe and predictable operation.

Traction Force and Vehicle Dynamics Theory

The movement of a low speed electric rickshaw is controlled by the interaction between traction force available at the wheels and the different resistant forces acting against movement. The rolling resistance plus aerodynamic drag, plus the grade resistance and inertia force during acceleration make up the total traction force needed to accelerate the car [2]. These forces are important to understand to be able to perform an accurate analysis of motor sizing and energy consumption.

The major reasons that cause rolling resistance are tire deformation and friction between the tires and the road. It can be expressed as:

$$F_r = C_r \, . \, m \, . \, g$$

Cr is the rolling resistance coefficient and mmm is the combined mass of the vehicle and passengers and ggg is the acceleration due to gravity. In low speed vehicles over rough city roads, rolling resistance can turn out to be a large fraction of the overall resistance.

Aerodynamic drag is resistance to motion of a vehicle and it rises in square of velocity:

$$F_d = \frac{1}{2}\rho C_d A v^2$$

C_d is the drag coefficient, A is the frontal area, and v is the speed of a vehicle. Aerodynamic drag is not so relevant at lower speeds but as the vehicle speed approaches regulatory limits the aerodynamic drag becomes more relevant.

Where the vehicle is operated on inclined surfaces, grade resistance occurs and is given by:

$$F_g = mgsin(\theta)$$

where θ the angle of incline of the road. Even minor slopes can create a significant increase in the torque load in heavily loaded rickshaws. All these forces combine together to decide the torque demanded by the wheels and hence the motor power rating. Exact calculation of traction force is hence very important to the design of the system and performance analysis.

Battery Energy Modeling and Efficiency Considerations

Electric vehicles use energy storage as a vital part. The battery pack that was utilized in this project was a 24 V battery pack consisting of two 12 V batteries that were connected in series. The nominal energy content in a battery pack is:

$$E_{nom} = V \times C$$

V is the battery voltage and C is battery capacity in ampere-hours. Not, however, all this energy is practically usable. In order to extend the battery lifetime and limit abnormal degradation, a small portion of the nominal energy is taken as the operational energy.

In the case of lead-acid batteries, a depth of discharge (DoD) of about 50 percent is usually suggested to increase cycle life and reliability [3]. This limit should also be exceeded in regular intervals as it may cause sulfaction, loss of capacity and early failure. Consequently, usable energy was used to compute the energy calculations in this project as opposed to nominal capacity.

Besides battery constraints, the efficiency of systems is also affected by the losses of drive train, loss of controller and loss of motor. These aspects decrease the useful energy provided to the wheels. It is important to use realistic efficiency values in order to have the range estimation and meaningful performance analysis.

Electric Motor Control Using PWM

The most popular technique of controlling the speed and torque of DC motors in low-voltage electric vehicles is Pulse Width Modulation (PWM). PWM rather than modulating the supply voltage itself modulates the average voltage to the motor by switching the supply ON and

OFF at a constant frequency. The speed of the motor and the torque is dictated by the ratio of ON time to total switching time, also called the duty cycle [4].

In this project an Arduino based microcontroller was used to create PWM signals to operate an IBT-2 motor driver. The ramping of the PWM was introduced to allow the use of PWM to increment or decrease the duty cycle during acceleration and deceleration. The method helps avoid abrupt torque and reduces mechanical stress on the elements of the drive train, as well as enhances the comfort of the passengers.

It is particularly necessary to tune the PWM properly in rickshaws that tend to run in conditions of different loads. Torque variations may also lead to instability, too much current draw and wear of components. Close and stable vehicle operation was realized through control of PWM transitions.

Speed Limiting and Hysteresis Control

The need to regulate speed is based on the necessity to adhere to safety regulations and to avoid the high usage of power. The simplest speed cut-off at a fixed threshold may result in a lot of ON/OFF switching as vehicle speed changes around the cut-off threshold, resulting in uncomfortable jerking, and stress to components.

A control strategy that is normally used to curb this problem is a hysteresis-based one [5]. In the hysteresis control, there are two speed limits that are set, one being the upper limit at which the motor assistance is disabled, and the other one being the lower limit at which the assistant is re-enabled. This forms a dead band that makes the system oscillate and do not oscillate.

This project was restricted to 25km/h, in which hysteresis was established in software. This method was a way of ensuring smooth transitions close to the speed limit at the same time being safe and energy efficient.

Regenerative Braking Theory

Regenerative braking allows an electric motor to work as a generator during deceleration turning kinetic energy into electrical energy which can then be stored in the battery. Although regenerative braking proves to be very effective in high-speed electric cars, the energy-saving in low-speed cars is low, owing to the lower kinetic energy levels [6].

Regardless of these drawbacks, regenerative braking is useful in urban stop-and-go traffic. Repeated deceleration events permit partial recovery of energy and less energy and brake wear are used. Regenerative braking in this project was applied in a conservative manner so that braking force is not too high and also so that the rider can have the comfort of the braking.

The small recovered energy factored towards better system efficiency without the requirement of serious mechanical complexity and safety hazards.

Solar Energy Integration in Electric Vehicles

Electric vehicles that include solar energy are usually provided as an auxiliary source of energy but not the main energy source of propulsion. Solar panels have various factors that affect their power output such as the solar irradiance, panel orientation, temperature and the efficiency of the controller [7].

Solar energy was applied in this project to help in charging the batteries when idle or when the load was at the minimum level. A correction factor of efficiency was used to take into consideration the actual losses in the field like the wiring resistance, and inefficiency in the controllers. Though solar power cannot propel the vehicle, it minimizes the use of grid electricity and increases the battery life.

This is especially beneficial in areas where the sun is plentiful and where there exists scarce charging resources.

Hybrid Energy Management Strategy

The hybrid energy management approach incorporates rider control, motor aid, battery power, solar charging and regenerative braking into a single control system. The smart allocation of torque between the motor and the rider gives the system a trade off between comfort, efficiency, and range.

Experimental and simulation analysis showed that a torque contribution ratio of about 20% rider input and 80% motor assistance gave the highest usability/energy consumption trade off. These kinds of hybrid approaches are particularly apt towards developing nations, where energy prices, infrastructural constraints and sustainability issues play a major role [8].

On the whole, the offered hybrid prototype can be proved to be an effective and feasible approach to low-speed electric rickshaws that should be used in urban areas.

Code:

```
  //Nano: PAS (A0) -> cadence -> speed -> torque -> motor
  //Improved startup smoothing:
   // PWM per-second rise cap
   // Initial-assist percentage cap for first strokes
   //Low-pass filtering on speed
   //Minimum cadence threshold
#include <Arduino.h>
// --- Hardware pins ---
const uint8_t PAS_A = A0;
const uint8_t RPWM  = 5;
const uint8_t LPWM  = 6;
const uint8_t R_EN  = 7;
const uint8_t L_EN  = 8;

// --- Wheel/drivetrain params (set these) ---
float WHEEL_CIRCUMFERENCE_M = 2.10;    // meters
float WHEEL_REV_PER_CRANK_REV = 2.5;   // gear ratio

// --- Speed limit ---
const float MAX_SPEED_KMH = 25.0;
const float SPEED_HYST_KMH = 1.0;

// --- ADC/PAS detection ---
const int magnets = 6;
const unsigned long sampleWindowMs = 200;
const int oversampleN = 8;
```

```
const int oversampleDelayUs = 200;

int idleADC = 4;

int peakADC = 80;

int thresholdADC = 20;

const int hysteresisADC = 6;

unsigned long debounceMs = 30;

unsigned long lastValidEdge = 0;


// --- Torque map ---

int cadence_points[] = {0, 20, 40, 60, 80, 100};

int torque_points[]  = {0,  5, 10, 15, 20, 25};

const float maxTorque = 25.0;

const float alpha = 0.20; // smoothing on torque

float torque_filtered = 0.0;


// --- Assist config ---

const float MOTOR_SHARE = 0.80;   // 80% of human torque

const float SHAPE_GAIN = 0.6;

const float SHAPE_REF_CADENCE = 90.0;


// --- Startup smoothing / limits (NEW) ---

const unsigned long SOFT_START_MS = 800;       // original ramp time

const float MAX_PWM_RISE_PER_SEC = 120.0;      // max PWM increase per second (0-255 scale). lower -> gentler

const int INITIAL_ASSIST_PCT = 30;            // percent of target allowed on first engagement (0-100)

const unsigned long INITIAL_ASSIST_MS = 800;  // how long initial cap remains after assist enabled

int currentPwm = 0;

unsigned long lastRampMillis = 0;
```

```
unsigned long assistEnabledAt = 0;            // millis when assist first enabled


// --- Additional safety / thresholds ---
const int PWM_MAX = 255;
const int PWM_MIN = 0;
const float MIN_CADENCE_RPM = 10.0; // below this cadence, don't assist (avoid spurious)
bool assistDisabledBySpeed = false;
// --- speed smoothing ---
float speed_lpf = 0.0;
const float SPEED_LPF_ALPHA = 0.25; // 0..1, larger = less smoothing


// Forward declarations (prototypes)
int adcAverage();
void calibratePAS();
float lookupTorque(int cadence);
int torqueToPwm(float t);
void rampPwmTowardLimited(int target);
// ---------- setup ----------
void setup() {
  Serial.begin(115200);
  while (!Serial);


  pinMode(RPWM, OUTPUT);
  pinMode(LPWM, OUTPUT);
  pinMode(R_EN, OUTPUT);
  pinMode(L_EN, OUTPUT);
```

```
  digitalWrite(R_EN, HIGH);
  digitalWrite(L_EN, HIGH);
  analogWrite(RPWM, 0);
  analogWrite(LPWM, 0);
  analogReference(INTERNAL);

  Serial.println("Starting PAS-assisted motor (80% motor torque share) with smoother startup.");
  Serial.println("Calibrating PAS (5s): stay still ~2s then pedal ~3s.");
  calibratePAS();
  Serial.print("Cal done. idleADC="); Serial.print(idleADC);
  Serial.print(" peakADC="); Serial.print(peakADC);
  Serial.print(" th="); Serial.println(thresholdADC);
  lastRampMillis = millis();
}

// ---------- main loop ----------
void loop() {
  // 1) count pulses in window
  unsigned long windowStart = millis();
  unsigned long localPulses = 0;
  bool state = false;
  while (millis() - windowStart < sampleWindowMs) {
    int adc = adcAverage();
    int th_hi = thresholdADC + hysteresisADC;
    int th_lo = thresholdADC - hysteresisADC;
    bool newState;
    if (adc >= th_hi) newState = true;
```

```
    else if (adc <= th_lo) newState = false;

    else newState = state;


    if (!state && newState) {

      unsigned long t = millis();

      if (t - lastValidEdge > debounceMs) {

        localPulses++;

        lastValidEdge = t;

      }

    }

    state = newState;

    delayMicroseconds(250);

  }

  // 2) cadence RPM

  float cadence_rpm = (localPulses / (float)magnets) * (60.0 / (sampleWindowMs / 1000.0));


  // 3) compute raw speed (km/h)

 Float raw_speed_kmh = cadence_rpm * WHEEL_REV_PER_CRANK_REV *
WHEEL_CIRCUMFERENCE_M * 0.06;


  // 4) low-pass filter the speed to prevent spikes

  speed_lpf = speed_lpf + SPEED_LPF_ALPHA * (raw_speed_kmh - speed_lpf);

  float speed_kmh = speed_lpf;


  // 5) torque estimate

  float torque_est = lookupTorque((int)round(cadence_rpm));


  // 6) motor base torque = 80% of human torque
```

```
float motorTorqueBase = MOTOR_SHARE * torque_est;

// 7) shaping factor for low cadence
float cadenceFrac = constrain(cadence_rpm / SHAPE_REF_CADENCE, 0.0, 1.0);
float shapeFactor = 1.0 + SHAPE_GAIN * (1.0 - cadenceFrac);
float motorTorque = motorTorqueBase * shapeFactor;
motorTorque = min(motorTorque, maxTorque);

// 8) speed cutoff handling
if (!assistDisabledBySpeed && speed_kmh >= MAX_SPEED_KMH) {
  assistDisabledBySpeed = true;
  Serial.println("Assist disabled: reached max speed.");
} else if (assistDisabledBySpeed && speed_kmh <= (MAX_SPEED_KMH - SPEED_HYST_KMH)) {
  assistDisabledBySpeed = false;
  Serial.println("Assist re-enabled: below threshold.");
}

// 9) enforce min cadence threshold
if (cadence_rpm < MIN_CADENCE_RPM) {
  motorTorque = 0.0; // no assist at very low cadence
}

// 10) compute pwm target
int pwmTarget = torqueToPwm(motorTorque);
pwmTarget = constrain(pwmTarget, PWM_MIN, PWM_MAX);

// 11) if assist disabled by speed -> target zero
```

```
if (assistDisabledBySpeed) pwmTarget = 0;


// 12) if assist just enabled (first time), apply initial assist cap
unsigned long now = millis();
static bool wasAssistActive = false;
bool assistActive = (pwmTarget > 0);
if (assistActive && !wasAssistActive) {
  // just became active
  assistEnabledAt = now;
  // cap currentPwm to INITIAL_ASSIST_PCT of target immediately
  int cap = (pwmTarget * INITIAL_ASSIST_PCT) / 100;
  if (currentPwm > cap) {
    // let it decay to cap quickly to avoid sudden drop; leave as is
  } else if (currentPwm < cap) {
    // raise gently toward cap (ramp function will handle)
  }
}
wasAssistActive = assistActive;


// 13) ramp PWM toward target but limit rise rate per second
rampPwmTowardLimited(pwmTarget);


// 14) write to IBT (single direction)
analogWrite(RPWM, currentPwm);
analogWrite(LPWM, 0);


// 15) If we are within INITIAL_ASSIST_MS of enabling, ensure we don't exceed initial cap
```

```
  if (assistActive && (now - assistEnabledAt <= INITIAL_ASSIST_MS)) {
    int cap = (pwmTarget * INITIAL_ASSIST_PCT) / 100;
    if (currentPwm > cap) {
      currentPwm = cap;
      analogWrite(RPWM, currentPwm);
    }
  }
  // Debug
  Serial.print("cadence: "); Serial.print(cadence_rpm); Serial.print(" RPM");
  Serial.print(" | speed: "); Serial.print(speed_kmh, 2); Serial.print(" km/h");
  Serial.print(" | pwmTarget: "); Serial.print(pwmTarget);
  Serial.print(" | pwmOut: "); Serial.print(currentPwm);
  Serial.print(" | assistOff: "); Serial.println(assistDisabledBySpeed ? "YES" : "NO");

  delay(20);
}
// ---------- oversampled ADC ----------
int adcAverage() {
  unsigned long sum = 0;
  for (int i = 0; i < oversampleN; ++i) {
    sum += analogRead(PAS_A);
    delayMicroseconds(oversampleDelayUs);
  }
  return (int)(sum / oversampleN);
}
// ---------- calibration ----------
void calibratePAS() {
```

```
  const unsigned long DUR = 5000;
  unsigned long start = millis();
  unsigned long minV = 1023, maxV = 0;
  while (millis() - start < DUR) {
    int v = adcAverage();
    if (v < minV) minV = v;
    if (v > maxV) maxV = v;
    delay(10);
  }
  idleADC = (int)minV;
  peakADC = (int)maxV;
  if (peakADC <= idleADC) peakADC = idleADC + 4;
  thresholdADC = idleADC + (peakADC - idleADC) / 2;
  if (thresholdADC < idleADC + 2) thresholdADC = idleADC + 2;
}

// ---------- torque lookup ----------
float lookupTorque(int cadence) {
  int n = sizeof(cadence_points) / sizeof(int);
  if (cadence <= cadence_points[0]) return torque_points[0];
  if (cadence >= cadence_points[n-1]) return torque_points[n-1];
  for (int i = 0; i < n - 1; ++i) {
    if (cadence >= cadence_points[i] && cadence <= cadence_points[i + 1]) {
      float x0 = cadence_points[i];
      float x1 = cadence_points[i + 1];
      float y0 = torque_points[i];
      float y1 = torque_points[i + 1];
```

```
    return y0 + (cadence - x0) * (y1 - y0) / (x1 - x0);
   }
  }
  return 0;
}
// ---------- torque -> pwm ----------
int torqueToPwm(float t) {
  if (t <= 0) return 0;
  if (t >= maxTorque) return PWM_MAX;
  return (int)((t / maxTorque) * (float)PWM_MAX);
}
// ---------- ramp toward but limit rise rate per second ----------
void rampPwmTowardLimited(int target) {
  unsigned long now = millis();
  unsigned long elapsed = now - lastRampMillis;
  lastRampMillis = now;
  if (elapsed == 0) return;

  // compute max allowed delta in this elapsed chunk
  float maxRisePerMs = MAX_PWM_RISE_PER_SEC / 1000.0; // pwm steps per ms
  float maxDelta = maxRisePerMs * (float)elapsed;

  int delta = target - currentPwm;
  if (delta > 0) {
   // limit rise
   if ((float)delta > maxDelta) {
    currentPwm += (int)floor(maxDelta);
```

```
    } else {
      currentPwm = target;
    }
  } else {
    // allow fall (down changes) faster — immediate or gently?
    // we'll allow faster fall but limit to symmetric value for safety
    if ((float)(-delta) > maxDelta) {
      currentPwm -= (int)floor(maxDelta);
    } else {
      currentPwm = target;
    }
  }
  // clamp
  if (currentPwm < PWM_MIN) currentPwm = PWM_MIN;
  if (currentPwm > PWM_MAX) currentPwm = PWM_MAX;
}
```