Design and Performance Analysis of Electric Bicycles

Shaik Musharaf [1], Bolagani Manikanata[2] , Chadalavada Pavan Kumar[3], Kesana Vijay[4], Dr. T Narasimha Prasad[5]
[1,2,3,4]UG scholar, [5]Associate Professor
[1,2,3,4,5]Dept of EEE, St.Ann's College of Engineering and Technology, Chirala,India
Email id : musharfmushu635@gmail.com, manikantabolagani143@gmail.com, vijaykesana123@gmail.com, chpavankumark@gmail.com,narasimhaiete@gmail.com

Article Received: 20 Feb 2025 *Article Accepted: 27 Feb 2025* *Article Published: 31 March 2025*

Citation
Shaik Musharaf , Bolagani Manikanata , Chadalavada Pavan Kumar, Kesana Vijay,Dr. T Narasimha Prasad, "Design and Performance Analysis of Electric Bicycles, Journal of Next Generation Technology (ISSN: 2583-021X), 4(3), pp. 17-28. March 2025. https://zenodo.org/records/15244903

Abstract

The rising demand for sustainable and eco-friendly transportation solutions has driven the development of electric bicycles (e-bikes) as an efficient alternative to traditional commuting methods. This project focuses on the design, development, and optimization of an e-bike to enhance performance, energy efficiency, and user experience. The e-bike integrates a lightweight frame, a high-capacity battery, and a brushless DC motor to provide smooth acceleration and extended range. Features such as battery monitoring, A GPS system is added to enhance the functionality of the electric bicycle, providing navigation and tracking capabilities for users. Through rigorous testing and analysis, the e-bike is designed to deliver optimal speed, range, and rider comfort while minimizing environmental impact. This project aims to contribute to the growing shift toward sustainable urban mobility by providing an affordable, reliable, and eco-friendly transportation solution.

The selection of batteries and motors is tailored to meet desired output and all road conditions, ensuring the bicycle's efficiency and effectiveness.

Keywords: Hub motor, BLDC motor, battery, electric bike, ecofriendly, electric mobility.

I. INTRODUCTION

The design and development of electric bicycles (e-bikes) have garnered significant attention in recent years due to their potential to revolutionize urban mobility and reduce environmental impact. A critical component of this innovation lies in the hardware architecture of e-bikes, which integrates mechanical structures with electrical and electronic systems to deliver efficient, safe, and user-friendly transportation solutions [1]. The core hardware components—such as the electric motor, battery system, controller unit, drivetrain, sensors, and frame design—collectively determine the performance, reliability, and user experience of the e-bike [2]. Modern e-bikes typically utilize brushless DC (BLDC) motors or hub motors for propulsion, chosen for their compactness, high torque-to-weight ratio, and low maintenance requirements [3]. Battery technology, particularly the use of lithium-ion (Li-ion) cells, has significantly advanced the range, charging time, and overall efficiency of e-bikes, replacing older lead-acid and nickel-metal hydride systems [4]. The battery management system (BMS) plays a crucial role in monitoring cell voltage, temperature, and state-of-charge to ensure safety and longevity [5]. Additionally, microcontroller-based control units are employed to manage motor output, process sensor data, and enable features like pedal-assist and regenerative braking [6]. Mechanical hardware design is equally critical. Factors such as frame geometry, weight distribution, and material selection (aluminium alloys, carbon fiber, etc.) directly impact rider comfort, durability, and the integration of electrical components [7]. Sensor systems, including torque and cadence sensors, provide feedback to the controller to ensure responsive and intuitive pedal assistance, enhancing the rider's experience and conserving energy [8]. Integration of hardware components must also account for space constraints, heat dissipation, waterproofing, and modularity for ease of maintenance and upgrades [9]-[12].

Given the growing diversity in e-bike applications—from commuter models and cargo bikes to high-performance sport e-bikes—there is a pressing need for research that explores and compares different hardware configurations and their impact on performance metrics such as efficiency, range, and ride quality. This paper presents a comprehensive overview and analysis of electric bicycle hardware systems, focusing on the interplay between mechanical and electrical components, and evaluates current design trends, innovations, and challenges in developing optimized e-bike platforms.

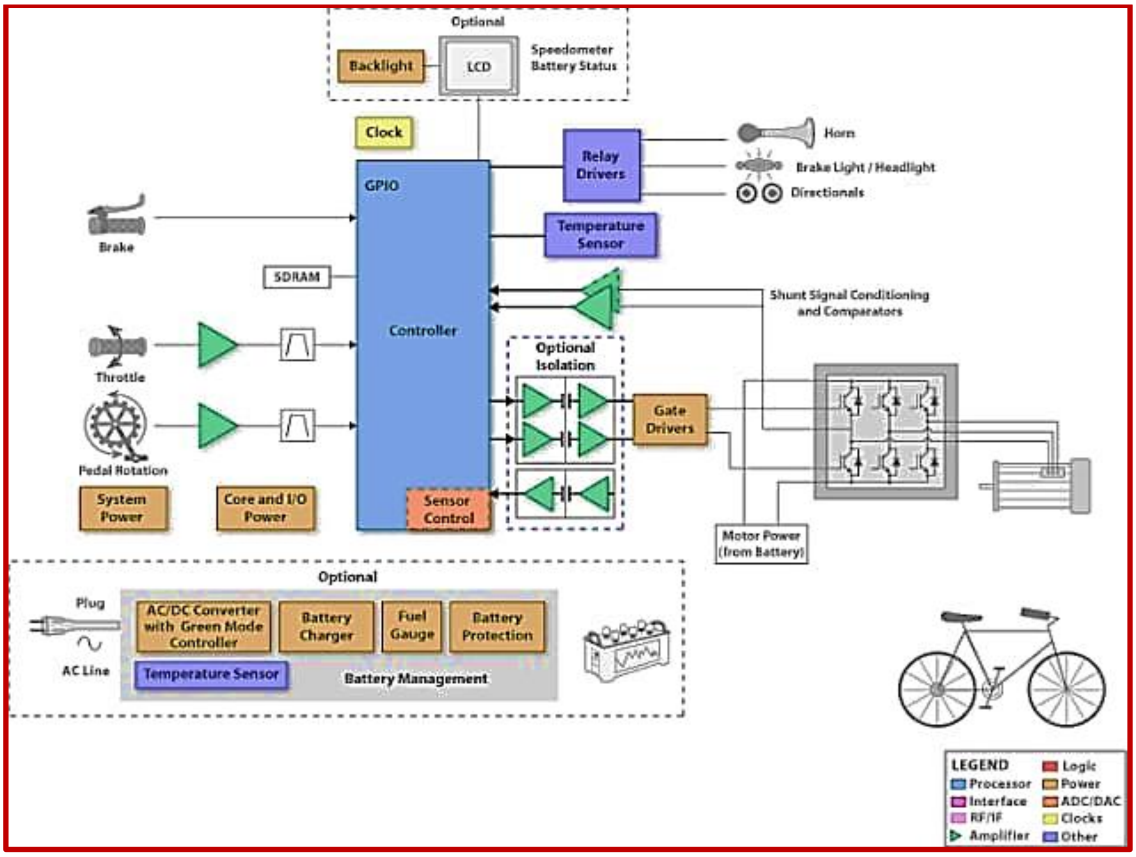

Figure 1: Block diagram of proposed E-bicycle design

II. POWER TRANSMISSION

The powertrain of an electric bicycle (e-bike) is a specialized system designed to provide electric assistance to the rider, enhancing pedalling efficiency and reducing physical effort. Unlike traditional bicycles that rely solely on human power, an e-bike integrates an electric propulsion system with mechanical components to deliver a hybrid mode of transportation. An electric bicycle powertrain typically consists of four main components: the electric motor, battery pack, controller, and drivetrain. The electric motor is the heart of the system and can be located in the front hub, rear hub, or mid-drive (crank area). Hub motors are often simpler and easier to maintain, while mid-drive motors offer better weight distribution and improved torque, especially useful on inclines or rough terrain. The battery stores electrical energy and supplies power to the motor. Most modern e-bikes use lithium-ion battery packs due to their high energy density, relatively low weight, and long cycle life. Battery capacity directly affects the range and performance of the e-bike, and it is usually measured in watt-hours (Wh). The controller acts as the intermediary between the battery and the motor. It regulates the power output based on rider input, sensor data, and selected assistance levels. Many e-bikes are equipped with pedal-assist systems (PAS), which use sensors to detect pedalling speed, force, or cadence and provide proportional motor assistance. Some models also include throttle control, allowing the rider to engage the motor without pedalling. Finally, the drivetrain, which may include a traditional bicycle chain, gear system, and rear derailleur, works alongside the motor to transfer power to the wheels. In mid-drive systems, the motor utilizes the bike's gear system, which enhances efficiency and hill-climbing capability.

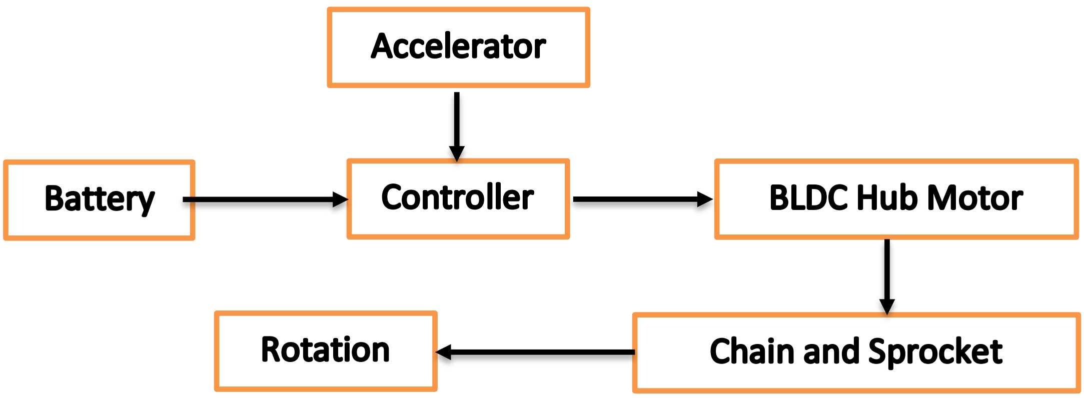

Figure 2: Block diagram of converting Electric Bicycle

Overall, the powertrain of an electric bicycle is a carefully integrated system that blends electric and mechanical components to improve rideability, increase range, and offer a sustainable mode of personal transportation. Figure 1 shows the block diagram of the proposed E-bicycle design and its component integration. The power transmission mechanism is shown in Figure 2.

III. MATHEMATICAL MODELLING OF POWER TRAIN

Mathematical modelling is an essential tool in analyzing and optimizing the performance of electric bicycle powertrains. By developing equations that represent the physical and electrical behavior of the system, it becomes possible to simulate performance, estimate energy consumption, and design efficient control strategies.

A. Mathematical modelling

The total power required to propel an electric bicycle is influenced by several forces acting on the system, such as rolling resistance, aerodynamic drag, gravitational force (especially on slopes), and inertial forces during acceleration. The total tractive force F_{total}

F_{total} needed at the wheels can be modelled as:

$$F_{total} = F_{rolling} + F_{aero} + F_{gravity} + F_{accel}$$

Where:

$F_{rolling} = C_r \, m \, g$ is the rolling resistance

F_{aero} is the aerodynamic drag

$F_{aero} = \frac{1}{2} \rho \, C_d A \, v^2$

$F_{gravity}$ is the gravitational component on an incline

$F_{gravity} = g\sin(\alpha)$

F_{accel} is the inertial force due to acceleration

$F_{accel} = ma$

Here:

- m: mass of the e-bike and rider (kg)
- g: acceleration due to gravity (9.81 m/s^2)
- Cr: rolling resistance coefficient
- ρ: air density (kg/m^3)
- C_d: drag coefficient
- A: frontal area (m^2)
- v: velocity (m/s)
- α: slope angle of the terrain
- a: acceleration (m/s^2)

The required mechanical power at the wheels is given by:

$$P_{mech} = F_{total} v$$

Assuming motor efficiency η_m, the electrical power drawn from the battery is:

$$P_{elec} = \eta_m P_{mech}$$

The energy consumed over a trip of time duration t is:

$$E = \int_0^t P_{elec}(t)\, dt$$

Additionally, in the case of a mid-drive motor, torque is distributed through the crankset and gear system. The motor torque T_m is related to the wheel torque T_w via the gear ratio G:

$$T_w = T_m G\, \eta_g$$

Where η_g is the efficiency of the gear system.

These equations provide the foundation for simulating ride conditions, optimizing battery capacity, sizing the motor, and designing control algorithms. With suitable numerical methods, they can be implemented in simulation environments like MATLAB/Simulink to validate performance under different real-world conditions.

B. Design Calculations

Mass Range Calculations

Person Weight	=	100kg
Battery Pack	=	6kg
Motor & Controller	=	4kg
Cycle weight	=	10kg
Total	=	120kg

So, Battery & Motor are required to propel the Bicycle with the weight of 120kg.

Motor Load calculation

F_p = Propulsion Force

F_{aero} = Windage & Friction Drag

F_d = Down force from Gravity

Consider the Grad @ 3.14%

$\alpha = \tan^{-1}(\text{slope})$

$= \tan^{-1}(3.14/100) = 1.8$ degree

To Finding Fd (Gradient Resistance)

$F_d = m * \sin\alpha$

$= 120 * 9.81 * \sin 1.8 = 37$ N

To Find F_{aero} (Aero Resistance)

$C_d =$ Aerodynamic Area Co-efficient = 0.74

$\rho =$ Density = 1.225kg/m3

A = Frontal Area of Bicycle = 0.37 m3

V = Velocity of Bicycle = 25 km/h = 6.94m/s

$F_{aero} = \frac{1}{2}\rho\, C_d A\, v^2$

= ½ * 0.74 * 1.225 * 0.37 * (6.94)2

= 8.07 N

To Find FR (Rolling Resistance)

$C_R =$ Rolling CO-efficient => 0.0041(for cycle)

$F_R = C_R$ mg cosα

= 0.0041*120*9.81*cos1.8

= 4.8 N

Total Propulsion Force, FP

$F_p = F_d + F_{aero} + F_R$

= 37+8.07+4.8

= 49.8 N

Propulsion Power = F_p * Velocity

= 49.8 N * 6.94 m/s

= 345.6 W

Thus, The Motor is to be 350 W

C. SELECTION OF BATTERY PACK

Battery is the main source to drive the motor, so as per the above design calculations, power required to drive the motor is obtained . Thus how long and how fast the ride required to be last is based on the battery capacity . The battery design calculations are mentioned below:

Range required: 30km

SPEED OF CYCLE: 25 km/hr

i.e., 25 km for 1hr and 30km for 1.2hr

345.6 W Power to be extracted for 1.2hrs, to cover 30km distance Therefore,

345.6 *1.2h = 414.72wh

414wh battery Pack is required

36v*11.5 ah=414wh

(or)

48v*8.62 ah=414 wh

Considering Cycle Applications And Safety

36V* 11.5Ah is selected , How many series? How many parallel?

Single lithium ion cell=3.6v, 2.5Ah capacity ,

thus 5 cells in Parallel = 5*2.5Ah

= 12.5Ah

10 such parallel cell group in series =10*3.6v

=36v

10S, 5P configuration will yield 36v 12.5Ah.

C Rating = (7.5*5) /12.5

= 3C For Discharge

Charging allowed is 0.5C = 05*12.5

= 6.25 Amps

Safe current is 0.2C = 0.2* 12.5

= 12.5AMPS

So, 42 V 2.5A Charger needed

D. CONTROLLER SPECIFICATIONS

36V*xA = 350W

X=9.7Ama

9.7< 37.5 - Battery is safe

9.7<13 ±1A – controller is safe

So 36v, 13 ±1A controller needed – normal voltage

FULL CHARGE (42V)

→ 42V*xA= 350W

→ X =8.3A

How Controller Works

42V * (0 to 8.3A) = 350W

41V * (0 to 8.5A) = 350W

40V * (0 to 8.75A) = 350W

31V * (0 to 11.3A = 350W

So Required Voltage, A = 11.3 < 13 ± 1 Amp

So, find Spec arrived

350W motor

36V 12.5Ah (450Wh) battery pack

36V < 13±1A controller

42V 2.5Amp charger is suitable for:

30Km range

25Km/hr

3.14% grade

120Kg cycle load

IV. INSTALLATION OF BATTERY, CONTROLLER AND OTHER PARTS

After connecting all cell wires to BMS we heat sealed the battery pack using a sheet of PVC heat wrap. we added fuses if the charging current is more than 5 amp. Then we got an IP 65 box for storing the battery pack to get additional protection for the battery. We drilled and made two holes for charging and output of the cycle. We made a stand for the battery using scrap metal and placed it in centre rod between the cycle handle and seat. We installed throttle, switch, light and horn to the handle bar. Then all connections from all parts are connected to controller. And the controller is cover with another IP box and placed it under the seat rod.

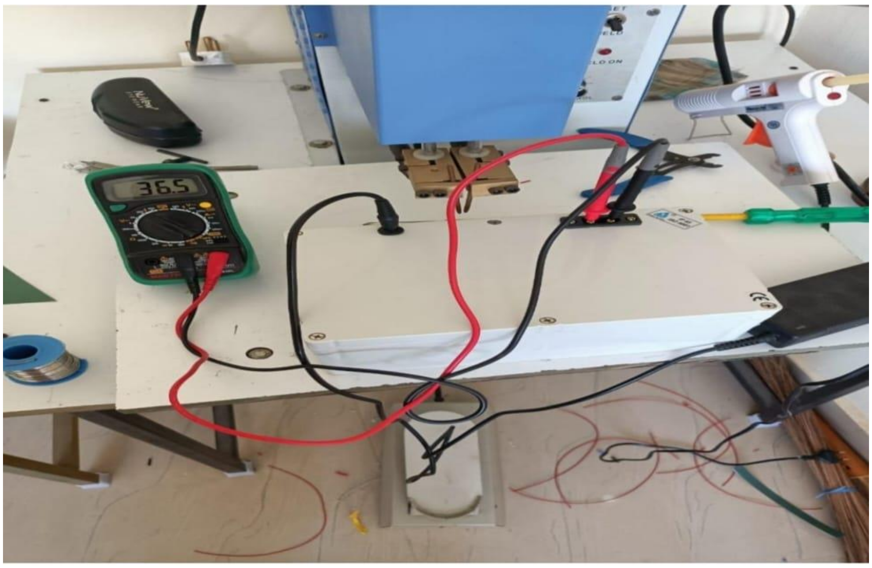

Figure 3: Battery Testing

V. TESTING OF THE ELECTRIC MOTOR BICYCLE

After completion of the conversion of E-cycle, we took it for testing it on road with different condition. So, the top speed was around 30 kmph with the range of 35+ km (depends on driving condition). The charging time was around 4hrs (0-100%).

The acceleration speed was good enough that it can pick up the top speed as soon the throttle is twisted.

VI. RESULTS & DISCUSSION

The performance of the electric bicycle was evaluated based on a combination of simulation results and real-world testing. Key parameters examined included speed, motor efficiency, battery usage, and range under various terrain conditions. The findings offer insight into the effectiveness of the proposed powertrain system and its suitability for urban and semi-urban commuting.

1. Speed and Acceleration

Under standard road conditions, the e-bike achieved a peak speed of 25 km/h, aligning with regulatory limits in many regions. The acceleration from 0 to 20 km/h was achieved in approximately 5.2 seconds on flat terrain, indicating a responsive powertrain performance. On inclined roads with a 5° gradient, acceleration was reduced by approximately 30%, which is consistent with the additional load calculated in the powertrain model.

2. Energy Consumption and Battery Performance

The energy consumption was observed to be around 12 Wh/km under normal riding conditions with pedal assist set to medium. The 36V, 10Ah lithium-ion battery provided an effective range of approximately 30–35 km per charge. These values are consistent with simulation predictions, validating the accuracy of the mathematical model used for force and power estimation. Battery voltage drop over time remained within safe operational limits, and no significant overheating was detected during extended use. This suggests that the motor and controller operated efficiently under the designed load conditions.

3. Powertrain Efficiency

The overall efficiency of the powertrain was calculated to be approximately 82%, taking into account motor losses, gear friction, and power electronics. Mid-drive motor configurations demonstrated better performance on slopes compared to hub motor setups due to torque multiplication through the bicycle's gear system.

Motor Specifications:

Compatible Motor	: Hub Motor
Body Material	: Aluminium
Cable Length(cm)	: 15
Current Limit(A)	: 15
Rated Voltage(v)	: 31 to 36
Rated Power(W)	: 350
Weight(gm)	: 211
Length(mm)	: 90
Width(mm)	: 50
Height(mm)	: 30

Table 1: Motor Specifications

Battery Specifications:

Type	Lead acid battery
Rating (AH)	7
Voltage rating	12V
No of batteries in Series	3

Table 2: Battery Specifications

E-Bicycle Prototype:

Figure 4: E-Bicycle Prototype

The results demonstrate that the electric bicycle powertrain is highly effective for short to medium-distance commuting, particularly in urban settings. The balance between performance and energy efficiency suggests that the proposed system meets practical user needs without excessive energy consumption. Variations in terrain and rider input were found to have predictable effects on energy usage, aligning well with the theoretical model.

VII. CONCLUSION

The study successfully demonstrated the design, modelling, and evaluation of an electric bicycle powertrain optimized for urban and semi-urban transportation. Through mathematical modelling and experimental analysis, the e-bike was shown to perform efficiently in terms of speed, torque, and energy consumption. The proposed design of E-bicycle has almost every feature compared to every cycle in market. It is cost efficient and it follows all the 3Rs i.e., Reduce, Reuse and Recycle of the eco system. A good lithium-ion battery which gives the range 40km (or even more, depends on the driving conditions.) and a top speed of 30 km/h.

VIII. FUTURE SCOPE

Future work may explore advanced battery technologies, improved regenerative braking mechanisms, and the application of intelligent energy management systems to further enhance the performance and sustainability of electric bicycles.

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