# ECE 445 - Design Document

Electric Bicycle with Fully Electric Architecture

Spring 2023


Team 15

Ellie Urish

Jason Zou

Willard Sullivan

## Table of Contents

# 1 Introduction

**1.1 Our Problem**:

Most current electric bikes use a combination of chain and motor to provide pedal assistance. The issue with these systems is the complexity of dealing with a chain and motor simultaneously. The complexity of these systems that are constantly exposed to the elements means that durability is a concern. This problem is especially prevalent with bike sharing programs, where easy maintenance and care is essential to keeping costs down.

**1.2 Our Solution:**

Our idea is to construct an electric bike/moped that is fully powered by electricity, which means that instead of using a chain to transfer human power to the wheels, the pedals would instead be connected to an electric generator which would then feed a motor for the wheels.

While this configuration is not as efficient for driving the wheels as a direct chain would in terms of just human power, it allows for a very simple mechanical design with few moving parts. This could allow for very little maintenance, as there is no longer a chain or gears to take care of. Furthermore, most of the components can be sealed away from the elements by mounting them internally to the bike frame or within sealed containers that can be mounted to the bike frame. Additionally, an all electric system would also allow for regenerative braking (a reach goal) to be implemented more elegantly, allowing for energy to be recovered during braking and a better experience on hilly terrain while also reducing wear on the brakes.

**1.3 High-Level Requirements List:**

- The Power System will be able to effectively charge the 36V battery with power from the pedal-generator and then route ~36V from the battery to the hub motor. The Power System must also be able to supply the 5V that is required to power the microcontroller.
- Rear wheel motor can propel the vehicle to 5 mph on flat ground with ~180 pounds of load.
    - Note that this is a prototype, ideally this vehicle will be much more capable.
- Motor speed can be controlled through a throttle system by the user.
- Must have at least 40% efficiency of power conversion from pedaling to electricity.

**1.4 Visual Aid:**

Below is an artistic rendering of our prototype, which includes all of the major components or additions of our project. Please reference the 2.5 Physical Design section for specifics on implementation. Furthermore, note that colors in the visual aid do not correspond to colors used in the Block Diagram.

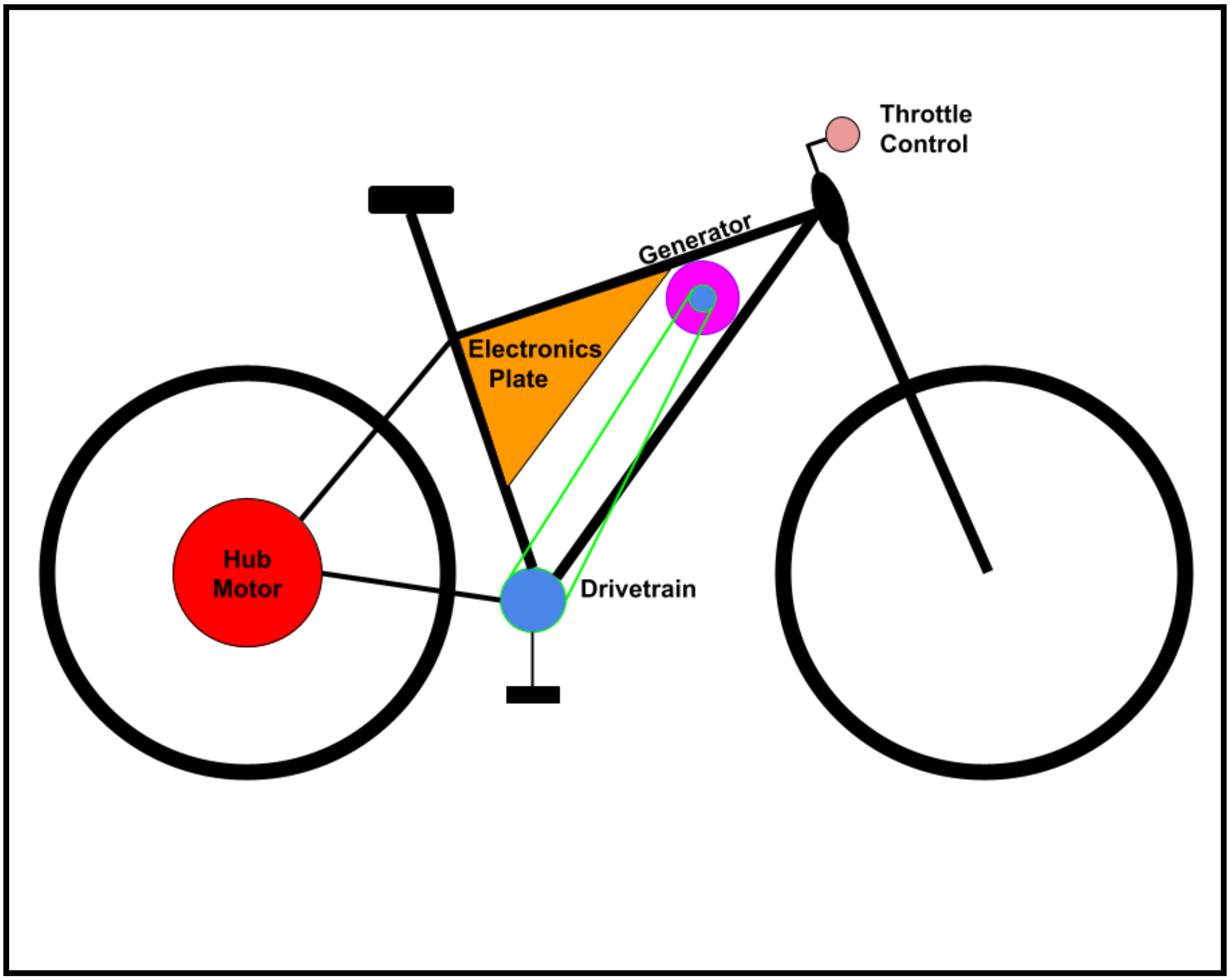



*Figure 1: Artistic rendering of our physical design.*

# 2 Design

## 2.1 Block Diagram:

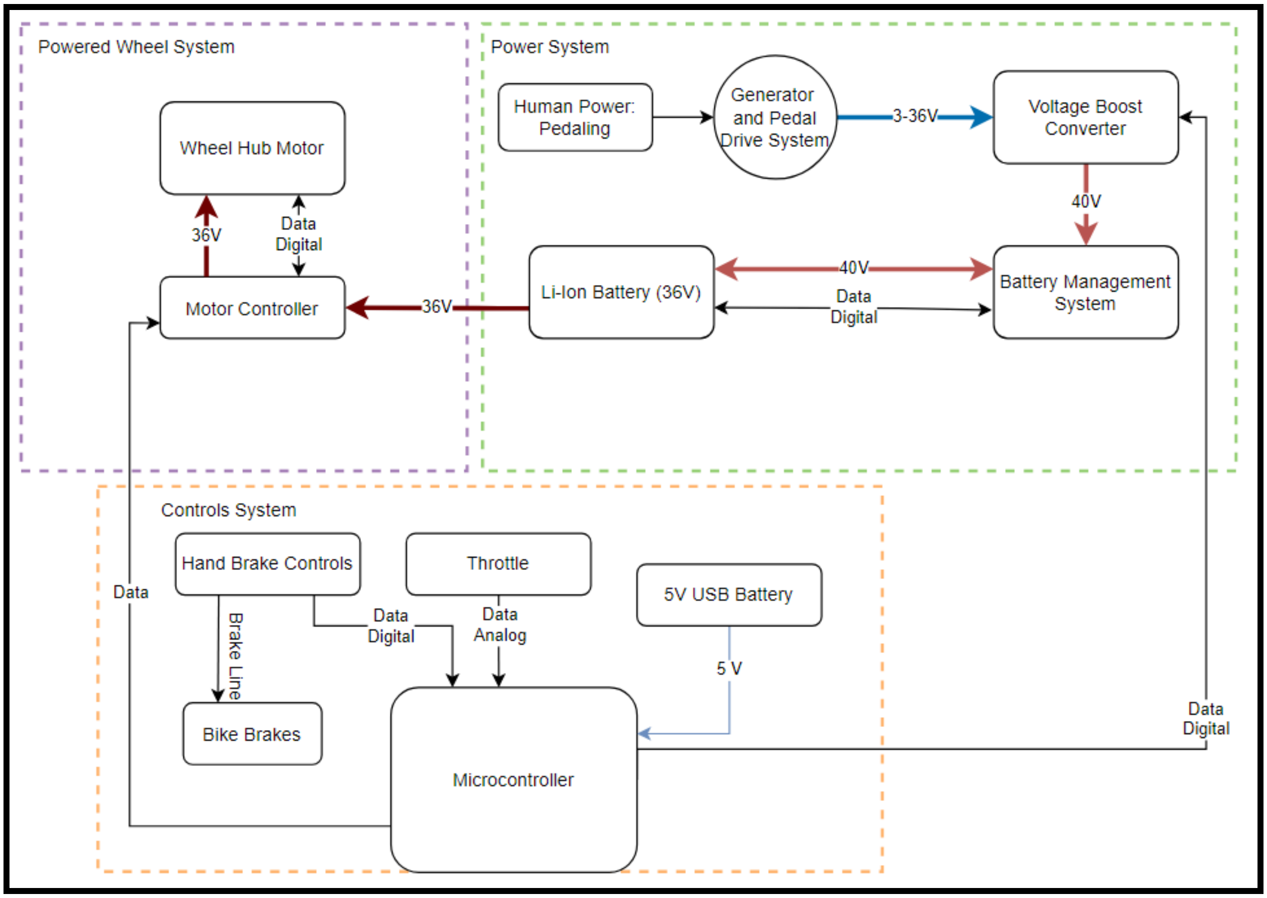



*Figure 2: The Block Diagram of our electrical design.*

## 2.2 Subsystem Overview:

Subsystem 1 - Power System

The purpose of the generator is to generate electricity from the mechanical rotation of the pedals, aided with a chain with a sprocket ratio to achieve a better mechanical advantage. We are using a 36V DC motor as our generator, which is connected with a short chain to the pedals. The generator is connected to a 36V switching boost converter to provide a steady voltage level for the battery charging. The battery is used to power the rear wheel hub motor. It is also used to power the control system at a stepped down 5V.

The main responsibility of the power system is to facilitate the charging of the battery with the pedal generator. This generator produces variable voltage levels depending on the speed, so we require a switching boost converter to produce a constant 36V for the battery charger. The power system gets input from the control system for this process. The generator will only be allowed to charge the battery when it is producing enough voltage for the converter to achieve

36V, this can be monitored with a pin on the converter that outputs whether it is producing the desired voltage.

The power system is also in charge of distributing the power from the battery. It provides 36V to the rear motor controller and 5V to the control system through a linear regulator.

| Requirement | Verification |
|---|---|
| Supply 36V +/- 1V to the Powered Wheel System at up to 7A | Set throttle to full speed, insert voltage and current probes between battery and motor. |
| Supply 5V +/- 0.1V to the Controls System at up to 500mA | Measure voltage and current from battery to PCB header. |
| Regulate input from generator to charge battery: supply constant 36V from switching converter to battery charger | Measure voltage output from the switching converter while pedals are turning, ensuring that it is a steady 36V. Bring the generator to a stop, and ensure that the switching converter turns off when the generator is no longer producing sufficient voltage. |

Subsystem 2 - Powered Wheel System

The rear wheel is powered by a 36V hub motor that is built into the center of the wheel. This motor takes power from the power subsystem and receives speed control signals from and sends encoder data to the microcontroller. The rear motor's speed is controlled by a twist throttle on the handlebars, and the wheels can be brought to a stop with standard bike hand brakes. We use a software PID controller on the MCU to regulate the speed of the rear wheel.

The internal hub motor is connected to a motor controller, which handles power and speed signals. This allows us to abstract motor control to a speed and direction, instead of having to drive the actual motor leads.

| Requirement | Verification |
|---|---|
| Drive hub motor with 36V | Connect to the battery, ensure wheel turns. |
| Accept speed control from MCU as an analog 5V signal | Turn throttle from off to full, ensure wheel ramps up in speed and remains steady when throttle is held at a fixed setpoint. |
| Transmit encoder signal to MCU | Spin the rear wheel at a fixed speed, measure this speed with a tachometer. Output encoder reading from MCU, and ensure that the values match up. |

Subsystem 3 - Controls System

The controls system is housed on a custom PCB. It contains two soldered-on chips: a microcontroller and a switching boost converter. It is connected to the battery, the generator, the rear motor, and the throttle. The software on the MCU has several functions: It determines the rear motor setpoint from the throttle and regulates its speed, it monitors the status of the generator and enables the boost converter to begin charging the battery if the generator is producing enough power, and it also monitors the battery's charge level and disables the power to the rear wheel if the battery drops too low.

The throttle is implemented with a potentiometer, which acts as a voltage divider. Reading the voltage across the throttle with the MCU will allow us to determine the desired speed. Given our setpoint, we use a software PID loop to adjust the input to the motor controller based on the measured speed from the encoder. This allows us to drive the rear wheel at a desired speed, rather than controlling the power we send to it.

The control system provides signals to the power system to control battery charging. When the pedal generator is turning it can generate a varying voltage and may sometimes drop too low. This causes the switching converter to be unable to produce a steady 36V, which is indicated to the MCU through an output pin. If this happens, we disable the switching converter and the battery charger. We also wish to disable charging if the battery reaches 90% capacity. On the other side, we also disable the entire rear wheel system if the battery drops to 10% capacity or below; if it drops below this capacity, its voltage can drop to an unusable level under load.

| Requirement | Verification |
| --- | --- |
| Read desired speed from throttle as a 5V analog signal | Turn throttle back and forth, ensure reading on MCU is accurate. |
| Regulate speed of rear motor and correct for error with encoder signal using a PID control loop | Set the rear wheel to a specific speed, measured with a tachometer. Ensure that the wheel maintains setpoint when resistance is applied to the wheel with the handbrake. |
| Control charging/discharging of the battery | Ensure that the MCU can read the current charge status of the battery. Pedal the wheels until the generator is up to speed, ensure that the battery begins charging. Let the battery charge level drop to 10%, and ensure that the system stops sending power to the rear wheel. |

**2.3 PCB Schematic:**

Below is an early schematic of our PCB, where we have two main circuits - the microcontroller circuit and the boost converter circuit. We based the Microcontroller circuit based off of information provided on the ECE445 website, online documentation about pin layouts and implementation, as well as our preexisting knowledge on microcontrollers. Additionally, we based our boost converter circuit on the one provided on the provided TI's part manual as well as the Webench generated schematic. The Webench schematic is shown below.

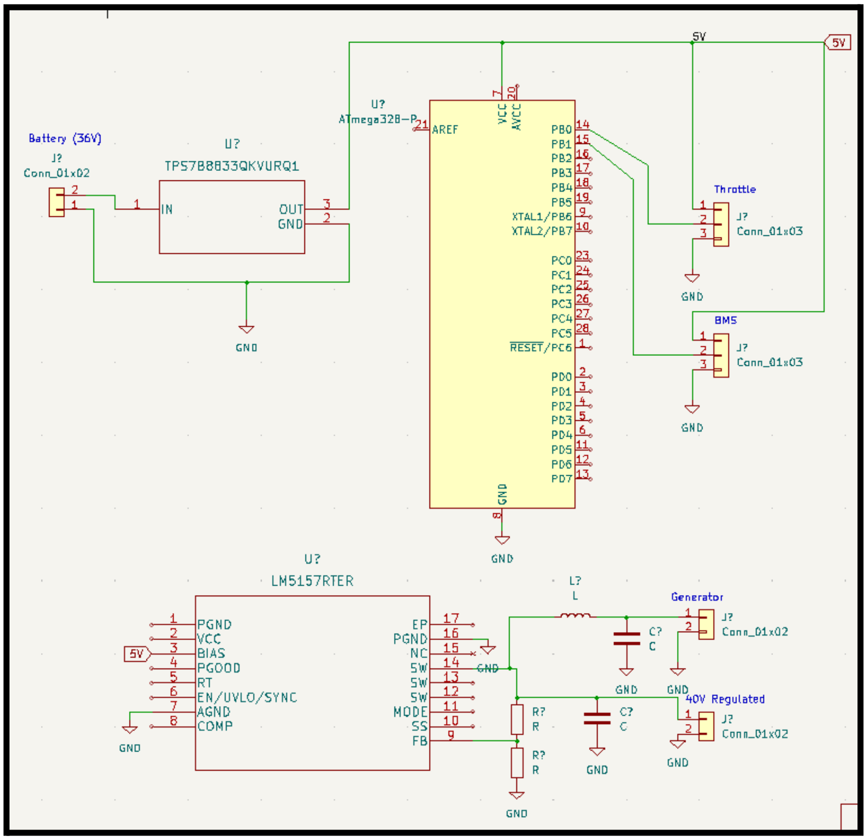



*Figure 3: Early PCB design in KiCAD.*

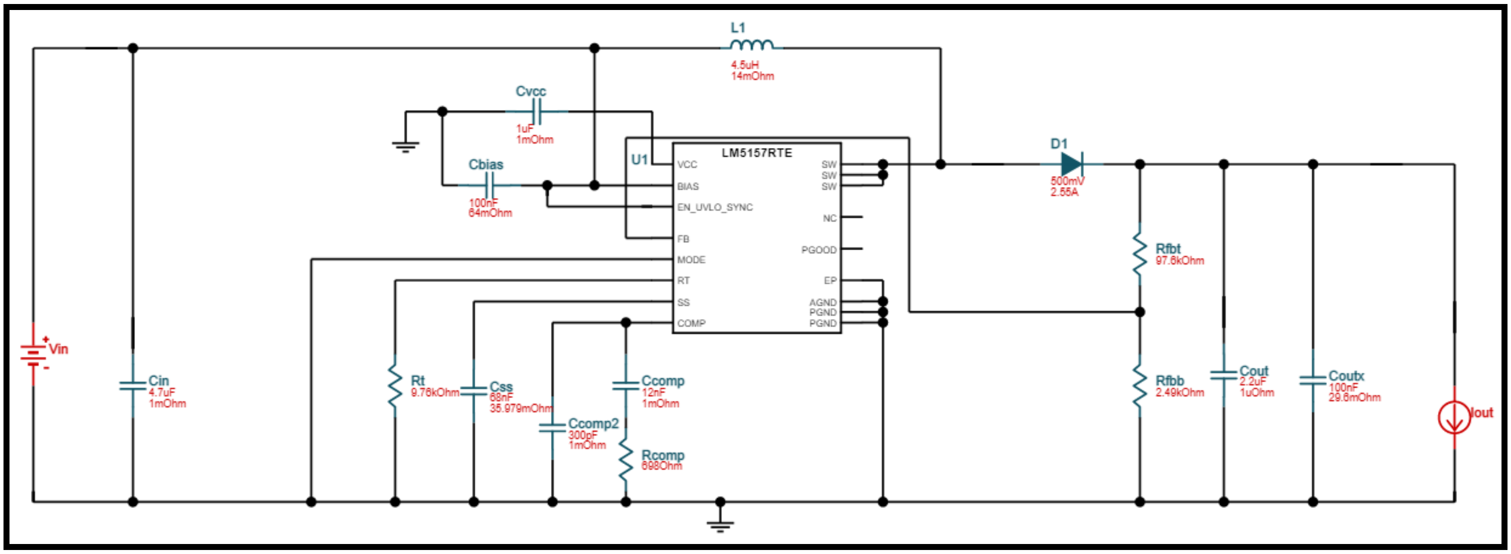



*Figure 4: Boost Converter LM5157 design schematic.*

**2.4 Tolerance Analysis:**

A critical part of our design is the switching boost converter, which regulates the lower input voltage of the pedal generator to a consistent 40V for charging the battery. This ensures that we can harness the unstable input power of the pedals. To show the feasibility of regulating input voltages of 10-20V to 40V, we used Matlab Simulink to simulate the operation of a switching converter, connected to a resistive load that mimics the power requirements of our battery charger. The circuit is shown below, it is a modified version of the Matlab boost converter example, with input and output voltage tweaked to represent our application:

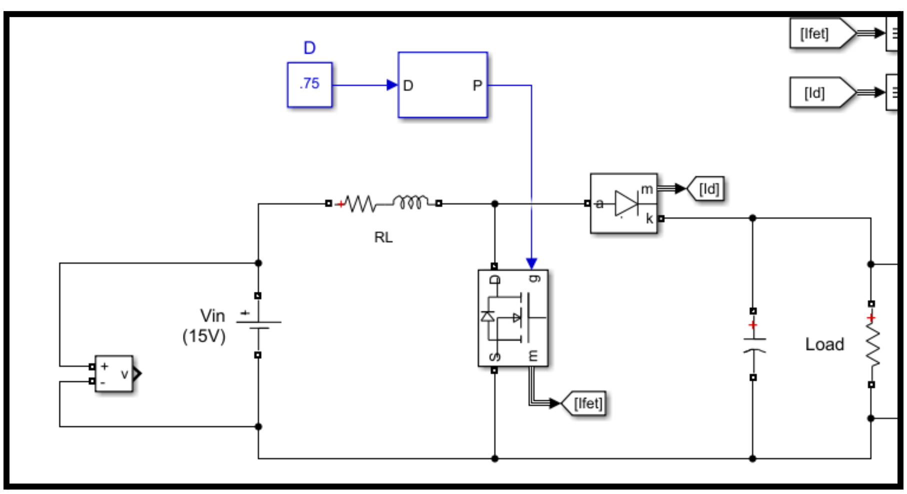



*Figure 5: MATLAB Simulink simulation schematic.*

Below we show the performance of the regulator circuit at 10V, 15V, and 20V input voltage, simulated for 100ms:

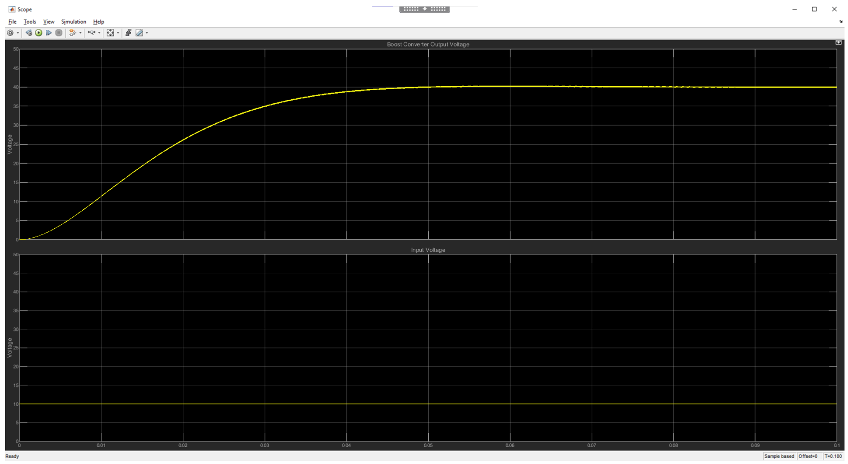



*Figure 6: Simulation output with a 10V input.*

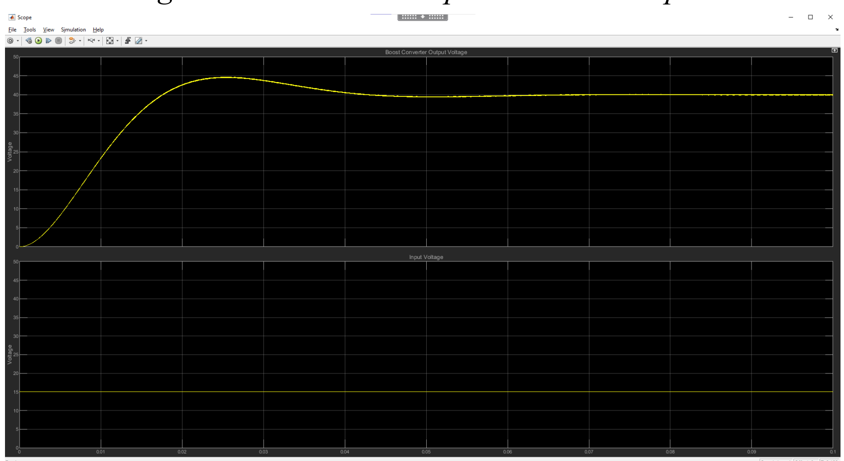



*Figure 7: Simulation output with a 15V input.*

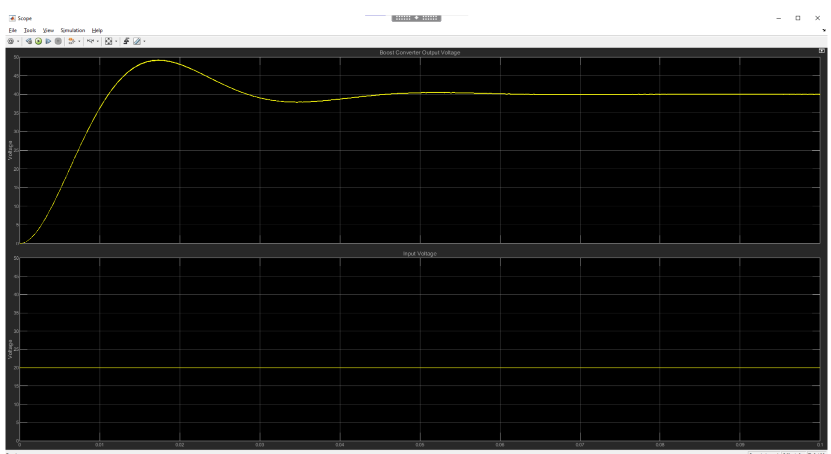



*Figure 8: Simulation output with a 20V input.*

As shown in the simulation, this type of converter is capable of stabilizing at our desired output voltage, and holding it within the +-1V range we require. There is a concern about the transients present at higher input voltages; in the case of 20V input, the output voltage spikes to +10V above our desired output voltage. This is because this simulation is effectively open loop control as there is no feedback to the system of the actual output voltage. In our design, we use a TI LM5157 chip which has closed loop control; it receives the output voltage as feedback to the system and can compensate for the error more effectively. An example of this compensation system is shown below, the feedback is fed through a PID controller which controls the duty cycle of the gates.

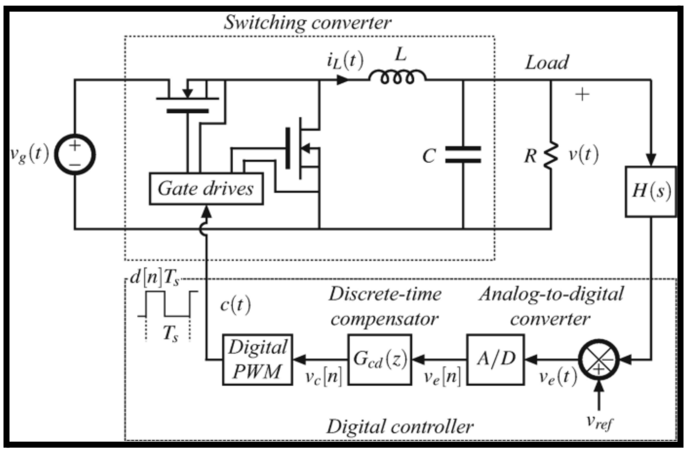
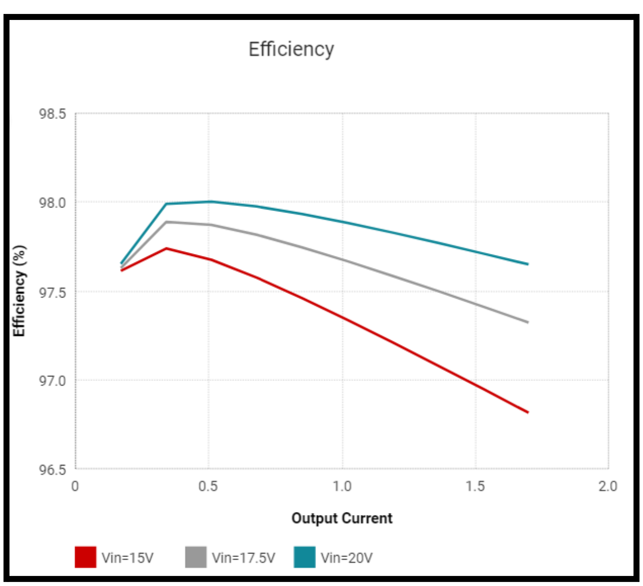
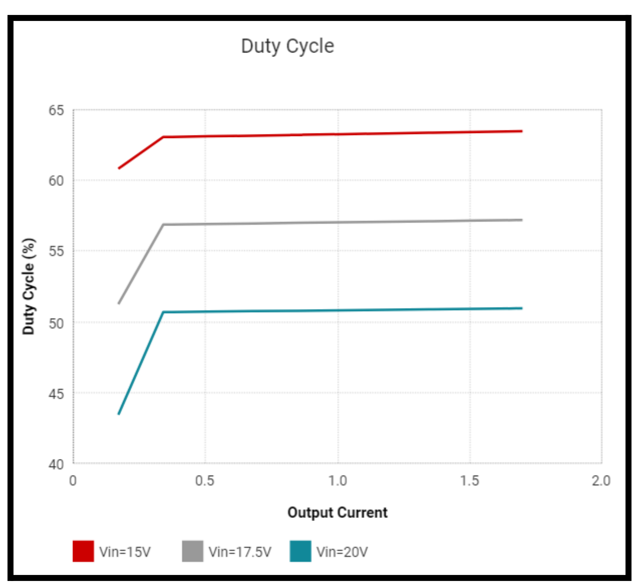



*Figure 9: Design for a Boost Switching Convertor with a control system.*

Additionally, we used TI's Webench online simulator to further design and simulate the boost converter circuit. With this tool, we were able to confirm that our desired input voltage range can be accepted to return the output voltage that we desire, in which the efficiencies and duty cycles vary by input voltage and output current. We were very pleased with the results, where the efficiency ranges from 96-98% and the duty cycle from 50-65%, which will charge the battery at a reasonable rate.



**2.5 Physical Design:**

Design as a Whole

Due to time and resource constraints, our prototype will not be as mechanically refined as we would prefer. Instead, we will focus more on the electronic and power aspects of the design. However, our prototype will still operate very similarly to an ideal end product. We are working extensively with the ECE Machine Shop so that we can build the best prototype possible with our constraints. Additionally, please refer to the Visual Aid on section 1.3 for a schematic of our prototype.

The bike that we have chosen for this project is a rigid-style mountain bike, which is being provided by the machine shop. We decided to choose this type of bicycle as it has a rigid frame that replicates typical commuter or ride-share bicycles and provides easier mounting points for our various electronics, such as the generator or the PCB. The strength of the bike is crucial to our design as it is the frame in which all of the subsystems are attached. An image of a similar bike is below.

*Figure 10: A similar bicycle to the one we decided to use.*

Generator Drivetrain

The most complex mechanical aspect of our design will be the generator drivetrain system, where we have decided to use a chain and sprocket system. One of the reasons we were inspired to initiate this project was due to our past experiences with a chain system, which are often cumbersome without the proper care. Furthermore, a goal for this project was to keep as many of the parts internal to the bike, which we had to set aside to accomplish the prototype. We initially wanted to connect the axle of the motor to the bike's crank; however, this was deemed to be infeasible due to the small inner diameter of the bike's bottom bracket, which is the section of the frame that houses the bearings for the crank. We next tried to develop a driveshaft system, where the driveshaft would be run through the bike's downtube, but this was deemed too complex to achieve in our short timeframe. Below is an initial sketch of our driveshaft system.

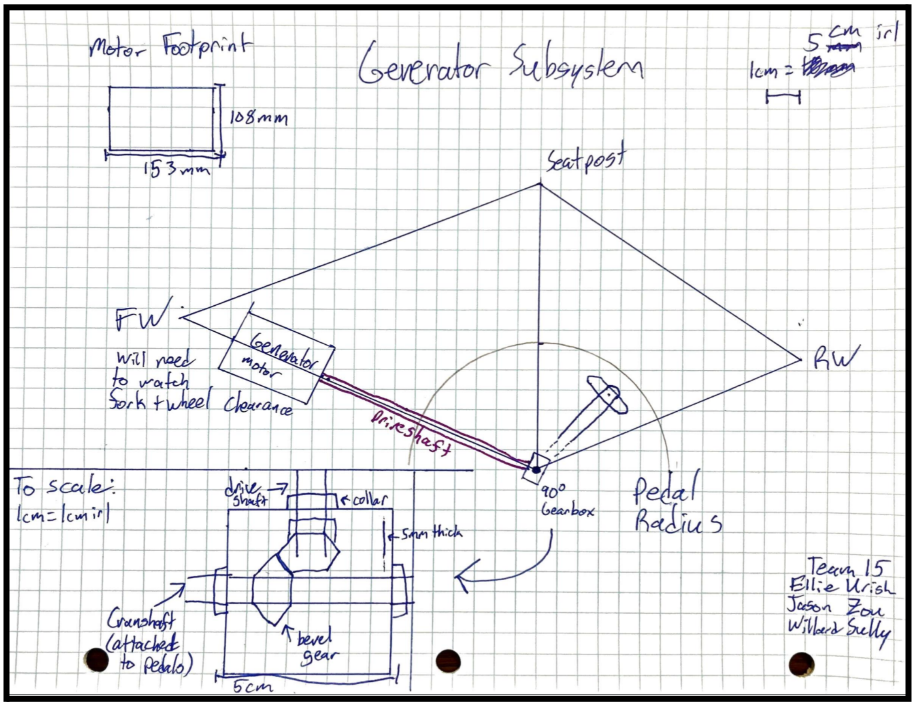



*Figure 11: Our initial physical design implementation.*

Finally, we settled on a chain drive system, where the generator would be mounted close to the top of the headtube and be connected to the preexisting chainrings. Although we need to smooth out some aspects of the generator mounting system, it will likely be attached by mounting it to a metal plate and then securing it to the bike with hose clamps. An additional benefit to this system would be the additional mechanical advantage provided by the difference in size of the chain ring with respect to the sprocket on the motor; the user can spin the generator much faster with a larger chain ring with a smaller sprocket. For example, with a 5:1 gear ratio, where the input gear has 50 teeth and the output gear has 10 teeth, the user can produce an output angular velocity 5 times greater than their input velocity. With this comes some mechanical aspects that we need to consider, such as the ideal gear ratio for a user who is pedaling at a constant rate.

<u>The Rear Hub Motor</u>

Another major component of our product is the hub motor wheel, which is an electric motor attached to the hub of the rear wheel - this gives the motor the ability to rotate the wheel and thus move the bicycle. For this project, we have obtained a 26'' Bafang 36V hub motor and wheel combination. This component will replace the given rear wheel on the back of the bicycle.

<u>The Other Electronics</u>

The other components, such as the PCB, motor controller, and battery, will be mounted to a plexiglass plate that is then mounted to the bicycle. Ideally, we are able to 3D Print enclosures for the electronics to protect them from varying environments. This plate will be mounted to the bike frame with hose clamps or zip-ties. Depending on the size of the battery, we may have to alter the mounting location of this component.

## 3 Ethics and Safety

With any transportation device, the user not only assumes various types of risk, but also is able to assume a level of trust with their vehicle. As outlined in Section 1.2 in the ACM Code of Ethics, the statement “ensure that all harm is minimized” [1] stands out to us. To ensure we achieve this, one of our requirements is to keep the three subsystems adequately contained so there is no risk of electrocution. Furthermore, we plan to limit the acceleration and top velocity of the bicycle to discourage reckless use. The main braking system of the bicycle will also be a standard bicycle braking system that is mechanical and separate from the main control system to ensure that the user will always be able to come to a stop safely.

Our product falls into a gray area - it is not necessarily a bicycle, nor is it a Moped. In the State of Illinois, our type of vehicle falls best in the Electric Bicycle category, which is a bicycle that has some sort of assistance by a gas or electric motor. These vehicles, in the state of Illinois, “are legally bicycles, as long as their motors are smaller than 750W (one horsepower) and their pedals are fully functional.” [2]. Electric Bicycles are subject to the same laws as bicycles, but also do not require insurance nor registration - to abide by the ACM Code of Ethics, we will encourage users to have some type of liability insurance or make sure they are well versed in the risks of using this type of vehicle, including wearing usual protective equipment such as a bicycle helmet.

Our product requires a 36V Lithium-Ion battery that will be used to power the bicycle, but also will be charged with a pedal-generator, which will output ~40V. While these types of batteries are relatively safe, they can easily become a fire or explosion hazard when proper care is ignored; especially since the battery is on a moving vehicle outdoors, a proper enclosure with a cooling system is essential. Furthermore, to prevent other electrical failures, we will follow safety guidelines sent in place by OSHA (Occupational Safety and Health Administration) [3] and by the ECE Department, which include:

- Charging the battery per the manufacturer's instructions and maintaining safe battery charge capacities between ~10% and ~90% and temperatures
- Ensuring our PCB does not short components and designing our PCB in such a way as to minimize shorting risks
- Storing the battery in a safe environment with an insulating cover on the terminal leads.
- Ensuring that fire safety equipment such as a fire extinguisher and battery bag are always present and aware

## 4 Cost Analysis

Below is an image of our cost analysis, which includes pricing on parts, components, and labor. For an interactive cost analysis, visit Cost Analysis. Note that a detailed component itemized list is below, where each component has a quantity of 2.

| Item/Part | Cost | Link | Notes | Group Member | Hours per Week | Notes |
|---|---|---|---|---|---|---|
| 36V DC Electric Front Bike Wheel | $0.00 | https://jaq35.co | This wheel is originally $45, however, an associate allowed us to borrow theirs. | Willard | 10 | |
| 36V DC BY1020D Motor | $0.00 | https://electricsc | This motor is originally $65, however, the Machine Shop allowed us to borrow theirs. | Ellie | 10 | Assuming Group Members make $30/hr, we will calculate the total cost using: ($/hour) x 2.5 x hours to complete. |
| 36V 8A eBike Battery | $45.00 | https://jaq35.co | We might opt to use a different battery, but one of similar specifications. | Jason | 10 | |
| 36V Motor Controller | $20.00 | https://www.ama | We might opt to use a different controller, but one of similar specifications. | Machine Shop | 2 | |
| eBike Handlebar Throttle Control | $0.00 | https://www.ama | The Throttle Control is roughly $20, however, an associate allowed us to borrow theirs. | | | Cost calculations will assume work over 12 work weeks. |
| Bike | $0.00 | | We are using a bike provided from the Machine Shop. | | | |
| PCB / Components | $8.72 | | This includes necessary components, such as resistors and capacitors. Itemized list below. | | | |
| Microcontroller | $5.00 | | | | | |
| QFN - DIP Adapter | $14.22 | https://www.digi | Quantity - 2. This is for ease of use for boost converter chip | | | |
| Boost Converter | $6.58 | https://www.ti.co | Quantity - 2 | | | |
| Other Parts | $15.00 | | | | | |
| Item/Part Total Cost | | | | Work Total Cost | | |
| $114.52 | | | | $28,800.00 | | |
| Grand Total | | | | | | |
| $28,914.52 | | | | | | |

| Name | Component | Cost |
| --- | --- | --- |
| CIN | 4.7 uF Capacitor | $0.36 |
| CSS | .068 uF Capacitor | $0.20 |
| L1 | 10 uH Inductor | $3.36 |
| RCOMP | 698 Ohm Resistor | $0.20 |
| RFBB | 2.49 kOhm Resistor | $0.20 |
| RFBT | 7.6 kOhm Resistor | $0.20 |
| RT | 9.76 kOhm Resistor | $0.20 |
| CBIAS | .1 uF Capacitor | $0.20 |
| CCOMP | .022 uF Capacitor | $0.20 |
| CCOMP2 | 300 pF Capacitor | $0.34 |
| COUTX | .1 uF Capacitor | $0.20 |
| CVCC | 1 uF Capacitor | $0.20 |
| D1 | 60V, 2A Diode | $0.92 |
| COUT | 2.2 uF Capacitor | $1.94 |
| Total | | |
| $8.72 | | |

## 5 Schedule

Below is the schedule breakdown for our project over the course of the semester, which details the week a task should be initiated and the person/persons responsible for that task.

| *Week* | *Task* | *Person* |
| --- | --- | --- |
| 02/20/2023 | Start PC Design | Everyone |
| | Research Boost Converter, Microcontroller | Ellie/Everyone |
| | Research Compatible Battery and Charger | Jason |
| | Start bike repair | Willard |
| | Discuss mechanical design with Machine Shop | Everyone |
| | **Complete Design Document** | Everyone |
| | **Complete Team Contract** | Everyone |
| 02/27/2023 | Continue PCB design for First Round Order | Willard |
| | Continue Machine Shop mechanical discussion | Everyone |
| | Model Boost Converter in Simulink | Willard/Ellie |
| | Find compatible motor controller | Jason |
| | Finalize PCB BOM | Willard |
| 03/06/2023 | Explore PID control design for speed control | Willard/Ellie |

| | | |
|---|---|---|
| | Finalize Machine Shop mechanical discussion | Ellie |
| | **Teamwork Evaluation 1** | Everyone |
| | Order Battery, Motor Controller | Jason |
| 03/13/2023 | **Spring Break** | Everyone |
| | Continue discussions on PID speed control | Everyone |
| 03/20/2023 | Assemble PCB | Willard/Ellie |
| | Gather data on Hub Motor for PID design | Jason/Ellie |
| | CAD Model for board enclosure | Willard |
| | Begin programming the Microcontroller | Jason |
| 03/27/2023 | **Finalize PCB for Second Round Order, Pass Audit (03/28)** | Everyone |
| | Debug PCB1 - Microcontroller | Jason |
| | Debug PCB1 - Generator | Willard |
| | Debug Software | Ellie |
| 04/03/2023 | 3D Print Enclosure, if applicable with Machine Shop design | Willard |
| | Debug PCB1 - Microcontroller | Jason |
| | Debug PCB1 - Generator | Willard |
| | Debug Software | Ellie |
| | Cross Check - Debug | Everyone |
| 04/10/2023 | Final Testing and integration - Software | Ellie |
| | Final Testing and integration - PCB - Microcontroller | Jason |
| | Final Testing and integration - PCB - Generator | Willard |
| | Prepare for Mock Demo | Everyone |
| 04/17/2023 | **Mock Demo** | Everyone |
| | Final touches - Mechanical / PCB | Jason |
| | Final touches - Software | Ellie |
| | Begin Final Paper | Willard |
| | Prepare for Final Demo | Everyone |
| 04/24/2023 | **Final Demo** | Everyone |
| | Prepare for Presentation | Everyone |
| 05/01/2023 | **Final Presentation** | Everyone |

## References


1. “The code affirms an obligation of computing professionals to use their skills for the benefit of society.,” Code of Ethics. [Online]. Available: https://www.acm.org/code-of-ethics. [Accessed: 09-Feb-2023].
2. “Illinois laws for moped, scooter, and Electric Bikes,” Horwitz, Horwitz & Associates, Ltd., 16-Sep-2022. [Online]. Available: https://www.horwitzlaw.com/blog/illinois-moped-laws/. [Accessed: 09-Feb-2023].
3. “Preventing fire and/or explosion injury from small and wearable lithium ...” [Online]. Available: https://www.osha.gov/sites/default/files/publications/shib011819.pdf. [Accessed: 23-Feb-2023].
4. “Boost Converter,” Mathworks [Online]. Available: https://www.mathworks.com/help/sps/ug/boost-converter.html [Accessed 23-Feb-2023]