BikeBike Revolution: Energy Efficient E-Bike

ECE 445 Design Document

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1. Introduction

1.1 Problem and Solution Overview

Biking is a longtime hobby and top choice of exercise with a broad audience. Indoor cycling in particular has been a great form of activity that is currently on the rise in popularity [1]. While cycling burns energy for the purpose of staying fit, there are more optimal applications for this mechanical power: to convert it back into electrical energy and use it to power the bike, thus turning the bike into an electrically assisted E-bike. Many advantages can come out of this situation as the energy put into and coming out of the system is largely efficient. Developing a solution to enable the E-bike to double as an indoor and outdoor bike can help users save financially, enjoy the hobby, and exercise in multiple environments - whether stationary or covering real ground.

Our solution is to allow a pedal-assist E-bike to convert into an indoor stationary bike, and to use the energy generated from pedaling indoors to power the E-Bike for use outdoors. The amount of energy generated after pedaling for an hour is about 80 Wh including losses, while the average fully electric E-bike is rated between 300-1000 Wh [2], [3]. The amount of power generated is feasible in an electrically-assisted bike, which can be rated as low as 144 Wh. We plan to implement a multi-input system to allow the battery to adapt to the grid to ensure a reliable energy source if needed. The design includes an indoor stand to support the bike for safe use indoors with the hub motor / generator, battery, and power electronics mounted on the bike frame itself. The power electronics system consists of DC-DC and AC-DC power conversion, as well as a digital control circuit.

1.2 High-Level Requirements List

1. From full charge, the bike must be able to travel with electric-assisted power from a range of 50W to 250W and travel with a rate of at least 10mph.
2. In generator mode at a maximum input, the bike should be able to generate at least 100W of power by the user pedaling the bike. In this mode, the bike must also be able to switch to using power from the grid in order to get charged.
3. The DC-DC converter must be able to exhibit at least 75% efficiency when taking in varying values of voltage output from the generator.

2. Design

2.1 Block Diagram

Our block diagram consists of four interconnected subsystems: the power electronics, hub motor / generator, control module, and sensing module. The major components that drive the system's longevity, effectiveness, and efficiency are within the battery, converters, controls, and the motor. The ratings on these parts are integral to satisfy our requirements of enabling pedal-assist functionality for a certain amount of time, as well as charge the bike at a satisfactory pace in generator mode. The efficiency of power transmission as shown in Figure 2 is not only achieved by these main components but also by direct data transmission between the modules through the digital controls and sensors.

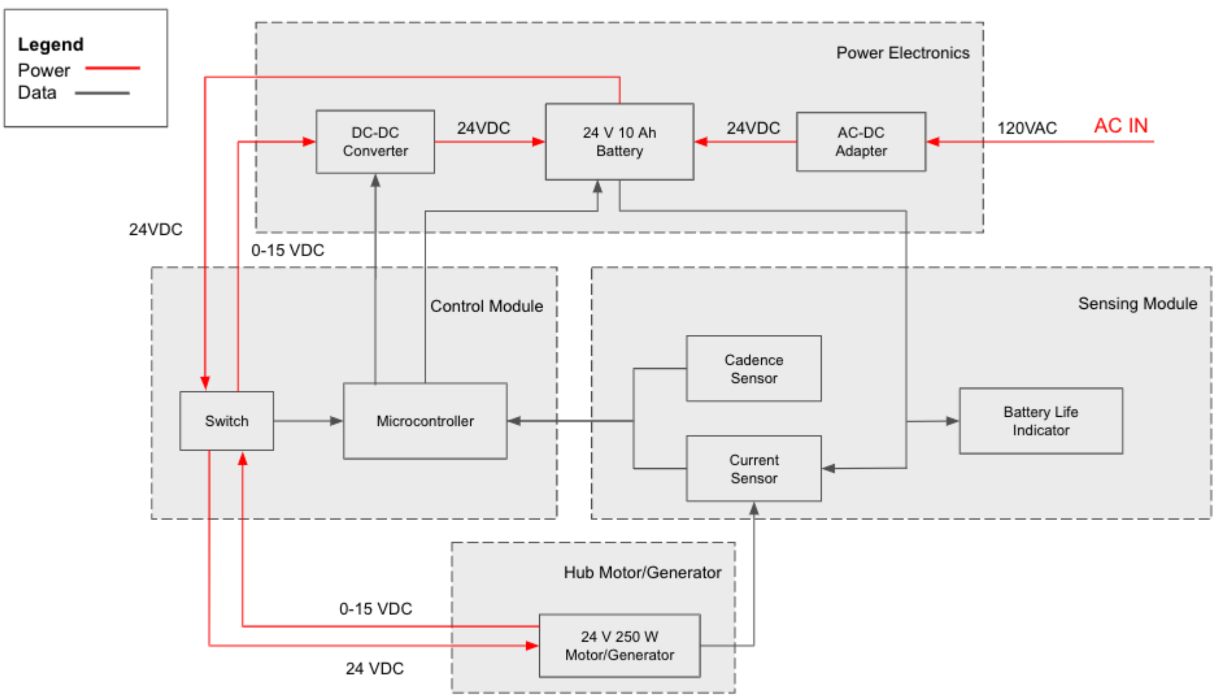

Figure 1. Block Diagram for BikeBike Revolution.

2.2 Physical Design

Our adaptive E-bike will contain almost all of the subsidiary components in our design, including the motor driving on top of the rear wheel secured by a mounting bracket. The power electronics and battery are attached to a plate that is secured on the frame of the bike. An available outlet on the battery will charge the battery using the grid. The cadence sensor will be connected to the chain rings of the pedals. We will be using a Schwinn World Tourist Road Bike, with the frame that is drawn in Figure 2. Two stands will also be designed to support the bike while it is being used indoors as the rear wheel will need to run freely in order for the generator to function. All components will be interfaced with robust wires that connect between the motor, cadence sensor, power electronics, and battery.

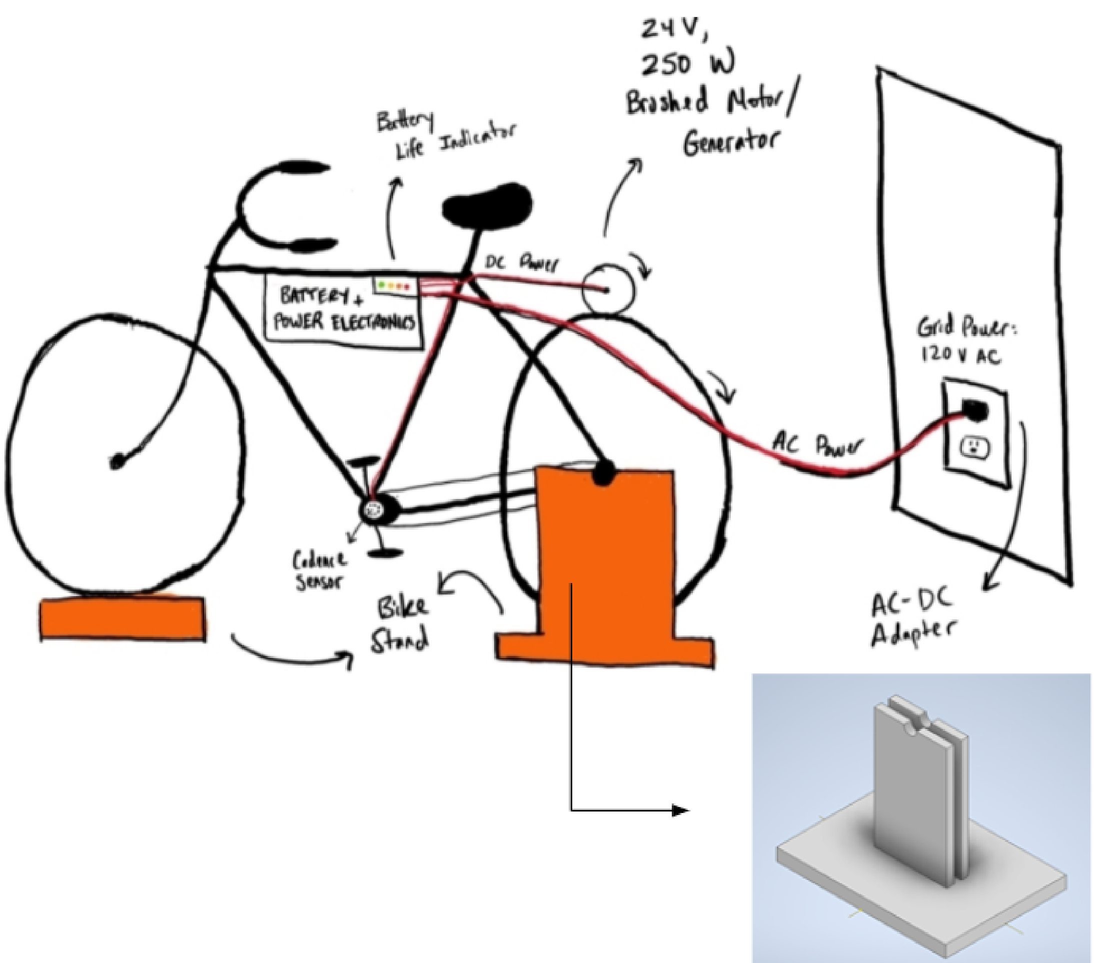

Figure 2. Simple Drawing of Integrated Elements of BikeBike Revolution and Preliminary Indoor Bike Stand CAD Model.

2.3 Power Electronics

2.3.1 Battery: The 24 V, 10 Ah battery is where the power used in the system is stored. Depending on the signal from the microcontroller, it can either discharge current to the switch and to the motor or take in current from the AC-DC adapter or the DC-DC converter, which charges the battery at a rated voltage.

Requirement	**Verification**
Must be able to power the motor for at least one hour at range of 50 W to 250 W from full charge	A. Directly connect the battery to the motor B. Let the motor run until the battery is out of charge and ensure that the motor is able to run for at least an hour

2.3.2 Grid Power: The 120 V AC power supply coming from the standard American outlet will be also utilized in this system as a way of providing a powerful and reliable energy source to the E-Bike if necessary. This source will be indirectly charging the DC battery on the bike.

Requirement	**Verification**
Outputs a constant 120 V AC power	A. Measure output terminals with a multimeter to confirm expected value B. Effectively connects to AC-DC adapter through the plug

2.3.3 AC-DC Adapter: An AC to DC power conversion needs to be made in order to connect the 120 V AC grid power to the 24 V battery. We decided to use a 100-240 V AC to 24 V DC adapter for this step as it is the simplest and has easy accessibility for implementation to the rest of the system.

Requirement	**Verification**
Takes in 120 V AC from the outlet and outputs 24 V DC through the port	A. Screw wires in the female DC connector and use a multimeter to measure the value B. Is able to durably connect and deliver 24 V DC to the battery itself

2.3.4 DC-DC Converter: DC to DC power conversion will be integral to safely and successfully transfer different voltage ratings between the motor, generator, and battery. A boost converter will most likely be used in order to step up the varying input voltage from the generator to the 24 V that is needed for the battery. We chose a converter over a transformer as it is lighter and more cost effective.

Requirement	Verification
Converts input voltage from 1-15 V DC from the generator and outputs 24 V DC to the battery	A. The boost converter can be tested in the Senior Design lab at varying DC voltages, with the output measured and expected to be 24V ± 1V and input voltages varying from 1-15 V DC.

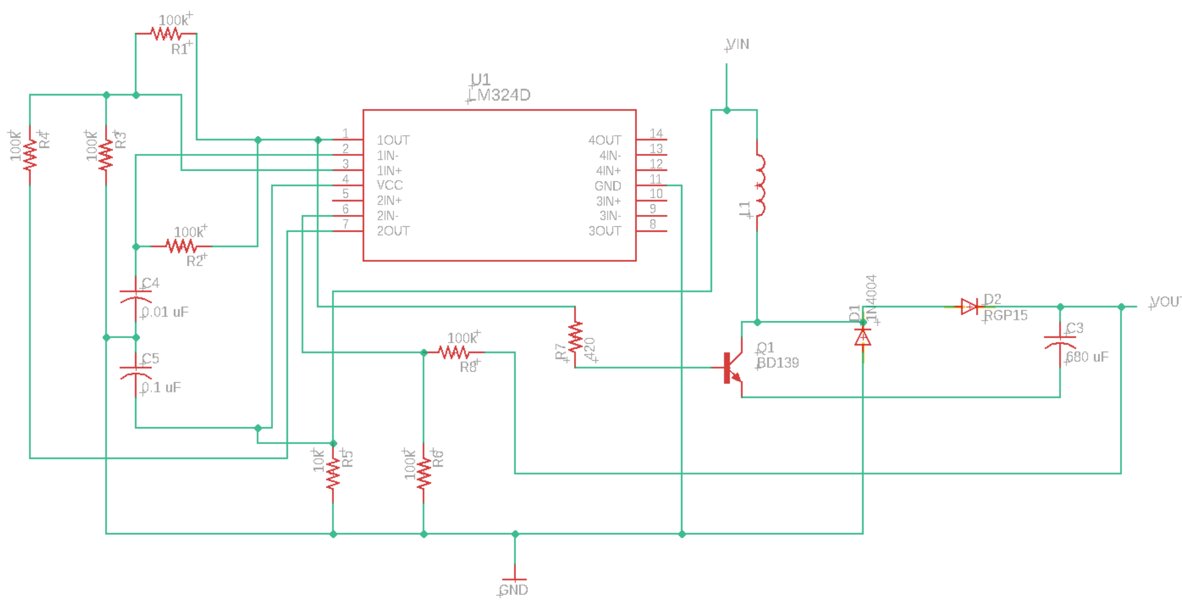

Figure 3. 12 to 24 V DC-DC Converter Circuit Schematic.

2.4 Hub Motor / Generator

2.4.1 Motor / Generator: The motor / generator is a single component determined by the switch to run as a motor or as a generator. We decided to use a 24 V 250 W Brushed DC Electric Motor for this project. In the motor mode, the motor draws power from the battery to drive the rear wheel of the bike. In the generator mode, current is generated as the user pedals and spins the generator. This current is sent out to the DC-DC converter to be stored in the battery.

Requirement	Verification

1. The motor must provide torque when running under normal conditions 2. The generator must be able to produce at least 100 W of power	1. A. Prop the bike up so that the wheels can freely spin B. Connect the motor to the battery C. If the motor is able to freely spin the wheel, it should be enough torque to electrically assist the pedal 2. A. Use a multimeter to measure the output of the generator B. Turn the generator faster and faster until the output power is greater than 100 W

2.5 Control Module

2.5.1 Microcontroller: The microcontroller takes in data from the switch, cadence sensor, and current sensor to determine how much power should be supplied to and from the battery. If the switch is in motor mode, the microcontroller allows the battery to supply power to the motor and depending on the cadence sensor, the microcontroller allows more or less power to be supplied. When the switch is in the generator mode, the microcontroller allows the DC-DC converter to supply power to the battery. The microcontroller also takes in data from the current sensor to check if the correct amount of current is traveling between the components, and corrects it if it is not at a rated value.

Requirement	Verification
Must be able to regulate current to/from battery	A. Put the switch on motor mode B. Increase current from the cadence sensor and observe if the output signal for the motor increases with a multimeter C. Put the switch on generator mode D. Increase current from the generator and observe if current is flowing into the battery with a multimeter E. Put the switch on off position and observe no current is going to/from the battery using a multimeter

2.5.2 Switch: The switch will control whether the motor-generator should be functioning as a motor, a generator, or in the off position. In the motor mode, the switch connects the battery to the motor. While in the generator mode, the switch connects the generator to the battery through the DC-DC converter. In the off position, it does not connect anything and the user can charge the battery directly from the grid.

Requirement	**Verification**
1. Must be easily flipped 2. Current must flow through the selected mode only	1. Flip the switch to ensure that it can switch between each mode without too much strain 2. A. Set the switch to motor mode B. Measure with an ammeter that current is flowing from the battery to the motor C. Set the switch to generator mode and pedal the bike D. Measure with an ammeter that current is flowing from the generator to the DC-DC converter E. Set the switch in the off position F. Measure with an ammeter that no current is flowing through the switch

2.6 Sensing Module

2.6.1 Cadence Sensor: The cadence sensor we will be using is to measure how fast the user is pedaling the bike. This sensor will be mounted on the pedals of the bike. The data from the sensor will be input to our microcontroller to direct the motor in pedal-assist mode, specifically to supply more power when pedaling speed decreases and less power when pedaling speed increases.

Requirement	**Verification**
Must vary output current depending on how fast the bike is being pedaled	A. Connect the output of the cadence sensor to an ammeter to read current B. Start spinning the cadence sensor slowly, gradually increasing the speed

	C. Observe that the output current responds to the change in speed

2.6.2 Current Sensor: The current sensor regulates how much current is going in and out of the battery and the motor to make sure the correct amount is being transferred. If the amount of current is incorrect, the current sensor will notify the microcontroller to adjust the current so that the system does not break. The current sensor is also a safety measure to ensure that too much current is not going into the battery.

Requirement	**Verification**
1. Regulates the current output of the generator to be ___ A (depends on current rating of the PCB) 2. Regulates the current output of the battery to be ___ A	A. Uses 2 ACS725LLCTR-29AB-T current sensor chip rated for at least 0 A for the battery and generator outputs with one sensor each B. Also uses a conductive resistor for low power loss and better capability for higher accuracy of measurement C. Sensors can be tested separately according to the current outputs of each component D. Easily connects to the leads of the battery and generator

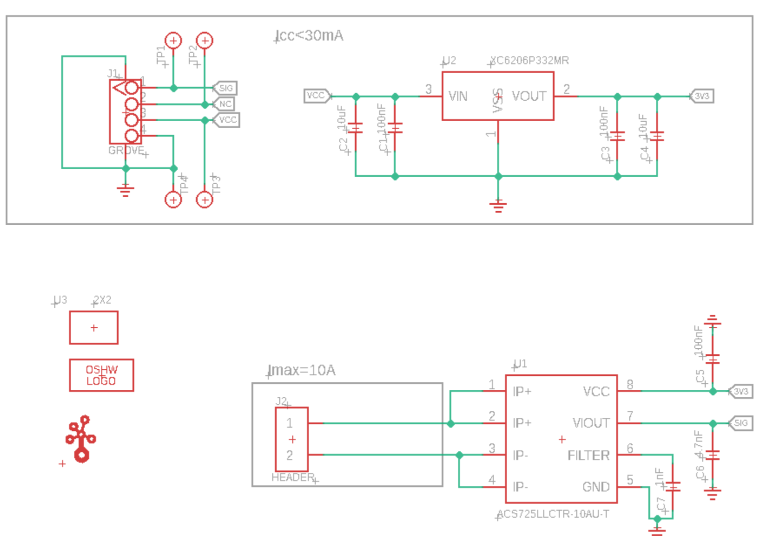

Figure 4. Current Sensor Circuit Schematic.

2.6.3 Battery Life Indicator: This component includes a voltage sensor which checks the voltage of the battery through a voltage divider and uses four LEDs to show how much charge the battery has left. As the battery life decreases, the voltage also decreases following the battery's voltage curve. The number of LEDs lit up is proportional to the voltage detected. One lit LED corresponds to 25% charge, so all four LEDs lit up means the battery is fully charged.

Requirement	Verification
1. Each LED must light up at its corresponding charge (first LED with 25%, second LED with 50%, third LED with 75%, and all four LEDs at 100%)	1. A. Monitor the battery voltage with a voltmeter B. Starting from full charge, drain the battery C. Observe the corresponding LEDs light up at the correct voltage level

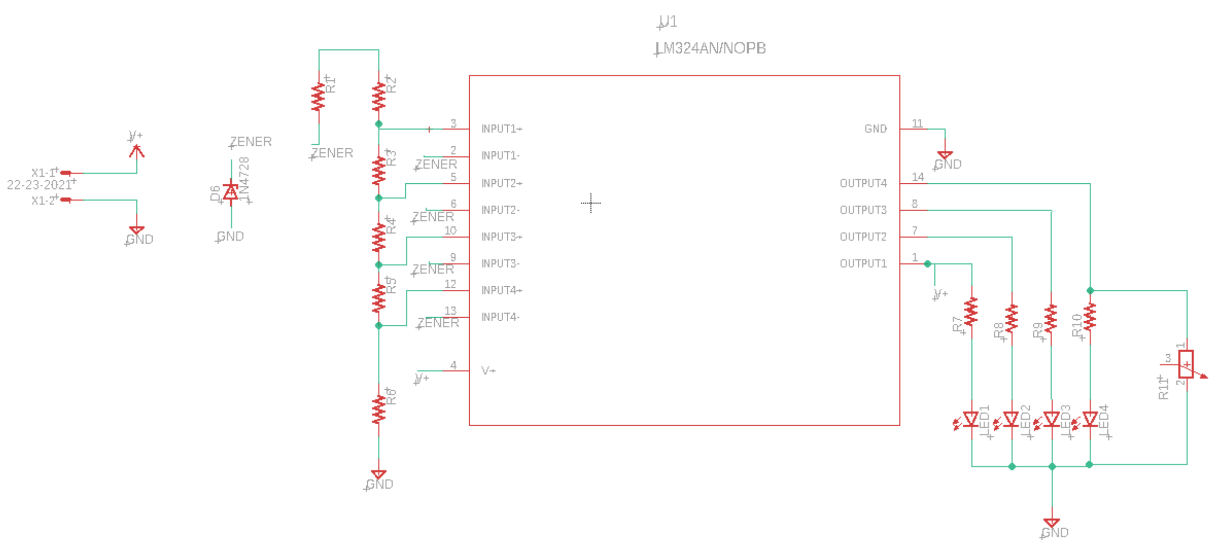

Figure 5. Battery Life LED Indicator Circuit Schematic..

2.7 Tolerance Analysis

The most critical component of our project is the motor / generator.

As one of our high-level requirements states, the bike should be able to generate at least 100W of power by the user pedaling the bike in generator mode at a maximum input.

3. Cost and Schedule

3.1 Cost Analysis

The cost of labor for three electrical engineering graduates is estimated to be $40/hour, 10 hours/week for 12 weeks. The total labor cost would then be $36,000.

$$3 \text{ graduates} \times \frac{\$40}{\text{hr}} \times \frac{10 \text{ hr}}{\text{week}} \times 12 \text{ weeks} \times 2.5 = \$36,000$$

3.2 Parts

The total cost of parts for our prototype is…

Part	**Cost**	**Quantity**	**Total**
Electric Motor 24V DC Scooter Motor Brushed Chain Motor (250W 2750RPM)	35.89	1	35.89
24 V, 10 Ah DC Battery	69.99	1	69.99
Cadence Sensor (Amazon, ZOOMPOWER)	18.50	1	18.50
100-240 V AC-24 V DC Power Adapter (Amazon, Shnitpwr)	11.99	1	11.99
PCB (PCBWay)	20.00	1	20.00
Microcontroller - ATMEGA48P-20AUR (Digikey)	2.40	1	2.40
S2F Switch (Digikey)	7.36	1	7.36
ACS725LLCTR-29AB-T Current Sensor (Digikey)	4.89	2	9.78
LM324 Amplifier (Digikey)	0.41	1	0.41
LEDs (Digikey)			

Machine Shop labor and supplies			
Misc. RCL components (Digikey)	10.00	1	10.00

3.3 Schedule

Week	Gina	Shannon	Yee Chan
2/28/21	Finalize motor simulations	Order motor, cadence sensor, batteries	Finalize PCB designs and order parts
3/7/21	Continue testing Simulink and Simscape motor system	Check in with ece machine shop on motor, stand, and cadence sensor implementation	Work with machine shop for bike stand / protective covering CAD models
3/14/21	Start assembling and soldering PCB components	Start assembling and soldering PCB components	Start assembling and soldering PCB components
3/21/21	Debugging control circuit / microcontroller	Bench test DC-DC power converter	Bench test voltage regulator and current sensor
3/28/21	Debugging power circuit and motor system	Debugging power circuit and motor system	Debugging power circuit and motor system
4/4/21	Implement PCB, cadence sensor, motor, LEDs, and battery	Implement PCB, cadence sensor, motor, LEDs, and battery	Implement PCB, cadence sensor, motor, LEDs, and battery
4/11/21	Test complete system	Test complete system	Test complete system
4/18/21	Plan final report and presentation	Plan final report and presentation	Plan final report and presentation
4/25/21	Prepare Final Presentation	Prepare Final Presentation	Prepare Final Presentation
5/2/21	Prepare Final Report	Prepare Final Report	Prepare Final Report

4. Ethics and Safety

4.1 Ethics

When designing this project, many factors went into the safety precautions that would be needed in order to finalize a secure product. Elements such as speed and power from the pedal-assist mode and even hazards that could be formed when using the bike in the generation mode can pose as harmful and dangerous to the user when not operated correctly. Electrical and physical malfunctions and overheating are potential risks exposed to the user, while there are also possibilities of exposing harm to the general public while using this product. The following sections identify the different hazards that our project may have and discuss the actions that we will take to adhere to IEEE ethical standards [4].

4.2 Public Safety Hazards

We must ensure that the safety of the public is protected and users of our e-bike are aware of any potential dangers associated with it. This is acknowledged in the IEEE Code of Ethics, #1: "to hold paramount the safety, health, and welfare of the public… and to disclose promptly factors that might endanger the public or the environment" [4].

The main concern regarding public safety is misuse of the e-bike, which could result in accidents or violation of traffic laws. Following the Illinois Vehicle Code under Sections 1-140.10, 1-140.15, and 11-1516, our e-bike would fall under the "low-speed electric bicycle" category, meaning that the motor must be less than 750W [5]. Additional restrictions on using the e-bike include that the bike cannot be used on a sidewalk, may not be operated at a speed greater than 20 mph, and can only be used by people aged 16 years or older [5]. We are using a motor that is less than 750W, meeting the requirement set by Illinois law. Informing users on how to properly use the bike and the limitations of the components can help mitigate actions that could endanger the user and others. However, we would not be responsible for users explicitly deciding to violate traffic laws.

4.3 Overheating Hazards

Some potential safety issues that could arise with our project include the components of our e-bike breaking or overheating, specifically our battery and motor-generator. If excessive voltage is supplied to the motor, this could cause overheating and motor failure. We will avoid this situation by controlling the amount of voltage supplied to the motor through a battery management IC that can be implemented as a safety feature for this hazard.

4.4 Electrical Safety Hazards

We are operating with a high voltage battery and motor, and if both components are not used properly, then a risk can occur with electric shock in the case of exposed wires or improper insulation and connection. Additionally, since our e-bike is meant for use outdoors, harsh weather conditions could damage the electronics, wiring, sensors, and motor if they are not properly protected against inclement weather. Our end product will ensure that all necessary components are covered with the appropriate material to combat against these kinds of scenarios.

References

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[5] U.S. Senate. 111th Congress, 1st session. (2009, Aug. 4). *Public Act 096-0125.* [Online]. Available: https://ilga.gov/legislation/publicacts/96/PDF/096-0125.pdf