Automatic Bike Collision Prevention System

ECE 445 Design Document - Spring 2026

Project #91

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Contents

1 Introduction

1.1 Problem

Cycling has long been an essential pillar of urban and academic mobility. For students navigating sprawling university campuses and professionals commuting through dense city centers, the bicycle represents an efficient, sustainable, and vital mode of transport. At UIUC, over 11% of students actively bike as their method of transportation [1]. However, as these environments become increasingly congested, the shared infrastructure between cyclists and pedestrians is becoming a site of growing conflict.

Despite its importance, cycling in high-traffic zones carries a constant risk of collision with distracted or oblivious pedestrians. Currently, bicycle safety is entirely reactive. Most cyclists have a bell attached to their handlebars that are used to warn pedestrians of the bike's presence. This bell acts as a clear indicator of a bicycle and alerts pedestrians to be aware of their surroundings and a potential high speed collision. This has been the main safety mechanic that cyclists have been using to alert pedestrians for the past several decades.

However, this system has many flaws. A cyclist must manually identify a hazard, process the risk, and activate a mechanical bell, hoping the pedestrian reacts in time. This sequence creates a high cognitive load for the rider and leaves zero margin for error, especially when pedestrians and riders alike are growing increasingly more distracted by mobile devices. Furthermore, manual detection is significantly compromised in low-visibility conditions, such as night-time commuting or heavy rain, where a rider's visual range is reduced.

1.2 Solution

To mitigate these limitations, we will implement an automated bicycle alarm, designed to act as digital "peripheral vision" for the rider. The system's core functionality centers on a triple-sensor array using SEN0610 mmWave radar sensors. These sensors are configured to provide a continuous 180° field of view, scanning for moving objects that enter the cyclist's forward or lateral path. By utilizing a Time-To-Collision (TTC) algorithm implemented on an

ESP32-S3 microcontroller, the system mathematically determines the urgency of a hazard, effectively removing human perception latency from the detection phase.

To ensure the system is effective without causing “alert fatigue,” we will implement a three-stage adaptive audible alarm using a PS1240 piezo buzzer. The alarm intensity scales based on the calculated risk level, providing a non-intrusive warning for distant objects and an urgent, high-frequency alert for immediate threats. Furthermore, the system includes an onboard potentiometer, allowing the rider to manually tune the detection sensitivity. This customization ensures the device remains functional across diverse environments, from quiet residential paths to high-density urban corridors, while an integrated power management system provides 8+ hours of continuous operation for a full day of commuting.

This system’s “peripheral vision” is achieved through the aforementioned synchronized tri-sensor array, utilizing spatial gating to differentiate between environmental noise and genuine collision threats. In a standard urban environment, a single-sensor system would be prone to “false positives” from stationary objects like parked cars or street signs. By utilizing three sensors we can better differentiate between threats and non-hazards: An object detected in only the left or right sensors is unlikely to be a threat, but by judging its direction, we can begin the alert, and if the object crosses into the path of the main, central sensor, we can measure its distance to know for sure if it is a threat.

1.3 Visual Aid

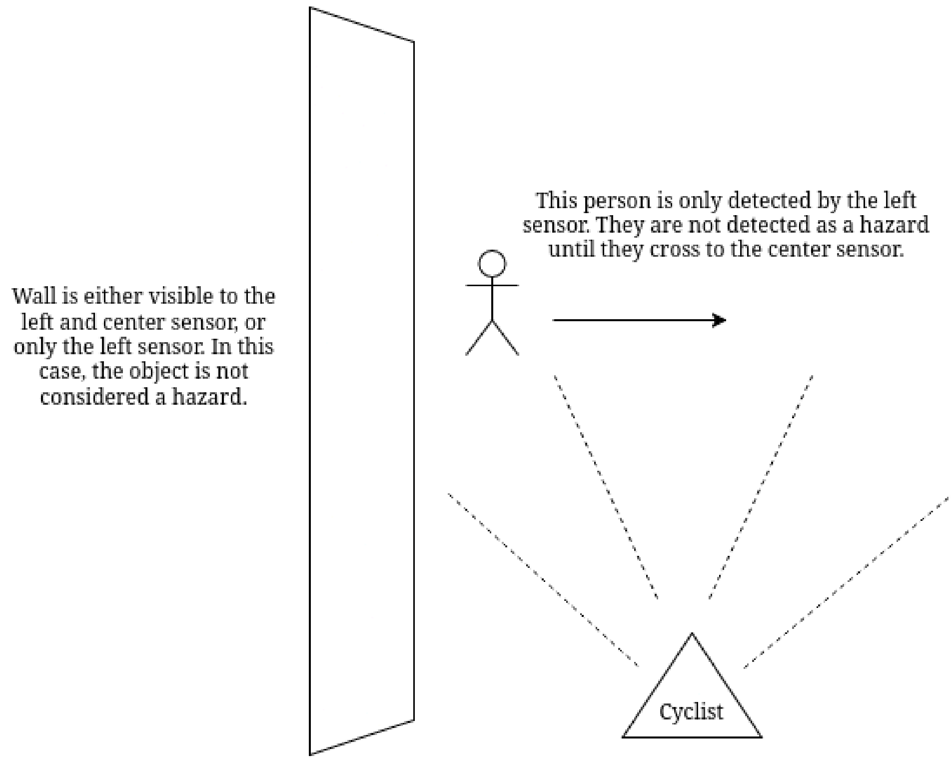

Figure 1: An example of the tri-sensor array

1.4 High Level Requirements

To consider our project successful, our system must fulfill the following:

1. The system must achieve a minimum 95% detection rate for moving hazards within a 5-meter range while maintaining a false-positive rate of less than 5% for static environmental objects like curbs or walls.
2. The total elapsed time from the initial sensor detection of an object to the activation of the audible alert must not exceed 200 milliseconds to ensure the cyclist has sufficient time to react.
3. The power management subsystem must provide a minimum of 8 hours of continuous operation on a single charge of the 18650 battery, ensuring the device remains active for a standard commuting or delivery shift.

2 Design

2.1 Physical Design

The radar array, potentiometer, and buzzer will sit on top of the bike's handlebars, while the microcontroller and battery system will be located nearby in the main frame of the bike or also on the handlebars, depending on the specific design of the bike itself. The entire system will be enclosed in a box to help protect the components from environmental hazards and from damage in the event of a collision.

2.2 Block Diagram

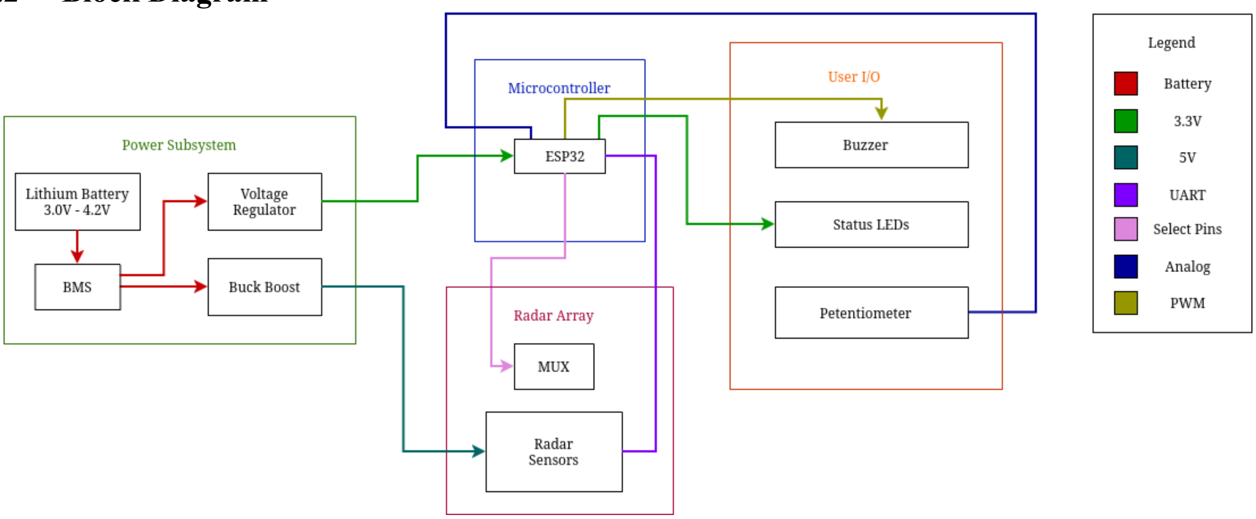

Figure 2: Block Diagram

There are four main subsystems: Power, Radar, Microcontroller, and User I/O. Power handles delivering the 5V and 3.3V rails, as well as a basic battery management system to prevent over/undervoltage. The microcontroller handles all the logic for the system and is what calculates the TTC. The radar array handles the detection. The user I/O contains the buzzer, status LEDs, and the potentiometer used to control the buzzer sensitivity.

2.3 Functional Overview & Block Diagram Requirements

2.3.1 Power Subsystem

The Power Subsystem is engineered to provide high-efficiency, regulated energy to the entire hardware suite while prioritizing long-term battery health and operational safety. The primary energy source is a single-cell Li-ion battery, which delivers a varying nominal voltage of 3.0V to 4.2V. To protect this cell from permanent damage, the system integrates a DW01A Battery Management IC coupled with DMN2040U Dual MOSFETs. This protection block acts as a high-speed safety switch, monitoring for over-discharge (tripping at 2.4V), over-charge (4.3V), and short-circuit conditions to ensure the system remains safe during the mechanical vibrations of bicycle transit.

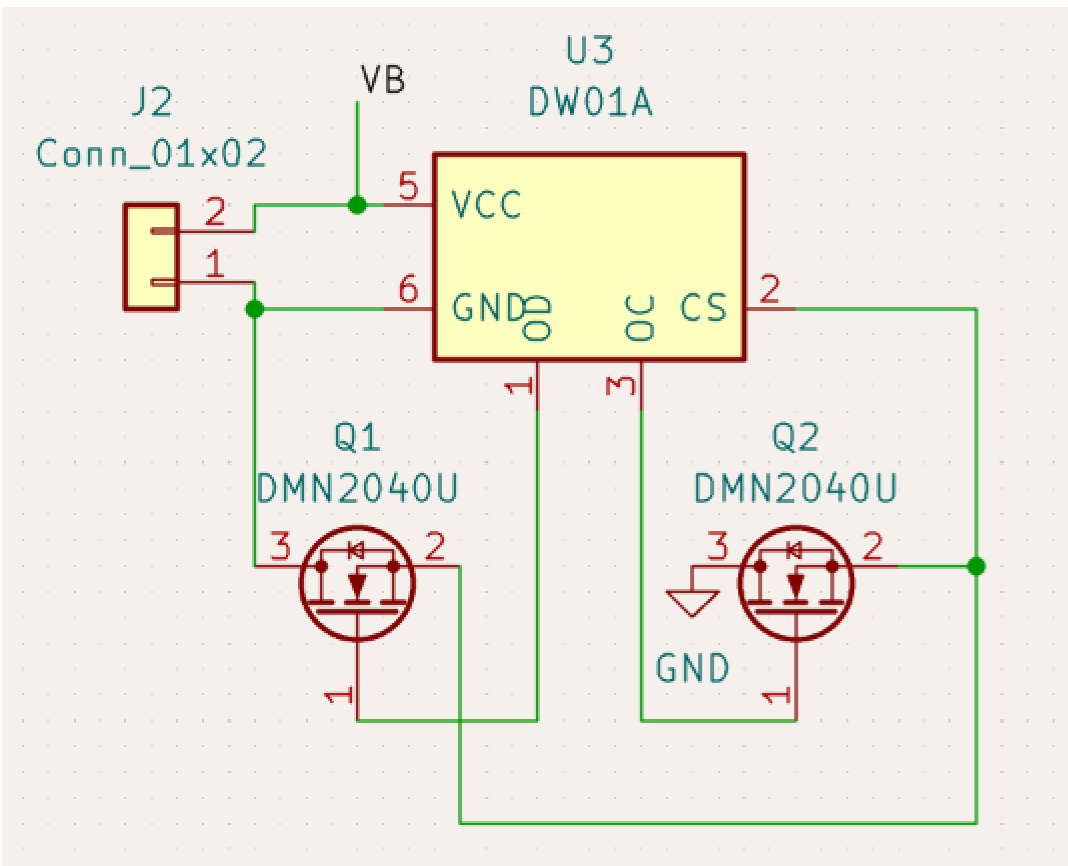

Figure 3: BMS

Energy regulation is handled through a dual-rail architecture designed to support both high-current peripherals and sensitive logic. A TPS63060 Buck-Boost Converter serves as the primary regulator, utilizing a 1.5µH or 2.2µH power inductor and high-precision feedback resistors (900kΩ and 100kΩ) to maintain a 5V rail. This rail powers the three SEN0610 radar sensors. To support the ESP32-S3 microcontroller, a secondary AMS1117-3.3V LDO steps the 5V rail down to a low-noise 3.3V logic supply.

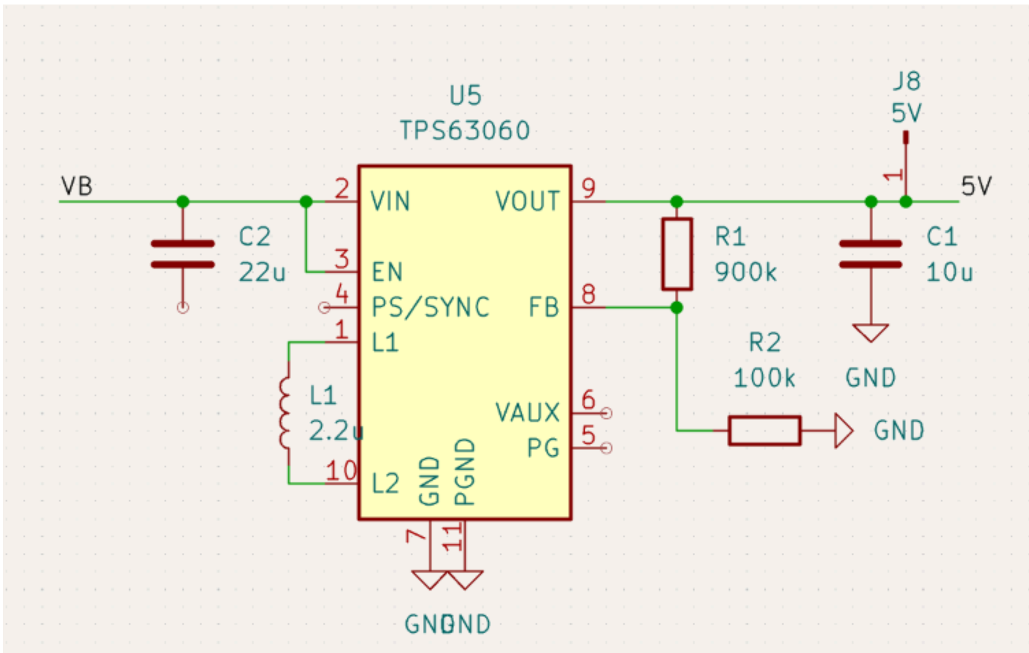

Figure 4: TPS

Requirement	**Verification**
The TPS63060 must provide a stable output of 5.0V ± 0.2V for any input voltage between 3.3V and 4.2V at a 500mA load.	Connect a resistor across the 5V rail as a dummy load. Sweep the input voltage from 3.3V to 4.2V using a DC power supply. Monitor the 5V rail with an Oscilloscope to ensure voltage stays within range.
The DW01A circuit must disconnect the battery from the system ground if the cell voltage drops below 2.4V to prevent over-discharge.	Connect a variable DC power supply to the battery headers. Slowly decrease voltage from 3.7V toward 2.0V while measuring the voltage across the system load with a DMM. Record the exact voltage at which the load voltage drops to 0V.

Table 1: RV for Power Subsystem

2.3.2 Radar Array Subsystem

The Radar Array serves as the primary sensing engine of the system, designed to create an expansive "digital horizon" for the rider. By mounting these sensors in a fanned configuration, the array achieves a total detection arc spanning 180 degrees, providing comprehensive coverage of both the forward path and the cyclist's lateral periphery.

Due to the high data throughput of three simultaneous radar streams and the limited number of available hardware UART ports on the ESP32-S3, the subsystem incorporates a CD74HC4051 Multiplexer (MUX) [2]. This MUX acts as a high-speed signal switch, allowing the microcontroller to rapidly cycle through each radar's UART transmit line. By toggling the Select A/B pins at a high frequency, the ESP32-S3 can sample data from all three sensors sequentially through a single RX pin, ensuring real-time trajectory tracking.

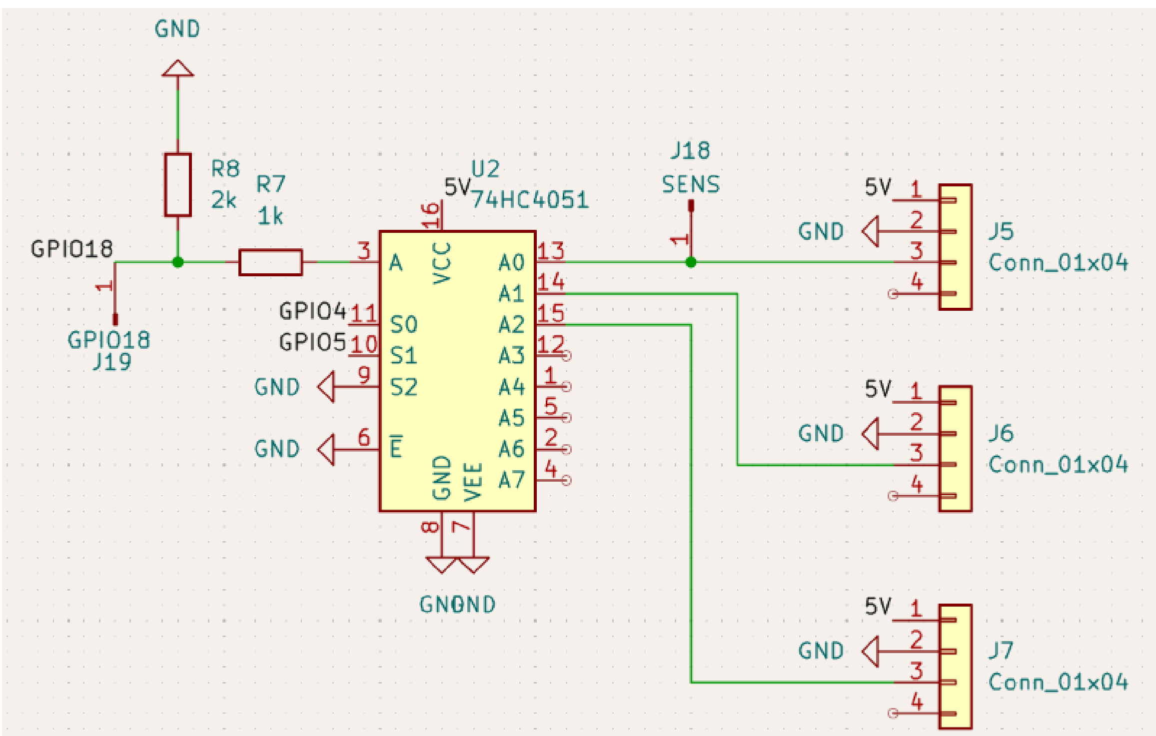

Figure 5: Radar array with MUX

Requirements	**Verification**
Each SEN0610 sensor must accurately detect moving human targets at a distance of 5m ± 0.5m.	Placing the sensors on a flat surface, measure out 5 meters and check for a reading.
The 74HC4051 MUX must switch between sensor channels and stabilize the signal within 50ns, ensuring at most 10% packet loss.	Connect an Oscilloscope probe to the MUX output and another to the Select A line. Trigger the scope on the Select line transition and measure the time until the UART signal on the output pin reaches a stable logic high/low level. Run a software script that sends 1,000 UART packets through the MUX while switching; count the successful checksums received by the ESP32 to calculate the loss percentage.

Table 2: RV for Radar Array Subsystem

2.3.3 Microcontroller Subsystem

The ESP32-S3 serves as the central processing unit and decision engine for the entire collision prevention system. It is responsible for orchestrating the high-speed data acquisition from the triple radar array via the CD74HC4051 multiplexer, utilizing its power to handle simultaneous communication and algorithmic processing. The microcontroller executes a custom Time-To-Collision (TTC) algorithm that filters raw spatial data, validates potential hazards, and determines the appropriate alert stage based on the pedestrian's closing velocity and distance.

Beyond data processing, the ESP32-S3 manages all system input/output (I/O) peripheral interactions. It monitors the analog input from the potentiometer to dynamically adjust detection sensitivity, and generates Pulse Width Modulation (PWM) signals to drive the PS1240 piezo buzzer for multi-stage auditory alerts. This PWM signal is at around 4kHz as it provides the best results [3]. It also controls the LEDs used to provide debug information to the user or for convenience during testing.

Requirement	**Verification**
The ESP32-S3 must complete one full cycle of the Time-To-Collision (TTC) algorithm for all 3 sensors in ≤ 50ms.	Insert "timestamp" code at the start and end of the TTC main loop. Run the system and print the delta to the Serial Monitor. Verify the loop time stays consistently below 50ms over a 5-minute test period.
The MCU must generate a 3.5kHz to 4.5kHz PWM signal at 3.3V ± 0.1V peak-to-peak to drive the PS1240.	Connect an oscilloscope probe to the GPIO pin driving the buzzer transistor. Trigger a Level 3 "Critical" alert. Measure the frequency and peak-to-peak voltage on the scope to ensure it matches the target frequency and logic level.

Table 3: RV for Microcontroller Subsystem

2.3.4 User I/O Subsystem

The User I/O Subsystem serves as the interface between the automated detection logic and the human environment. This subsystem is responsible for translating the digital hazard assessments from the ESP32-S3 into physical feedback that alerts both the rider and nearby pedestrians. The primary output is the PS1240 Piezo Buzzer, which provides audible warnings at around 75dB that scale in frequency and duty cycle as the TTC threshold narrows. This 75dB is around the average bicycle bell sound level [4]. To complement the auditory alerts, a series of status LEDs provide visual confirmation of the system's operational state, including power status and active sensor tracking.

Additionally, the subsystem includes an analog input interface. A device-mounted potentiometer allows the rider to manually calibrate the system's sensitivity in real-time. By adjusting this input, the rider can shift the SEN0610 radar detection thresholds to suit different environmental contexts by decreasing sensitivity in high-density pedestrian zones to avoid "alert fatigue" or increasing it on open roads for maximum lead time.

Requirements	**Verification**
The buzzer must produce a noise of 75dB ± 10dB at a distance of 5 meters to ensure it can be heard when at the max setting.	Place the device in a quiet environment. Trigger a Level 3 "Critical" alert. Verify the peak decibel reading falls within the 70-80dB range.
The system must vary the buzzer's duty cycle/frequency to provide at least three distinct auditory patterns corresponding to "Low," "Medium," and "High" risk levels via beeping speeds as 200ms difference, 100ms difference, and a continuous noise.	Connect an oscilloscope probe across the buzzer. Trigger each alert level in software and use the scope to verify the time difference for each beep.

Table 4: RV for User I/O Subsystem

2.4 Tolerance Analysis

2.4.1 Alert Timing

We expect an average cyclist to be riding at around 10mph when there is a significant amount of foot traffic.

$$10mi/h \times 1609.344m/mi \times 1h/3600s = 4.47m/s$$

This gives us a time to impact of:

$$Distance/Vbike = 5.0m \div 4.47m/s = 1.119s$$

The MUX has a 490ns propagation delay in its worst-case scenario [5]. We estimate a 50ms max time for our TTC algorithm. For the UART data time, the SEN0610 has a baud rate of 9600bps [6]. If we need to transmit 10 bytes of data, we get

$$100\ bits\ /\ 9600\ bps = 104\ ms$$

Adding these times up, we get 0.490 + 50 + 104 = 154.49ms, which should put us well within our 200ms delay requirement. This gives the cyclist and pedestrians 1119ms - 154.49ms = 964.51ms, or 0.96 seconds to react, which should be an adequate amount of time to prevent a collision.

3 Cost and Schedule

We can expect an average salary of around $40/hr as UIUC ECE graduates [7]. We can calculate the average labor costs per member to be:

$$\$40/hr \times 2.5 * 70hr = \$7000$$

This sums to $21,000 total for all three members.

Component	**Part #**	**Manufacturer**	**Quantity**	**Price ($)**
ESP32 Microcontroller	ESP32-S3-WROOM-1	Espressif Systems	1	6.23
ESP32-S3 DevBoard	ESP32-S3-DEVKITC-1-N8R8	Espressif Systems	1	15.00
Battery Management	DW01A	Shenzhen Slkormicro Semicon Co., Ltd.	1	0.10
3.3V Voltage Regulator	AMS1117-3.3	UMW	1	0.29
MUX	74HC4051	Texas Instruments	1	0.48
Piezo Buzzer	PS1240	Adafruit	1	1.50
Diode	DMN2040U	Diodes Incorporated	2	0.42 (x2 = 0.84)
NPN BJT	2N2219	Central Semiconductor Corp	1	3.18
Buck-Boost Converter	TPS63060	Texas Instruments	1	2.95
Plastic Enclosure	HP-090403	Polycase	1	18.05
Pushbutton	1505	Adafruit	1	0.95
Petentiometer	562	Adafruit	1	0.95
				Total: 50.52

Figure 6: Itemized list of Components and Cost

This gives us a grand total of $7050.52 for our project, not including the costs of any off-the-shelf components, such as resistors, capacitors, inductors, wires and LEDs, or machine shop and PCB costs.

Week	Task	Person
March 1 - 7	- Order parts - Design Review - Begin breadboard assembly - Look into SPI over UART possibility - Talk to machine shop about current design - Work on any required PCB revisions	- Rahul - Everyone - Everyone - Nathan - Rahul - Charlie
March 8 - 14	- Breadboard Demo - Initial PCB soldering - PCB testing - Work on any required PCB revisions - Finalize machine shop	- Everyone - Charlie & Nathan - Everyone - Everyone - Rahul
March 15 - 21	- Spring Break	
March 22 - 28	- Begin work on UART/SPI - PWM signals for different warning strengths - Battery connectivity - Work on any required PCB revisions - PCB Order request	- Nathan - Charlie - Rahul - Charlie - Rahul
March 29 - April 4	- Progress Report - Work on figuring out integration with machine shop design and assembly - Unit test all subsystems	- Everyone - Everyone - Everyone
April 5 - 11	- Progress Demo - More testing for subsystems and error mitigation	- Everyone - Everyone
April 12 - 18	- Test and verify all subsystems - Verify all high level requirements	- Everyone - Everyone
April 19 - 25	- Mock Demo - Last improvements	- Everyone - Everyone
April 26 - May 2	- Final Demo - Final Presentation	- Everyone - Everyone
May 3 - 7	- Finish final report - Lab checkout - Turn in Lab Notebooks	- Everyone - Everyone - Everyone

Figure 7: Schedule for Project Progression

4 Societal Impacts, Ethics, and Safety

The primary contribution of this system is the reduction of physical trauma resulting from bicycle-pedestrian accidents. By providing a proactive alert, the system creates a larger safety margin, potentially reducing the burden on emergency medical services and improving long-term health outcomes for commuters. Collisions carry significant economic weight, including medical expenses, property damage, and potential legal liabilities. This device offers an affordable, low-cost safety upgrade for existing bicycles, making advanced safety technology accessible to students and low-income commuters without requiring the purchase of an expensive e-bike or advanced kit.

This project is designed in strict accordance with IEEE Code of Ethics 1.1, which mandates holding the safety and privacy of the public paramount [8]. A significant ethical consideration for this project is the potential for automation complacency and risk compensation. There is a risk that cyclists, knowing that they have an automated alarm, may become less vigilant or more likely to engage in distracted riding. To mitigate this, the system is designed as a secondary aid rather than a primary safety measure. The multi-stage alert system is tuned to provide a "safety buffer" that prompts the user to re-engage with their surroundings, ensuring that the technology complements, rather than replaces, rider awareness. Additionally, the use of mmWave radars, as opposed to cameras, ensure that the privacy of the rider and pedestrians is maintained, and all data is processed locally on board in real time, with no capturing of identifiable information, eliminating risks associated with data storage or third-party transmission.

To ensure the physical safety of the end-user, this project adheres to UL 1642 standards regarding the integration of the 18650 Li-ion battery. Compliance with this standard ensures that the power source has undergone rigorous testing against thermal runaway and mechanical failure [9], [10].

The development and operation of this system present low inherent risk, provided standard laboratory and electrical safety protocols are maintained. The primary safety concerns are centered on the high energy density of the Li-ion battery and the mechanical integrity of the handlebar mount. To mitigate risks of thermal runaway or fire, the power subsystem utilizes a battery management system that monitors the 18650 cell in real time. It provides hardware-level protection against overcharging, over-discharging, and external short circuits, ensuring the device remains stable during both charging and high-vibration operation.

5 References

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