



# ECSE Capstone Final Report

Team 19

Semester 1, 2025



**ENGINEERING**  
DEPARTMENT OF ELECTRICAL,  
COMPUTER, AND SOFTWARE ENGINEERING

# Contents

<b>Executive Summary</b>	<b>III</b>
<b>Glossary of Terms</b>	<b>IV</b>
<b>1 Introduction</b>	<b>1</b>
<b>2 Problem Definition</b>	<b>1</b>
2.1 Project Background . . . . .	1
2.2 Problem Analysis . . . . .	1
2.2.1 Initial Problem Statement . . . . .	1
2.2.2 Discussion . . . . .	2
2.2.3 Evolved Problem Statement . . . . .	2
2.3 Users . . . . .	2
2.4 Requirements and Critical Success Factors . . . . .	2
2.4.1 Hardware Requirements . . . . .	2
2.4.2 Firmware Requirements . . . . .	3
2.4.3 Software Requirements . . . . .	3
2.4.4 Critical Success Factors . . . . .	3
<b>3 Solution</b>	<b>3</b>
3.1 Options Considered . . . . .	3
3.2 Initial Options Assessment . . . . .	4
3.3 Economic Assessment . . . . .	4
3.4 Societal Impact . . . . .	5
3.4.1 Sustainability . . . . .	5
3.4.2 Digital Inclusion and Accessibility . . . . .	5
3.5 Te Tiriti o Waitangi . . . . .	5
3.6 Best Way Forward . . . . .	6
<b>4 Implementation</b>	<b>6</b>
4.1 Value to EVolocity . . . . .	6
4.1.1 Improved Efficiency and Workflow . . . . .	6
4.1.2 Enhanced Competition Management . . . . .	7
4.1.3 Scalability and Portability . . . . .	7
4.1.4 Future Potential . . . . .	7
4.2 Stakeholders . . . . .	7
4.3 Project Scope . . . . .	8
4.3.1 In Scope . . . . .	8
4.3.2 Out of Scope . . . . .	8
4.3.3 Constraints . . . . .	8
4.4 Project Plan . . . . .	8
<b>5 Technical Overview</b>	<b>9</b>
5.1 System Overview . . . . .	9
5.2 Hardware Design . . . . .	10
5.2.1 Circuit Design . . . . .	10
5.2.2 Component Selection . . . . .	11
5.2.3 Initial PCB Layout . . . . .	11
5.2.4 Improved Final PCB . . . . .	12
5.2.5 Hardware Testing . . . . .	14
5.2.6 Breadboard Testing . . . . .	14
5.3 Firmware Development . . . . .	16
5.3.1 Sensor Measurement . . . . .	17
5.3.2 Data Packing into Compact Binary Format . . . . .	17
5.3.3 Digital Signal Processing (DSP) . . . . .	17
5.3.4 Network Connectivity and Data Upload . . . . .	18
5.3.5 Measurement and Configuration Storage . . . . .	19

5.3.6 Firmware Simulations, Implementation, and Testing . . . . .	19
5.3.7 Firmware Improvements . . . . .	20
5.4 Software Implementation . . . . .	20
5.4.1 Frontend Architecture and Design Goals . . . . .	20
5.4.2 Feature Overview and Improvements . . . . .	20
5.4.3 User Flow for Race Day . . . . .	21
5.4.4 Backend Architecture and API Design . . . . .	21
5.4.5 Database Management and Offline Operation . . . . .	22
5.4.6 Deployment and System Integration . . . . .	22
<b>6 Next Steps</b>	<b>23</b>
6.1 User Roles and Access Control . . . . .	23
6.2 Improved Data Storage . . . . .	23
6.3 Firmware Optimisation . . . . .	23
6.4 Hardware Refinement . . . . .	23
<b>Conclusions</b>	<b>24</b>
<b>Appendices</b>	<b>26</b>
Appendix A: Bill of Materials . . . . .	26
Appendix B: ORing Simulation in LTSpice . . . . .	26
Appendix C: Change bit weighs to correct DNL error . . . . .	27
Appendix D Current capture simulations in Wokwi . . . . .	27

## **Executive Summary**

This report details the design and implementation of a wireless data acquisition system for EVolocity's electric vehicle competitions for school children. The system enables real-time wireless transmission of ECU data, eliminating the need for manual retrieval of data by using a USB-C connection. It improves collection accuracy, speed and scalability. The project involved designing a custom ECU, developing embedded firmware and creating a full-stack web application for EVolocity officials to access performance data.

The proposed solution addresses the operational inefficiencies in ECU data handling, enhancing data collection's speed, accuracy and usability. It features a low-cost, purpose-built solution that exceeds EVolocity's technical and logistical requirements to streamline competition management and support the programme's future growth.

The design process involved evaluating various options for wireless communication, user interface design and data syncing strategies. The ideal solution for EVolocity and adherence to the values of Te Tiriti o Waitangi was considered at every stage of the project. The system was implemented with sustainability, digital inclusion and accessibility in mind, by using sustainable suppliers where possible.

The design includes unique features, such as easy setup by upcycling old laptops for the host server, automatic grading, custom event types, mobile-friendly views, zooming on measurements in graphs.

A prototype of the minimum viable product of the system's hardware, firmware and software components have been built and tested, demonstrating the feasibility of the solution. If this system is adopted, small changes can be made to the hardware and firmware to improve performance, cost, and the software can be extended to support additional features such as user roles and access control. The firmware and software are fully open-source and can be deployed easily.

## Glossary of Terms

<b>Acronym</b>	<b>Term</b>	<b>Definition</b>
ADC	Analogue-to-Digital Converter	A device that converts continuous analogue signals into discrete digital numbers, enabling digital systems to process real-world analogue input like sound or temperature.
CRUD	Create, Read, Update, Delete operations	The four basic operations of persistent storage used in databases and software development to manage data effectively.
ECU	EVolocity Control Unit	A custom-built electronic unit used in the EVolocity electric vehicle to measure and record data related to a vehicle's energy efficiency during races.
LED	Light Emitting Diode	A semiconductor device that emits light when current flows through it. LEDs are widely used for indication, lighting, and display technologies.
MVP	Minimum Viable Product	A product with just enough features to be usable by early adopters, who can then provide feedback for future development.
PCB	Printed Circuit Board	A board used for mounting and connecting electronic components using conductive tracks and pads.
RPi	Raspberry Pi	A small, affordable single-board computer developed to promote computer science education and is often used in prototyping and embedded system projects.
SMD	Surface Mount Device	An electronic component designed to be mounted directly onto the surface of a PCB.
SMT	Surface Mount Technology	A method for producing electronic circuits in which components are mounted directly onto the surface of PCBs, improving manufacturing efficiency and performance.

# 1 Introduction

EVolocity's national electric vehicle competitions aim to inspire the next generation of engineers by engaging students in the design, construction and racing of sustainable transport technologies. A crucial part of these competitions is the collection of performance data from each vehicle's ECU. However, EVolocity's current data collection method requires EVolocity officials to manually connect to each ECU via USB-C, which is time-consuming, inefficient and increasingly unsustainable as the number of participants grows.

This report proposes a wireless data acquisition system to resolve these challenges. The system enables real-time transmission of ECU data, eliminating the need for manual retrieval and significantly improving data collection accuracy, speed and scalability. To demonstrate the value of this system, the report presents a business case outlining the client's needs, key requirements, and the system's anticipated impact. It then provides a technical overview detailing the design, implementation and integration of the system's components, supported by testing results and evaluation of key decisions. The report also discusses the project's outcomes, potential future improvements and how the system aligns with EVolocity's long-term goals.

By addressing the operational inefficiencies in ECU data handling, this solution enhances data collection's speed, accuracy and usability and aligns directly with EVolocity's technical and logistical requirements. Its low-cost, scalable design and tailored software interface present the most suitable solution for enhancing competition management, supporting the programme's future growth and technological advancement.

## 2 Problem Definition

### 2.1 Project Background

EVolocity is the EV programme inspiring young Kiwis into sustainable engineering while fast-forwarding New Zealand's clean tech future. Competitions are held annually and involve student teams from intermediate and secondary schools nationwide. Each vehicle is equipped with an ECU that collects performance data such as power consumption and energy usage during races.

Currently, EVolocity officials are required to manually retrieve this data from each vehicle's ECU by physically connecting to the existing ECU via a USB-C cable. This process must be repeated for each team's vehicle, which becomes increasingly time-consuming and operationally burdensome as the number of participants grows. Furthermore, delays in data collection can impact event schedules, reducing scoring transparency and adding unnecessary stress to race-day logistics.

This project was initiated to address these inefficiencies and modernise how EVolocity handles race data. Our team has designed a complete wireless data acquisition system with minimal physical interaction, including a custom-built ECU, embedded firmware and a full-stack web application that allows officials to access real-time vehicle performance data with little to no manual intervention. This solution aims to streamline operations, enhance accuracy, and improve the overall competition experience.

### 2.2 Problem Analysis

#### 2.2.1 Initial Problem Statement

At EVolocity competitions, race officials retrieve data from the ECU of each vehicle manually by connecting to each one via USB-C. The current implementation is time-consuming and inefficient, particularly in fast-paced environments where quick data access is critical. End users, including race officials and event organisers, rely on this data to validate results and ensure fair competition. A wireless system to collect ECU data is needed to streamline this process and improve overall event efficiency.

### 2.2.2 Discussion

In its current form, EVolocity's data collection process requires EVolocity officials to connect to each vehicle individually using a USB-C cable. This introduces several limitations:

- **Operational efficiency:** With multiple teams competing in a competition, the time spent connecting to each ECU accumulates quickly, resulting in race delays and bottlenecks.
- **Real-time access:** Since data is collected only after a race has concluded, it is not available for live monitoring or rapid decision making.
- **Scalability:** As participation in EVolocity competitions grows, the current system becomes increasingly unsustainable.

These challenges undermine the smooth execution of competitions and place unnecessary strain on organisers. Moreover, the lack of automation diminishes the potential for advanced race analytics and performance feedback for student teams.

To address these issues, a new system is needed, one that can collect, transmit and visualise ECU data wirelessly and reliably during or immediately after races.

### 2.2.3 Evolved Problem Statement

The current method of collecting ECU data at EVolocity events, via a manual USB-C connection, is inefficient and time-consuming, resulting in delays, operational overhead and a suboptimal experience for EVolocity officials and participants.

## 2.3 Users

The primary user group of the system are EVolocity officials. They are responsible for collecting ECU data, validating results and managing competition day operations. Their primary needs are:

- Fast and reliable access to vehicle data.
- A user-friendly dashboard to manage competitions, events, and teams.
- Accurate performance data for scoring and compliance.
- A scalable system that simplifies logistics.
- A centralised platform for post-event analysis and reporting.

## 2.4 Requirements and Critical Success Factors

To ensure the project delivers meaningful value to EVolocity, a set of MVP requirements was established across hardware, firmware and software components. These requirements reflect both technical feasibility and the practical needs of EVolocity officials on competition day. Additionally, several critical success factors were identified to define what constitutes a successful outcome for the system as a whole.

### 2.4.1 Hardware Requirements

The hardware component of the system is responsible for accurately capturing performance data, specifically voltage and current, from the ECU in real time. It must achieve measurement accuracy within  $\pm 1\%$  per unit, with a precision of  $\pm 5\%$  across a batch. The system operates from a standard 12V power source and must include onboard voltage regulation to safely power its internal components. Wireless data transmission is handled by an integrated transceiver, which must reliably operate over a minimum range of 10 meters to accommodate competition-day setups. Additionally, onboard LEDs should provide simple visual feedback to confirm system power and status during deployment.

#### **2.4.2 Firmware Requirements**

The firmware, running on a microcontroller, is responsible for sensor data collection, temporary storage, and wireless transmission of sensor data to the server. It should follow a sequential control structure, often referred to as a state machine, to ensure tasks such as data sampling and transmission do not overlap in ways that could affect accuracy. The system is required to stream data at intervals of at least once every five seconds and maintain end-to-end measurement accuracy within  $\pm 1\%$ .

The firmware must be capable of storing at least one hour of sensor data locally on the microcontroller in situations where immediate transmission is not possible. Once connected to the server, data must be transmitted to the server within five minutes per hour of recorded activity. To ensure reliability in noisy or crowded environments, the firmware includes automatic retry mechanisms for failed transmissions.

#### **2.4.3 Software Requirements**

The software component consists of a backend server and a web-based user interface designed for EVolocity officials to manage competition data efficiently. The interface must support essential functionality such as creating and updating competitions, events, and teams, while also providing access to performance metrics from each team's ECU.

To support race-day workflows, the software must be mobile-friendly and intuitive, requiring minimal training. It should present data such as voltage, current, and energy usage in a clear and meaningful format, using visual tools like graphs or dashboards. The system must operate reliably over a local network without requiring internet access, while also supporting offline data storage and later syncing with an online database when connectivity is available.

#### **2.4.4 Critical Success Factors**

Several factors are critical to the success of the implementation. First, the wireless data transmission must be reliable with automatic retries and minimal data loss, even in noisy, crowded race environments. The system must support concurrent communication with at least 30 ECUs, ensuring it can scale effectively to the number of teams typically present at EVolocity events.

The full data pipeline, from sensor sampling to display on the web interface, must maintain an accuracy within  $\pm 1\%$  to ensure trustworthy performance metrics.

The user interface must be simple and intuitive, enabling EVolocity officials to operate the system with minimal training or technical support. To support efficient competition management, ECU data must be transmitted within five minutes of every one hour of recorded activity.

Finally, the system must be robust and maintainable. It should be well-documented, support modular improvements and scale across multiple teams and competitions without degradation. These qualities are essential to ensure the system remains useful and adaptable beyond the initial deployment.

### **3 Solution**

#### **3.1 Options Considered**

During the early stages of development, several design options were evaluated to determine the most effective approach for collecting and transmitting ECU data in a competition setting.

For wireless communication, the team considered both Bluetooth and Wi-Fi. Bluetooth is commonly used in embedded systems due to its low power consumption and simple pairing process. Wi-Fi, on the other hand, provides higher data throughput and longer range, which are important in environments with many simultaneous devices and potential interference.

When designing the user interface, the team evaluated both mobile-native applications and browser-based dashboards. Mobile apps offer tight integration with specific platforms but introduce development and maintenance overhead, especially when supporting multiple device types. Web-based interfaces, in contrast, can run on any device with a browser and are easier to maintain and deploy, providing a consistent experience across laptops, tablets and phones.

Finally, the team considered different data syncing strategies. One option was to have race officials upload data from each ECU after every race. An alternative approach was to enable automatic syncing whenever an ECU connects to the local network, reducing manual effort and making the system more responsive during competitions.

### **3.2 Initial Options Assessment**

Each major design decision was assessed based on its suitability for competition-day conditions, operational needs and the long-term maintainability of the system.

Wi-Fi was selected over Bluetooth due to its superior range and performance in multi-device environments. A key project requirement was the ability to support up to 30 ECUs concurrently transmitting data. Bluetooth, while power-efficient and easy to implement, typically supports only 7 to 20 simultaneous connections, well below the required threshold. Wi-Fi, by contrast, can support significantly more connections and provides higher data capacity, ensuring reliable performance in crowded settings.

Rather than building a separate mobile application, the team opted for a responsive web-based interface that works seamlessly on both mobile and desktop browsers. This choice reduces complexity, improves accessibility across a range of devices, and avoids platform-specific compatibility issues, making it easier for EVolocity officials to access the system with the tools they already use.

In terms of data transfer, a post-race upload workflow was considered but ultimately rejected due to its reliance on human intervention. The system instead uses automatic syncing whenever an ECU connects to the server, reducing delays and removing the need for officials to initiate data transfers. This design better supports efficient race management and real-time decision-making.

Overall, the selected options were chosen for their robustness, ease of use, and ability to scale across events, teams, and future deployments.

### **3.3 Economic Assessment**

A key advantage of the proposed system is its low cost and scalability, both of which are critical factors for deployment in a nationwide, non-profit, educational program like EVolocity. The project was designed from the outset to be affordable, with component selection and design decisions carefully made to balance performance with budget constraints.

The bill of materials for a single ECU totals approximately \$25.65 when ordered in bulk quantities of 50 units. This includes the microcontroller, voltage and current sensing components, passive elements, and a custom-designed PCB. Compared to commercial telemetry systems, which can cost several hundred dollars per unit, this represents a significant cost saving, especially when scaled across dozens of teams and events.

The firmware and software are fully open-source and custom-built for this application, eliminating the need for recurring licensing fees or third-party platform dependencies. The web interface and backend server are designed to run on local infrastructure, further reducing long-term operating costs and avoiding reliance on paid cloud services.

The software also includes a user-facing event creation feature, enabling officials to define and manage new types of competition-day events directly through the interface. This design choice ensures the system can adapt as EVolocity's competition structure evolves, without requiring ongoing developer input. By shifting control into the hands of event organisers, the system remains sustainable, flexible and more cost-effective to maintain over time.

Beyond direct financial savings, it also reduces the time and human resources required for manual data collection and scoring. These operational efficiencies translate to indirect economic benefits, such as reduced event overhead and a smoother experience for both officials and participants.

## **3.4 Societal Impact**

### **3.4.1 Sustainability**

The system was developed with sustainability in mind, both in terms of its physical design and long-term operational impact. EVolocity competitions span schools and regions across Aotearoa, and the ability to reuse, maintain and evolve system components over time helps reduce waste and align with sustainable engineering practices.

A key element of this sustainability strategy is the modularity of the system. Individual components can be replaced or upgraded without requiring a full redesign, which minimises e-waste and repair costs. As the system matures, future EVolocity staff can make incremental improvements, preserving the project's long-term value and reducing the environmental impact of replacing entire units.

Additionally, the system design reduces hardware wear by avoiding unnecessary writes to flash memory. Since ECU data is transmitted in near-real-time over a local network, there is no need for constant storage on the device itself whilst the ECU is connected to the server. This design choice extends the lifespan of the microcontroller and contributes to the environmental benefits of reduced hardware turnover.

The core firmware is built around the RPi Pico W microcontroller, used in each ECU. This device reflects strong environmental values and supports the sustainability goals of EVolocity. RPi has been awarded the Green Economy Mark in recognition of its sustainable practices and environmental leadership. The Pico W is compact, power-efficient and built for long-term support, making it a responsible choice for embedded systems that are deployed at scale. Raspberry Pi also offers Carbon Removal Credits for customers seeking to offset the environmental footprint of production, shipping and end-of-life disposal of their devices[?].

By combining responsible component selection with modular hardware and efficient local operation, the system supports EVolocity's broader goals of promoting sustainability and environmental awareness through engineering education.

### **3.4.2 Digital Inclusion and Accessibility**

The system was designed to be accessible across a wide range of devices and usage scenarios, supporting digital inclusion in diverse educational and event environments. By using a web-based interface instead of a platform-specific mobile app, the system can be accessed on any device with a modern browser.

Additionally, the system operates entirely over a local network and does not require an active internet connection to function. This ensures that events held in remote or low-connectivity areas are not disadvantaged and that performance data can still be accessed and managed reliably. This design choice supports equitable access and usability across different regions and resource levels, making the solution more inclusive for all EVolocity officials and organisers.

## **3.5 Te Tiriti o Waitangi**

This project incorporates the principles of Te Tiriti o Waitangi through a design process that considers people, place, and environmental responsibility. Māori concepts such as whakapapa, manaakitanga and kaitiakitanga were integrated into the development where appropriate.

The system builds upon the whakapapa of EVolocity's educational kaupapa and seeks to strengthen whānaungatanga by supporting the effective delivery of competitions nationwide. Accessibility was prioritised through a device-agnostic, offline-capable interface, ensuring an

equitable user experience for EVolocity officials, regardless of the location or available infrastructure. This reflects manaakitanga through inclusive design and respect for users' time, context and capacity.

Environmental sustainability was addressed through modular hardware, power-efficient design, and careful component selection, aligning with the principle of kaitiakitanga. The selection of environmentally responsible components, such as the Raspberry Pi Pico W, further supports this commitment. Surface-mount components were used to reduce material usage and minimise the carbon footprint. The system also reduces waste heat by utilising the microcontroller's efficient on-board power supply, lowering energy loss to Papatūānuku and helping preserve tapu, New Zealand's sacred natural resources.

Although formal co-design with Māori communities was not conducted, the development process was user-centred and iterative, reflecting the spirit of mātauranga and tutū. The project is understood as a wero, an opportunity to embed cultural responsibility into technical work and contribute meaningfully to the EVolocity mission.

### **3.6 Best Way Forward**

Following a detailed assessment of stakeholder needs, technical feasibility, and long-term value, the proposed wireless data collection system represents the most effective and sustainable solution for improving ECU data handling at EVolocity competitions.

The system consists of three core components:

- A custom-designed ECU built around the Raspberry Pi Pico W, capable of accurate data sampling and reliable wireless transmission.
- Embedded firmware that ensures end-to-end data integrity, near-real-time syncing, and power-efficient operation.
- A web-based interface and backend server that allow EVolocity officials to access competition data, monitor energy performance, and manage events efficiently.

This integrated solution eliminates the need for manual data retrieval, significantly reducing delays and labour overhead during events. The web interface is accessible across a wide range of devices and can operate over a local network, ensuring usability even at venues without internet connectivity.

The modular hardware design, low-cost components, and open-source software stack ensure that the system is maintainable and adaptable for future improvements. This makes the solution not only viable for current needs but also capable of supporting EVolocity's long-term goals around sustainability, growth, and inclusivity.

Adopting this system offers a clear path forward, modernising the competition infrastructure while aligning with EVolocity's educational and operational values.

## **4 Implementation**

### **4.1 Value to EVolocity**

Our wireless data collection system delivers transformative benefits to EVolocity, streamlining competition operations, enhancing event quality, and supporting long-term growth. By addressing the inefficiencies of manual ECU data acquisition, the system empowers EVolocity officials to deliver fair, engaging and efficient competitions

#### **4.1.1 Improved Efficiency and Workflow**

The system eliminates the time-consuming process of manually connecting to vehicle ECUs via USB-C, reducing data retrieval time to at most 488 seconds for an hour of data. EVolocity officials can access near-real-time ECU data wirelessly, reducing labour-intensive tasks. The

user-friendly web interface streamlines data validation and scoring, allowing organisers to focus on race management rather than data entry, significantly improving race-day workflows.

#### 4.1.2 Enhanced Competition Management

Wireless data transmission and a tailored dashboard enable officials to access ECU data shortly after each race, improving visibility into energy efficiency, vehicle performance and result validation. This ensures fair competition outcomes, with around  $\pm 0.8\%$  accuracy, boosting participant trust. Real-time access to performance metrics also streamlines competition-day decision-making and improves the overall experience for organisers. They gain a centralised tool for seamless competition oversight, elevating competition quality.

#### 4.1.3 Scalability and Portability

The system's PCB and RPi Pico W design supports 50 vehicles across multiple events, accommodating EVolocity's regional competitions. Its compact, easy-to-install hardware simplifies setup, reducing logistical challenges. The scalable backend server handles growing data volumes, ensuring reliability as competitions expand, making it a versatile solution for EVolocity's evolving needs.

#### 4.1.4 Future Potential

The system has been developed with modularity and extensibility in mind, providing a strong foundation for further development by EVolocity staff. Several areas of future enhancement have been identified:

- **User Roles and Access Control:** Adding authentication would support a multi-user system, enabling separate interfaces for officials and team participants to view results and leaderboards.
- **Improved Data Storage:** Migrating configuration and logs to external storage such as SPI flash or SD cards would reduce wear on the microcontroller and improve long-term reliability.
- **Firmware Optimisation:** Rewriting performance-critical routines in C/C++ could increase sampling rates, improve energy calculation accuracy and remove Python threading limitations.
- **Hardware Refinement:** The updated PCB design in this report lays the groundwork for future durability, easier mounting and thermal performance improvements.

These enhancements would further strengthen the system's performance, maintainability and alignment with EVolocity's long-term goals.

## 4.2 Stakeholders

Table 1: Stakeholder Analysis Table

Stakeholder	Interest	Influence	Engagement Strategy
Evolocity Officials	Streamlined data collection, accurate scoring, easy competition management	High	Frequent check-ins, testing sessions, requirement validation, demo during development
Evolocity Management	Program scalability, technical viability, cost-efficiency	High	Progress reports, cost analysis, long-term sustainability planning

Stakeholder	Interest	Influence	Engagement Strategy
Student Teams	Fair competition, reliable performance data, faster turnaround	Low	Indirect engagement via improved systems; future workshops or educational outreach
Sponsors	Positive brand alignment, innovative STEM education, reliable competition	Medium	Outcome visibility through improved event execution and data-driven metrics

### 4.3 Project Scope

This project focused on developing a wireless data acquisition system to improve the efficiency and scalability of ECU data collection during EVolocity competitions. The scope of the project included the design, development and testing of integrated firmware and software components.

#### 4.3.1 In Scope

- Design and assembly of a custom ECU, including a RPi Pico W and supporting sensor circuitry.
- Firmware capable of sampling voltage and current at a minimum of 125Hz, storing one hour of data and transmitting it wirelessly.
- A local network-based server to receive and store ECU data, with optional syncing to an online database when internet access is available.
- A responsive web-based interface for EVolocity officials to manage competitions, view team data and validate performance metrics.
- Documentation for system setup, usage and future development.

#### 4.3.2 Out of Scope

- Participant-facing dashboards or authentication-based role separation.
- Full-time cloud deployment or reliance on persistent internet connectivity.
- Mobile-native applications (the interface is mobile-friendly but browser-based).
- Real-time streaming during races (data is only transmitted when the ECU successfully connects to the server).

#### 4.3.3 Constraints

- No reliance on internet connectivity, due to limited infrastructure at competition venues.
- Low hardware cost per unit, to ensure affordability at scale.

### 4.4 Project Plan

The project followed a structured timeline across planning, development and testing phases. Figure 1 below outlines the intended schedule.

While the project generally adhered to the proposed schedule, minor adjustments were made during the integration phase due to unforeseen delays and iterative improvements to the firmware and software. These adjustments did not affect the delivery of the core system, and all primary deliverables were completed within the final reporting period.

The structured plan helped ensure consistent progress and alignment across sub-teams, while regular check-ins allowed the team to remain adaptive to technical challenges and changing priorities.

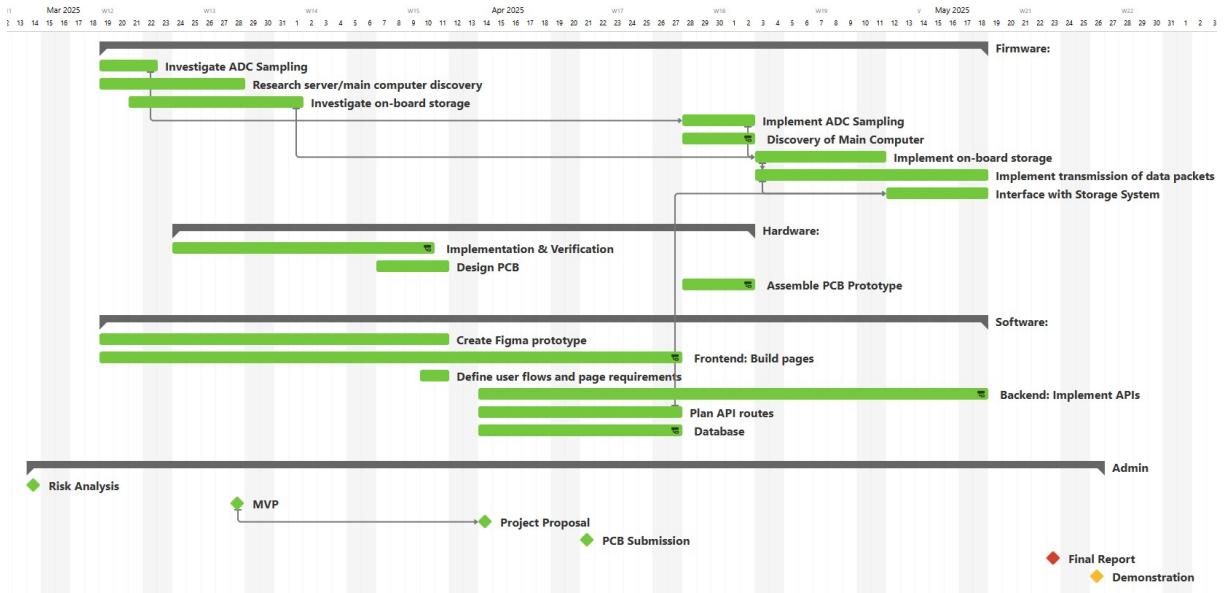


Figure 1: Gantt Chart demonstrating the planned sequence and duration of tasks.

## 5 Technical Overview

### 5.1 System Overview

Figure 2 shows the overall system architecture developed for this project. It was built collaboratively by three multidisciplinary teams: hardware, firmware, and software.

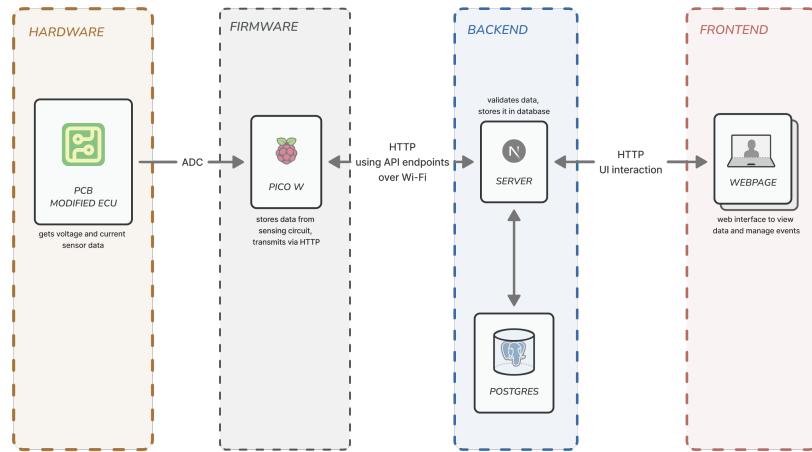


Figure 2: Detailed system architecture diagram showing the interaction between hardware, firmware, and software components.

The hardware team was responsible for designing the circuit for voltage and current sensing, including current signal amplification and a step-down linear voltage regulator, the initial and improved designs of the PCB, along with breadboard and PCB-level testing.

The firmware team developed the embedded software for the RPi Pico W microcontroller, managing accurate sensor data acquisition, digital signal processing, persisting measurements against power losses, and wireless transmission of values to the backend server.

The software team implemented a backend server that receives data from the ECUs, as well as an intuitive web interface to allow EVolocity officials to efficiently manage the competitions, teams, events and view performance metrics. The data that the ECUs send is stored in a database that is connected to the backend. This data is then displayed by the web interface, along with the other, non-ECU-related data.

## 5.2 Hardware Design

Figure 3 shows the final circuit design for the hardware component used to measure the voltage and current from the competitors' vehicles during the competition. The following sections elaborate on the simulation tool used and the components included in the circuit. The component selection further justifies how the components were selected, with attention to alternative options and the value ranges for resistors and capacitors. The PCB design includes an initial design used in the current system, and an improved version of the PCB. Hardware testing goes into detail about the breadboard and PCB testing results after assembly. A cost breakdown of the components used can be found in Appendix A.

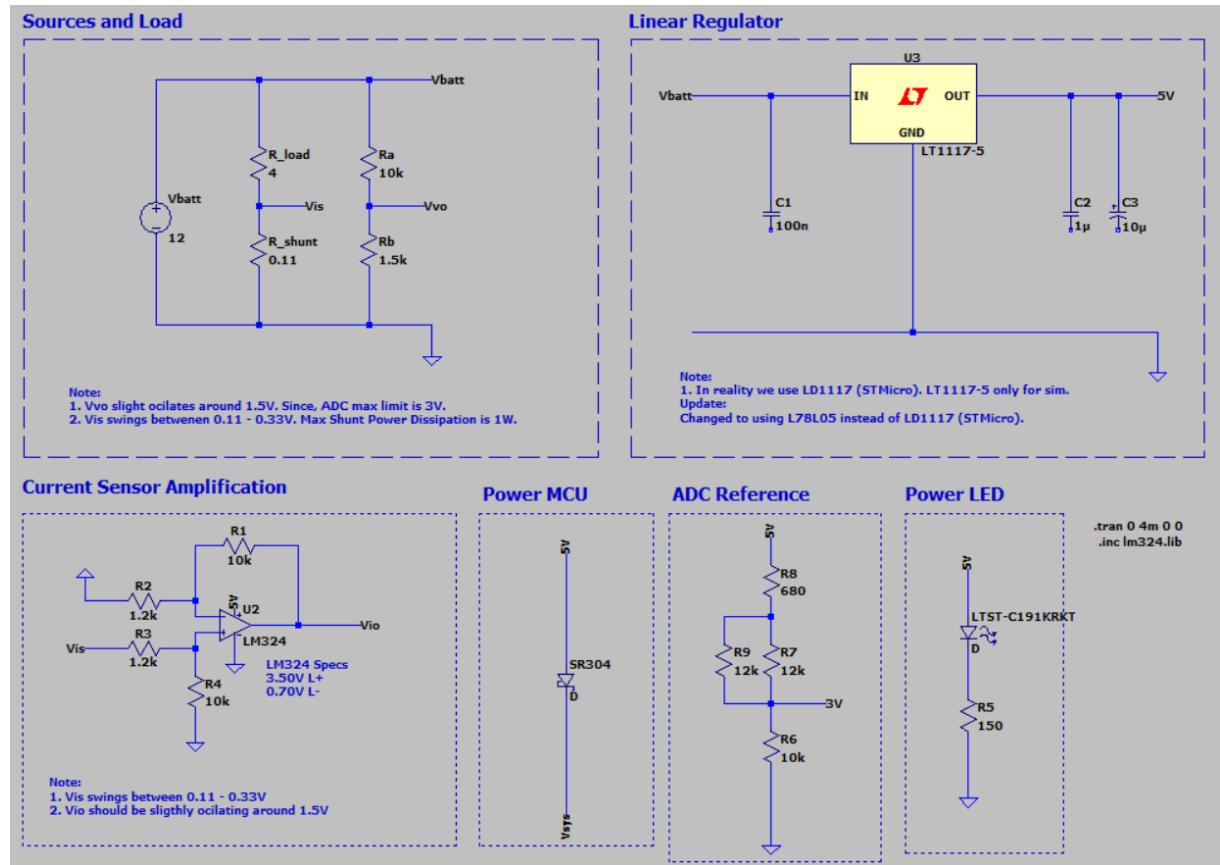


Figure 3: Overview of Final Circuit Design.

### 5.2.1 Circuit Design

For simulation, LTspice was chosen over PLECS due to its free licensing, extensive online component libraries and greater accessibility. In contrast, PLECS is costly and offers only generic component models, making LTspice the more practical option.

The circuit design, as shown in Figure 3 includes current and voltage sensing, an amplifier for the current sensing signal, a LED for debugging, a linear voltage regulator and a voltage divider for the ADC reference of the RPi Pico W.

Voltage and current sensing circuits must be included for EVolocity to monitor the power used by the competitors' vehicles during the event. An amplifier must be included for the current

sensing signal to convert the analogue signal into a digital signal. According to the datasheet of the RPi Pico W, the ADC range is limited to 0-3.3V, to accomodate this, an operational amplifier was added the circuit to amplify the current sensing signal to 3.3V.

A voltage divider was added to the circuit for the ADC reference to meet the 3.3V requirement for powering the ADC. Apart from that, the datasheet also suggested the 5V supply to the system of the RPi Pico W; therefore, a step-down linear regulator was included so that an input voltage of 12V is regulated into 5V. A Schottky diode was added to prevent excessive current before supplying 5V to the Raspberry Pi Pico W. To ensure that the circuit is powered with 5V from the linear regulator, an LED was included for debugging purposes.

### 5.2.2 Component Selection

The options considered for the linear regulator were LD1117V50 and L78L05. To minimise the cost, it was decided to use L78L05, as L78L05 is more cost-effective than LD1117V50; the L78L05 costs 14.92NZD in total for 50 units, whereas the LD1117V50 costs 21.06NZD in total. According to the datasheet, the L78L05 has an output voltage from 4.6V to 5.4V, and its dropout voltage is 2V.

LT6221 and LM324 were considered as suitable options for the operation amplifier . The cost was one of the major considerations made during the design of the PCB. The LT6221 costs 386.12NZD for 50 units, while LM324 costs 179.40NZD. After considering the 200Hz on the sampling frequency for ADC from the firmware team, the hardware team believed that having a high slew rate and gain bandwidth would not be necessary; hence, the LM324 was chosen for the operational amplifier. According to the datasheet, LM324 has a unity-gain bandwidth of 1.2MHz and a slew rate of 0.5 V/ $\mu$ s.

For the resistor values, resistances within the kilo-ohm range was chosen for most of the circuit to reduce noise from the environment and heat after soldering. For the shunt resistors of the current sensing circuit, 0.1  $\Omega$  resistors with a 3W power rating were chosen, allowing the maximum current to flow through.

For the capacitors, an electrolytic capacitor was used as an output voltage of the linear regulator, and it was within the microfarad range since it acts as a storage capacitor. Ceramic capacitors within the nanofarad range were included for decoupling purposes because ceramic capacitors have lower equivalent inductance and equivalent resistance.

### 5.2.3 Initial PCB Layout

For the initial design, a PCB was designed in the most cost-effective and eco-friendly way, aligning with Te Tiriti o Waitangi for guardianship and sacred resources. It was decided to make use of SMT for the PCB design, it reduces the carbon footprint, but also improves the accuracy of the electronic components, compared to using through-hole.

To reduce waste, the microcontroller was attached to the hardware by non-permanent headers, allowing for easy replacement without disposing of the entire Pico and ECU unit. The hardware components were picked to ensure a long lifecycle. The SMT resistors have a lifespan of 1000 hours at a temperature range from 68°C to 72°C, the SMT ceramic capacitors have a lifespan of 20 or more years at room temperature, and the electrolytic capacitor, test pins, and female headers all have a lifespan of around 10 years.

Figure 4 shows the design of the PCB layout. The PCB was designed to separate high-power, high-frequency components from the low-power signal processing components to reduce noise and interference. The right side is where the high-power, high-frequency components are put, while the left side shows the low-power signal processing components.

The PCB was also designed to be easy to solder and have good heat dissipation characteristics. The high power connections (the input, output, shunt resistors and linear regulator) are placed close to each other, and they are connected through power planes to reduce resistance and noise generation. A little interplane capacitance was utilised by using a 5V and ground plane.

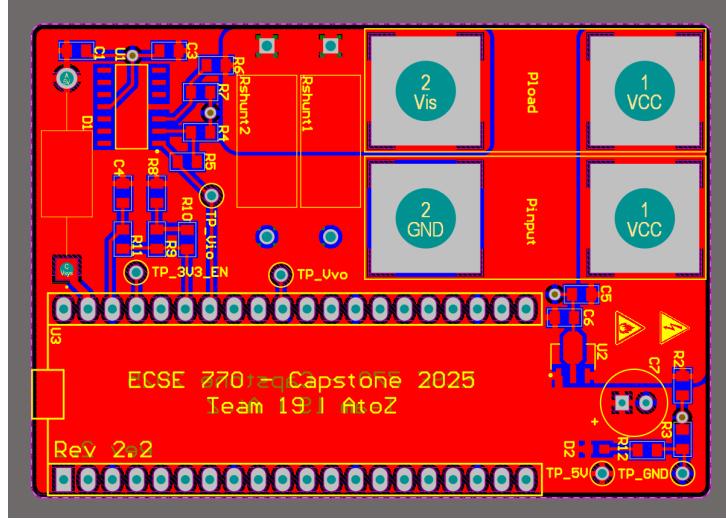


Figure 4: Altium render of current PCB top layer.

#### 5.2.4 Improved Final PCB

Comprehensive feedback from academic experts and internal team discussions drove the team to a decision on developing a new PCB Design. The decision to start on a new PCB design was viable since it allowed to cut out massive development time costs required in modifying the existing component placements. The flaws identified in the existing PCB design were mostly related to circuit schematic and practical considerations. Firstly, considering the circuit a variety of issues arose. For the project a Schottky diode being used to create an ORing power supply turned out redundant. This is because the battery power supply is always greater than the USB power supply since the USB supply experiences a voltage drop across the Pico onboard diode. Specifically, it is ensured the circuit will never create a back current and damage any connected device, i.e. laptops, due to the inbuilt diode on the Raspberry Pico W. A similar power circuit has been developed and evaluated in Figure 5 to verify the claim on the unnecessary diode. As simulated in LTSpice the USB current supply drops soon after a 5V battery supply is attached to power the Pico. The circuit image schematic to simulate the displayed waveform in Figure 5 can be observed in Appendix B.

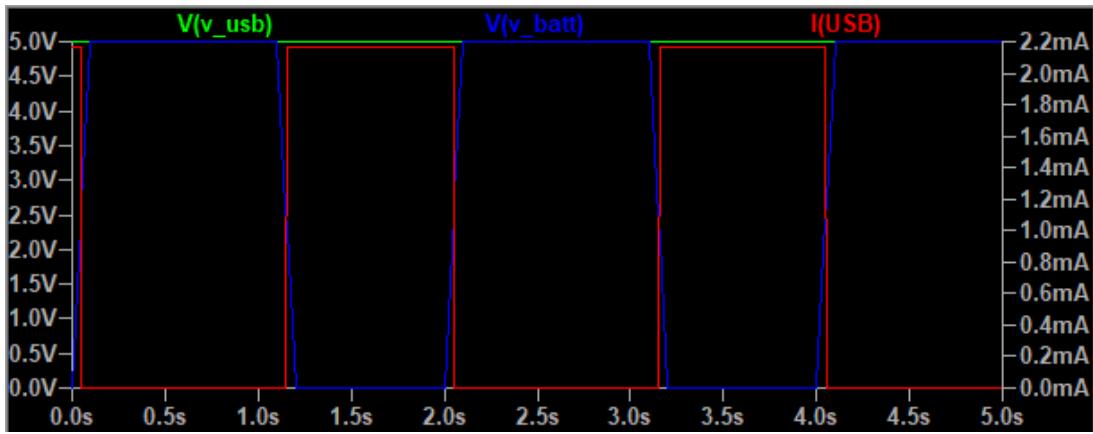
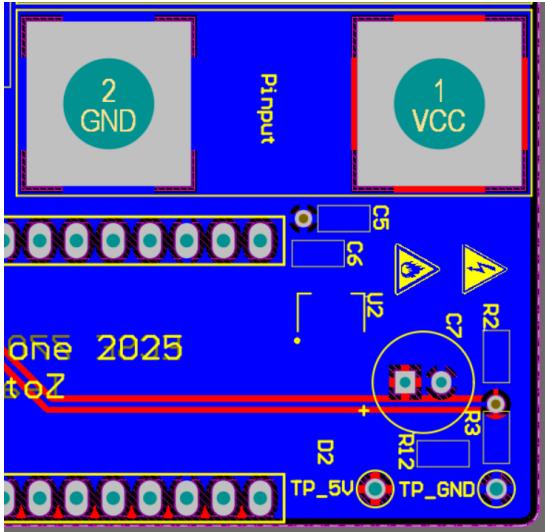


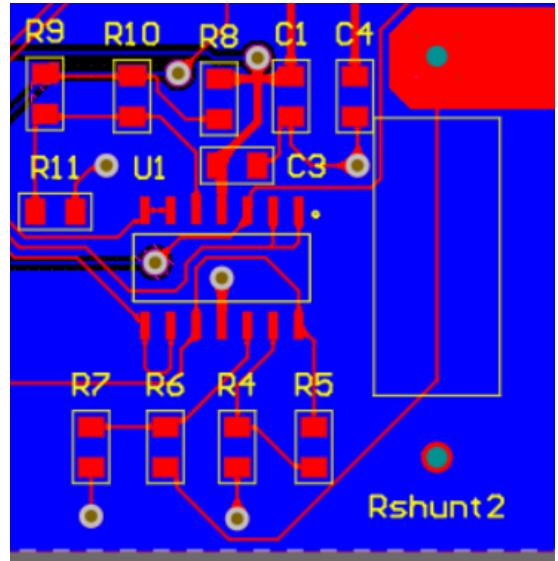
Figure 5: Waveform of USB Current

Obtuse silkscreen positioning was another significant issue identified during the PCB review meeting (in Figure 6a). The obtuse angles were addressed by orienting all the component labels to the same angle. Doing so will result in easier soldering and debugging. Figure 6b clearly shows the adjustment made to achieve the appropriate silkscreen labels.

Floating inputs for two op amps inside the LM324 SOIC-14 package were also another critical issue identified post-PCB manufacturing. The floating inputs issue was handled through



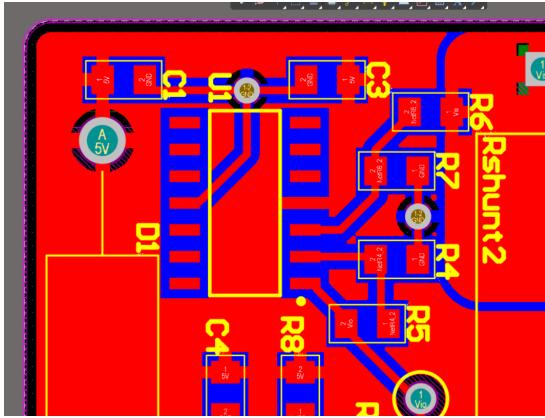
(a) Example of Obtuse Silkscreen.



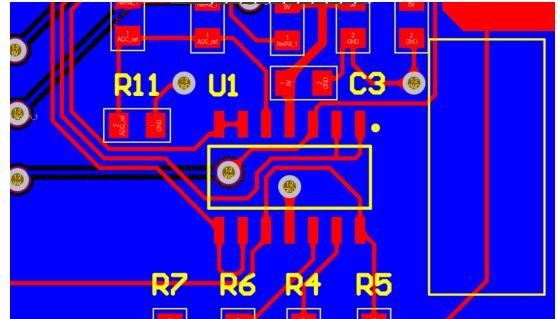
(b) Example of Corrected Silkscreen.

Figure 6: Example of obtuse and corrected Silkscreen.

utilising the unused ports as buffers for the voltage sensor, current sensor and ADC reference. Doing so was important as powering op amps, yet leaving their inputs floating would cause unwanted amplification of noise due to the environment. Moreover, the amplification would result in additional power dissipation by the op amp chip. A strategy to mitigate this issue is to ground the opamp positive input and connect the negative input to the output as in negative feedback [13]. Figure 7a and Figure 7b below give a perfect illustration of our modification to fix the floating input problem.



(a) Example of Floating opamp inputs.



(b) Example of Utilised op amp pins.

Figure 7: Examples of floating and utilise opamp pins.

Thermal Relief was another concern that needed to be addressed due to the increased risk of tombstoning and cold solder joints. Initial PCB developed had areas on the PCB that had uneven connections to the copper pour around it. Additionally, there was a collection of resistors that were laid out too closely. The mentioned uneven component connections to their surroundings are catalysts for tombstoning of SMD. Tombstoning occurs when one solder pad of a component is more wet compared to the other. The uneven viscosity in solder causes the component to either stand up or have a cold joint on the more viscous end of the component. An example of a possible catalyst for tombstoning on the initial PCB and the fix can be observed in Figure 8a and Figure 8b. The fourth and final revision of our PCB solved the uneven copper connection concerns through two ways. Firstly, by placing SMD resistors away from each other and preventing the heat from one resistor from quickly dissipating to

another during soldering and finally by designating a design rule to keep the connector width of polygon planes  $> 1.5\text{mm}$ .

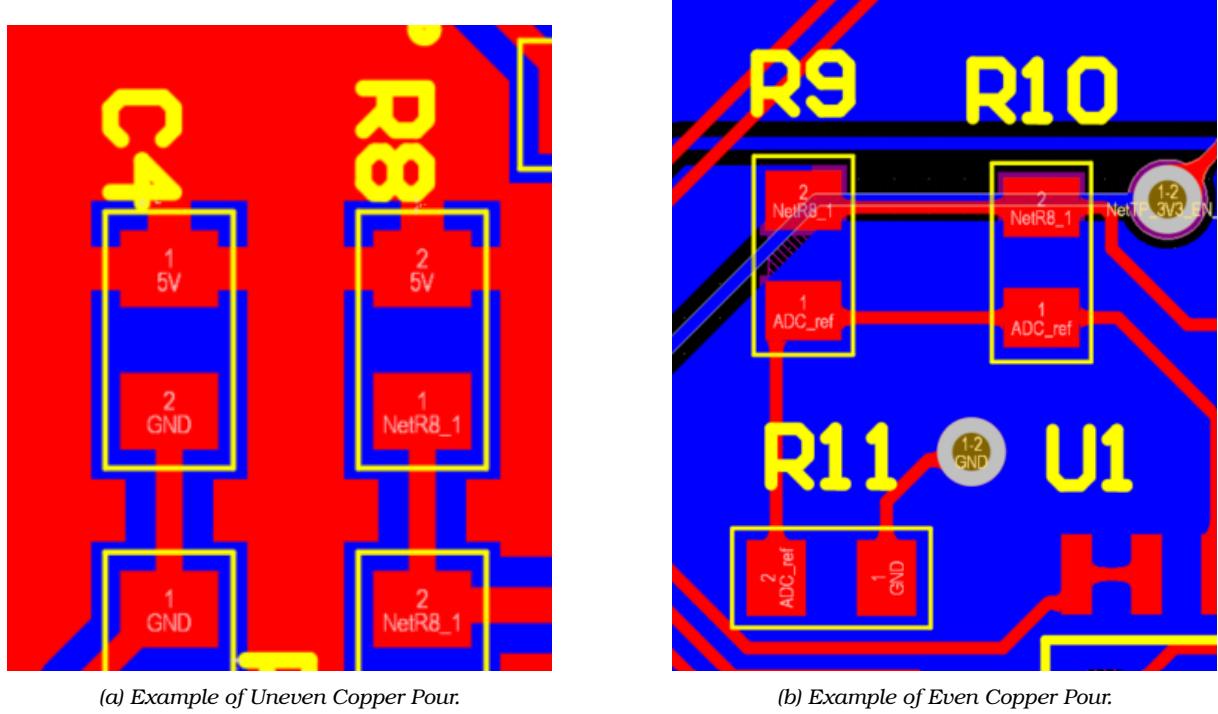


Figure 8: Examples of uneven and even copper pours.

### 5.2.5 Hardware Testing

Two phases of testing were conducted: breadboard testing and PCB testing. The breadboard testing is a process of prototyping, allowing us to debug and validate our design based on the initial position where the hardware validates and debugs the values they have got from the calculation, and adjusts the component values before moving onto the PCB design. The PCB testing shows the accuracy after soldering or assembling the components, and then the component values are adjusted for better accuracy if needed.

### 5.2.6 Breadboard Testing

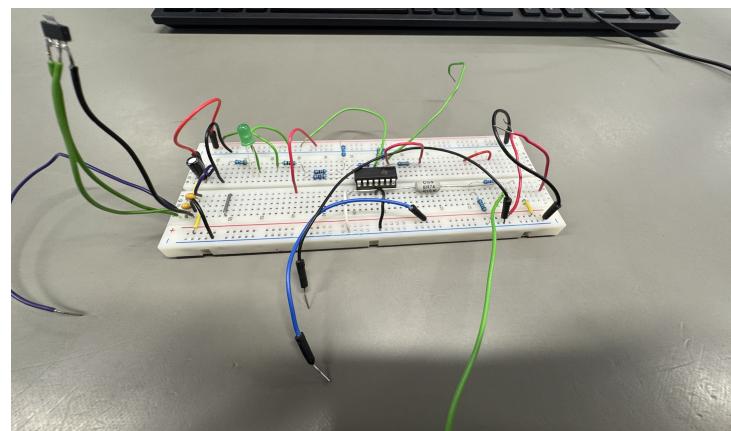
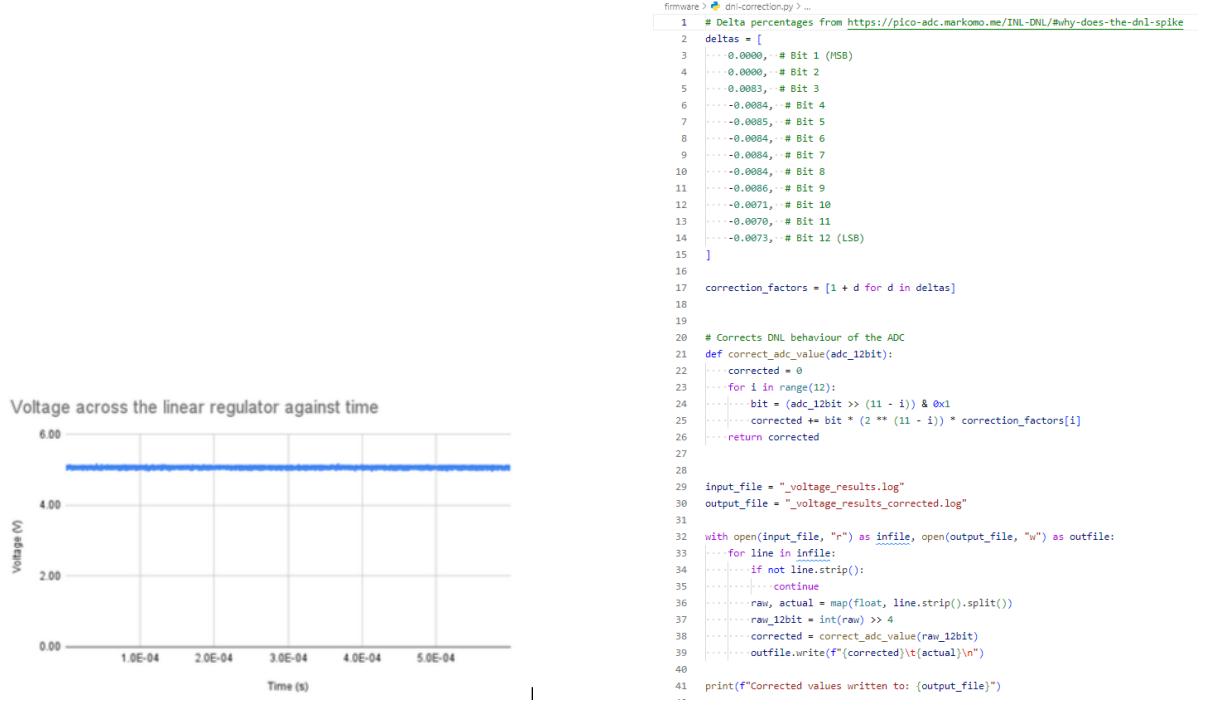


Figure 9: Breadboard used for testing

Figure 9 shows the breadboard used for testing. A breadboard was used to validate the circuit design before soldering the components onto the PCB. After testing on the breadboard, it was found that the output signals behaved similarly to the simulated results and had minimal

noise. Using the oscilloscope to probe the signal as a validation for voltage regulator and voltage supply for ADC reference, which are shown in Figures 10a and 10b. Figure 11 also shows the signals for voltage sensing and current sensing.



(a) Output of voltage regulator tested on breadboard.

(b) Output of ADC reference tested on the breadboard.

Figure 10: Breadboard testing outputs for the voltage regulator and ADC reference.

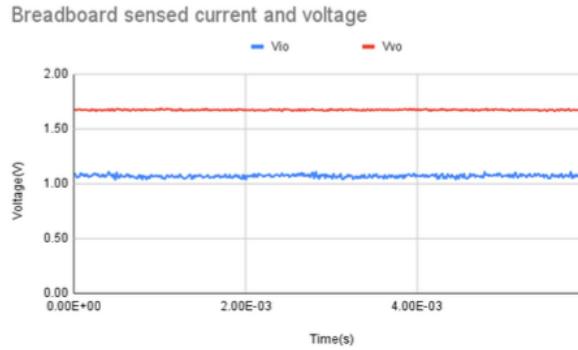


Figure 11: Voltage and Current sensor values tested on the breadboard

Following PCB assembly, testing was undertaken to ensure functionality and compliance with the design specifications. In the absence of an EVolocity car to test on, a realistic load from an Formula 1 race was used to simulate real driving conditions. The 5V regulator was measured under load to provide a stable output with minimal ripple. The current through the debugging LED which is connected to the regulator, was measured to be 19mA, which is well under the DC forward current of the chosen LED, ensuring longevity.

Figure 12 shows how the sensed voltage and current values change with the dynamic load shown in Figure 13. The measured voltage is relatively stable around 1.5V (1.495V-1.573V).The voltage value that represents the sensed current was measured to swing between -0.121V and 1.085V. This is a suitable range to observe current changes, with no clipping observed.



Figure 12: Voltage and current sensor oscilloscope readings from the PCB.

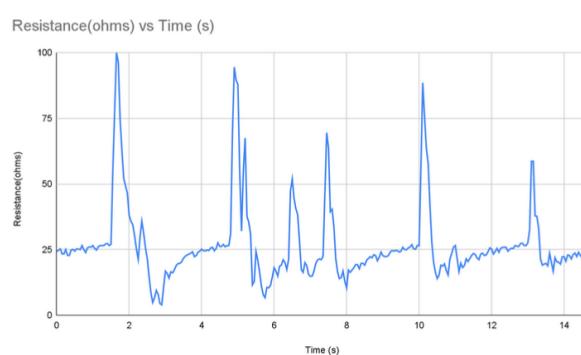


Figure 13: Realistic load used to test the PCB

### 5.3 Firmware Development

The primary objective of the firmware is to implement a robust system for collecting, storing, processing, and transmitting the values measured by the Hardware. To achieve this goal, the voltage and current are periodically sampled, along with the timestamps. A signal processing state calculates the energy and average values from the high sample rate into smaller amounts of information, and the data is streamed to the server or stored to flash depending on if a connection with the server is active, as per the firmware system data flow diagram.

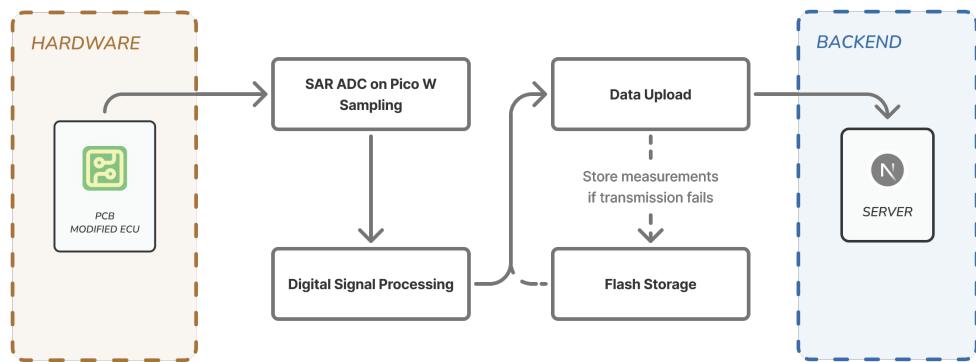


Figure 14: Flow of data through the firmware, from sampling to processing and transmission.

With the commitment to making the solution open and inclusive and aligning with the treaty principles of Partnership, MicroPython has been picked as our development language for the firmware. Python is commonly taught in schools and is one of the most common programming languages, with 51% of developers using this language. MicroPython allows for easily adding modularity to the firmware, improving readability without the complexity of CMake files. It also abstracts more complex peripheral register setup code, making it more accessi-

ble to school children. MicroPython APIs transparently bring improvements over raw C APIs, including utilising LittleFS, a file system designed for microcontroller flash applications with bounded/limited resource usage. Copy-on-write techniques are used to ensure resilience against random power losses. It also implements dynamic wear levelling and works around bad blocks. An annotation can enable the native code compiler or Viper compiler to generate optimised bytecode to improve performance.

### 5.3.1 Sensor Measurement

The first step of the firmware is to sample the signals from the hardware using Pico's analogue-to-digital converters (ADCs). The inputs are connected through pins GPIO26 and GPIO28 to measure voltage and current, respectively.

To ensure accurate timing, the Pico's Programmable Input/Output (PIO) was used with a custom assembly program to generate interrupts at a precise rate of 200Hz, independent of the software running on the processor cores. This improves performance over purely software-based timers, which will jitter or be indeterminate based on the current workload on the cores. A deviation to the overall program state machine logic was added after the project proposal; the implementation moved away from state machines, where sampling was stopped during uploading. ADC readings will now be continuously captured, even during data uploads. This implementation allows for continuous streaming to the server if the race track is small and the ECU remains connected while ensuring that the power limit can be continuously monitored. The measured ADC values are packed into a four-byte float instead of a Python-native float to improve memory efficiency and ease optimisation for the native code/Viper compiler for calculations.

### 5.3.2 Data Packing into Compact Binary Format

After sampling and signal processing, the results are packed into a compact binary format and placed into a queue for the data transmission task. To improve memory efficiency and flash usage, the values remain packed in the compact binary format for the remainder of the time it is handled on the Pico. The calculation and packing functions are optimised using the MicroPython Viper Native compiler, which allows MicroPython to compile the code to bytecode, improving performance for packing and unpacking data. Operating on Viper-native datatypes greatly improves performance, and in our tests, the overhead of conversion from a Python-native datatype is always worth it for compute-heavy functions.

### 5.3.3 Digital Signal Processing (DSP)

To avoid overloading the flash and backend with measurements and to improve accuracy, samples are batched into larger groups and unpacked. Key metrics, including the peak values and averages, are calculated, and the sample's timestamp is bundled with the data. Using this information, the software team can easily create a solution that can display the energy, power, current, and voltage usage with respect to time while ensuring that cars exceeding the power limits can be noted and penalised.

The signal processing task is run on a separate core to ensure that long computation times do not interfere with data uploading and that the sampling ISRs do not interfere with the signal processing. Thread-safe queue data structures are used for communication between the main task on core zero and the processing task on core one. The processing converts raw ADC values of the current and voltage to more accurate Volts and Amperes, alongside power calculation and energy calculations. Once 10 samples are connected for each, the average voltage, current, and power are calculated, along with the peak values for power. The energy calculations are performed on the microcontroller to obtain the total energy consumption to allow for high confidence in the preciseness of the timing of readings.

The ADC RP2040 microcontroller used by the Pico contains an unfixable hardware bug/errata (RP2040-E11) due to incorrect capacitor choices inside the microcontroller's ADC's successive approximation circuit, causing severe differential nonlinearity spikes. This is exhibited by jumps/discontinuities in ADC measurements, as can be seen in the red points in Figure 15.

To mask the effects of this, a calibration profile with different weights for each bit can be applied as shown in Figure 18 in Appendix C, as shown by the blue points.

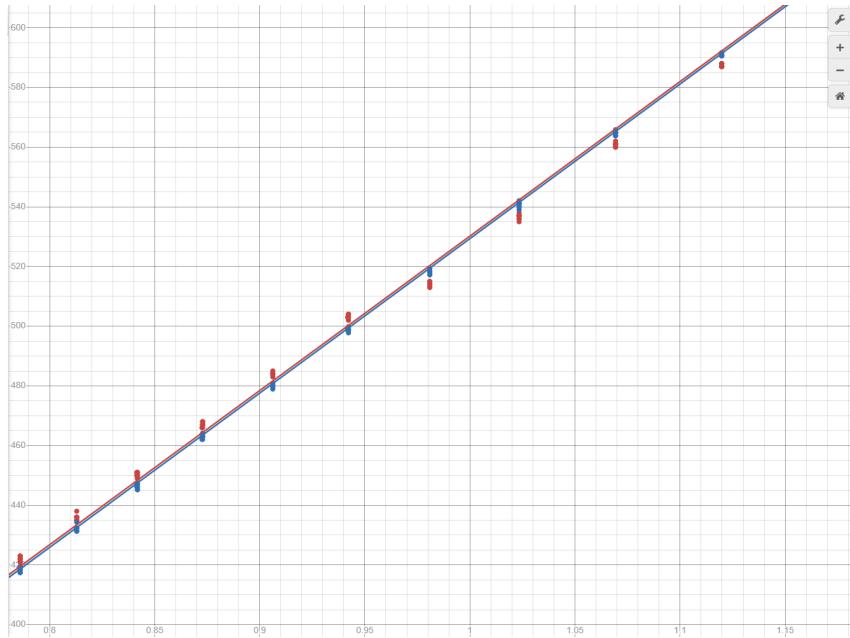


Figure 15: Raw vs actual current measurements from test load and ADC. Red points show raw ADC values, blue points show calibrated values.

The voltage and current is then scaled by the results from our simulations from our hardware team to calculate the true voltage and current.

### 5.3.4 Network Connectivity and Data Upload

The ECU attempts to connect to Wi-Fi and upload values to the server every five seconds. The onboard LED is used as a status indicator to show the status of the connection. A solid light indicates that the Pico is connected to the server, a slow blinking light indicates the ECU is connecting to Wi-Fi, and rapid blinking indicates the ECU is attempting to discover the backend server on the local area network.

The ECU attempts to connect to a hotspot hosted on a phone or the device hosting the server and then tries to discover the server's IP address. The server emits a UDP broadcast beacon packet on a predetermined port every 250ms, which the ECUs listen for. Once the IP address is obtained, the ECUs check if the server is our official server by checking a predetermined endpoint.

After connecting to the server, the ECU checks for the backlog of measurements stored on the flash that have not been uploaded to the server and performs a streaming upload (detailed in the Section 5.3.5). If no backlog exists and the server's connection is healthy, the ECU batches measurements from the previous calculations stage into STREAMING\_BATCH\_SIZE chunks to transmit to the server at once. Batching reduces the backend load and the ratio of CPU time spent on the overhead of requests to the time spent handling data transmission.

As the data is only stored in memory as a buffer, it is not written to disk provided that connection to the server is stable, allowing the solution to prolong the life of the flash's hardware. If the connection to the server is lost, measurements will be written to flash.

The ECUs and servers communicate over HTTP over TCP/IP. TCP implements error detection, handling and retransmission, allowing for guarantees that the measurements are transmitted correctly. HTTPS introduces significant overhead in both memory usage and compute overhead on the firmware. HTTPS and SSL encryption are unnecessary as WPA2 authentication used by the Wi-Fi access point utilises a four-way handshake to establish an encrypted

connection between ECUs and the host server, ensuring that packets cannot be spoofed or sniffed.

A broadcasting feature was also implemented to allow the Pico to broadcast its serial number to the server to identify itself when the button is held after the Pico is power cycled.

### 5.3.5 Measurement and Configuration Storage

The Pico's flash is known to be prone to corruption on power loss and has limited write endurance. The firmware employs some mitigations, such as using LittleFS, but it is also designed to write as little as possible to the flash. With only Session ID and serial number stored on the flash, the firmware is almost stateless across power cycles and is resilient to power losses. The serial number is obtained from the MAC address of the Pico, and it is stored to flash to allow for changing the value, but it is discouraged. The session IDs are incremented every time the ECU is turned on. Upon resetting, the software can handle duplicate session IDs by incrementing them to the next available session ID value.

JSON is used to store persistent configuration data, including the session\_id and pico\_id, to balance small file size and human readability. File system operations are cached to improve performance and reduce wear on the flash. This is done to allow caching values where possible to reduce the number of flash read/write operations. The Pico's default ID is its MAC address, which is unique per Pico and does not require changing.

As the Wi-Fi connection may drop during the race, measurements must be persisted to the flash in case of a power failure whilst out of range. A binary file stores the packed values from the signal processing phase. We append the batches of measurements to the end of the file. A free space check is performed before writing to the flash.

As the measurement protocol is the same as the previously packed values, the files can be streamed from the file as-is in chunks without loading the entire file into memory for transformation. Due to the nature of MicroPython's memory allocations, memory may become fragmented, meaning that whilst a large amount of memory may be free, contiguous memory blocks may be unavailable. Opportunistic dynamic chunk sizing during runtime is implemented to increase the amount of data chunked to up to 500 readings at once, provided that there is enough free continuous memory. Chunk streaming will allow efficient uploading of large measurement backlogs in chunks, reduce memory overhead whilst uploading, and allow more measurements to be uploaded compared to other formats, such as JSON.

### 5.3.6 Firmware Simulations, Implementation, and Testing

Before implementing the firmware, the firmware was tested in simulators to ensure each part of the required functionality in the MVP, such as ADC sampling, storage and transmission, would be met. Initial testing scripts written in Wokwi (Figure 19) used both C and MicroPython to evaluate the performance of the different language options. The simulation was done to ensure that the program continues working whilst adding new functionality.

Initially, a simple ADC capture loop was simulated and tested on the physical board. A simple function was implemented to capture the raw ADC value and convert it to a float of the corresponding input voltage. In the next iteration, chunking, along with a CRC32 checksum, was implemented. Checksum validation is a process used to ensure that a file or data block has not been altered or corrupted during transmission or storage.

After each driver was written and tested to be running as expected in the simulator, the tasks were made to work concurrently with the `asyncio` library.

To test the integration of the firmware before the software was completed, a mock server was created to take in values from the firmware and calculate the energy consumption of the load and recorded values. The mock server also served as a reference implementation for decoding the binary format.

For verification against the range of values, the mock server was modified to control and read the Virtual Instrument Software Architecture (VISA) protocol from the load to compare the

sampled value against the actual values. The measured current against the read current of a sweep of resistances is logged to a file and plotted onto Desmos below. The firmware's performance remained constant when we conducted additional measurements after swapping our Pico for an alternative unit.

### 5.3.7 Firmware Improvements

The most common point of failure with our hardware design was the RPi Pico W. By using female headers instead of soldering the pico to the board, we have made it easy to swap out. However, the flash is still prone to wearing out. Writing the configuration and measurements to an external SPI flash or an SD card will prolong the lifespan of the Pico.

Our sampling rate of 200 Hz can be further increased with further optimisations to the calculation code to improve the accuracy of our energy calculations. A rewrite in C/C++ may improve performance and bring additional benefits, allowing lower-level control over the hardware and allowing the hardware timers to be used. In addition, the Python Global Interpreter Lock hinders the full potential of multithreading with Python, which will not be the case with a C/C++ implementation.

## 5.4 Software Implementation

### 5.4.1 Frontend Architecture and Design Goals

The frontend was created in React using TypeScript and is designed to run smoothly on any modern browser for any phone or laptop. The goal was to create a simple, no-fuss user interface that was easy to use. Since the users are likely to be volunteers, they won't have time to learn a complicated system and they won't be looking for a flashy, visually stimulating interface—they want a pain-free scoring experience so they can focus on attending to the events and teams.

Thus, the frontend consists of three simple pages: a competitions, teams, and event types page—each for managing their respective areas. The application begins at the homepage that contains links for each page, and there is a navigation bar at the top of every consequent page for ease of navigation. The application does not include a login screen, as it will only be run by the EVolocity scoring team. Adding a login would create unnecessary steps for users.

### 5.4.2 Feature Overview and Improvements

The functionality of the website is as follows:

- **Manage Teams:** Users can create, edit, and view teams. This includes team names, vehicle class, and vehicle type.
- **Assign Team to ECU:** Users can match a team to its device serial number—thus linking the two for scoring. The serial number is 3D printed on each ECU for easy access. When a team presses their Pico's Wi-Fi button, the web application displays a real-time notification with the serial number of the pressed device. This allows volunteers to easily map teams to ECUs.
- **Manage Event Types:** Users can create, edit, and view events. This allows future event changes to be made directly through the UI rather than through code.
- **Manage Competitions:** Users can create, edit, and view competitions. When creating a competition, users can set the name, select at least three events, and assign at least one team. Teams can also be created here if they were missed earlier. If the user is online, they can also load and view past competitions.
- **Scoring and Leaderboards:** After each event is completed, users can press the 'Finish and Score' button to display the leaderboard for that event by vehicle category (e.g. Open Kart, Standard Bike, etc). An overall leaderboard is also maintained and updated as events are scored.

- **ECU Monitor:** The ECU displays three graphs for voltage, current, and energy. Hovering over each graph shows more detailed measurement data.

### 5.4.3 User Flow for Race Day

The final user flow diagram, Figure 16 includes updated steps to reflect changes in functionality:

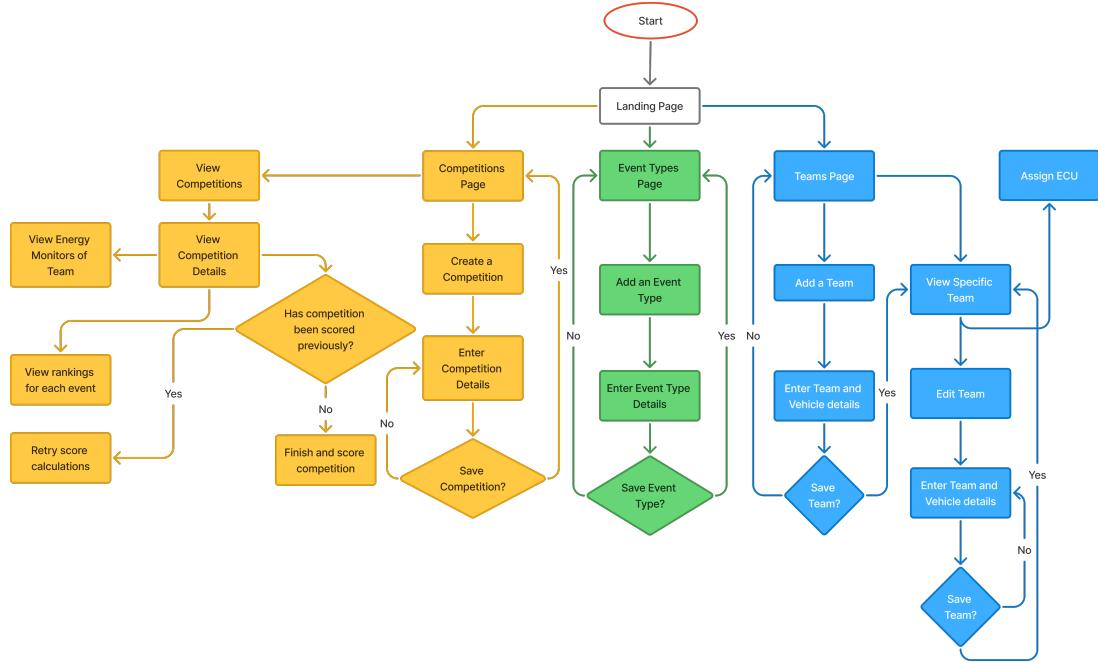


Figure 16: Updated user flow diagram reflecting team-to-ECU assignment and simplified scoring path.

- Add team-to-ECU assignment
  - Add team creation within competition creation
  - Add scoring and retry scoring
  - Remove “connect ECUs per event”

Team-to-ECU assignment can happen at any point until scoring. Assuming all teams are registered with their vehicle details, the team, event, and competition setup can be done before race day. Then on the day, users simply assign ECUs and press the 'Score and Finish' button per event—making the workflow as efficient as possible.

#### 5.4.4 Backend Architecture and API Design

The backend was developed using Supabase for the cloud database, while a local SQLite database was used during events to allow offline operation. It is paired with docker to ensure reliable and uniform deployment regardless of the environment. We have a robust API layer which connects Next.js and Supabase through Prisma. This allows seamless communication between the frontend interface, ECUs and the database. We chose these technologies to accommodate rapid development, reliability, and straightforward deployment.

The backend architecture uses a RESTful API structure and standard HTTP methods, including GET, POST, PATCH, and DELETE. Each endpoint was created for a specific resource for the application, including teams, devices, competitions, races, and sensor data. This structure allows for predictable and reliable interactions between different system components, essential for a multi-disciplinary system.

All API routes were structured using JSON formats and standard HTTP status codes to help debugging and communication between backend and frontend components. Error handling

and validation were implemented to help reduce the risk of failures due to malformed data inputs.

API endpoints were created for every relation only where necessary. Instead of having CRUD for every object type we only made the endpoints where needed (or would be needed in future). This created a simpler backend that does not have unused routes. There are also additional endpoints that are not from the schema, which are specialised for device assignment and device handshaking. These also ensure that in addition to wifi connectivity, the actual server is also online.

#### **5.4.5 Database Management and Offline Operation**

The cloud database uses Supabase, which is a PostgreSQL-based platform. For local usage, a lightweight SQLite database was used. Both shared the same schema structure, which made it straightforward to test and sync data between local and cloud environments. The defined schema contains models for race, event, competition, ranking, team, device, device configuration, record, sensor data, and notification.

Prisma was used during development to inspect and manage database contents. Prisma allows a level of abstraction between raw SQL code (used with both Supabase for cloud and SQLite for local) and the Next.js backend. This made testing and development easier across both environments. Pushing the schema through Prisma and using a seed script to populate the database with test data allowed for an easy development pipeline.

Due to the client's anticipation of unreliable internet connection during race day events, the backend was designed with offline-first and online connectivity functionality if available. A local SQLite instance was put into a docker container and will run entirely on the laptop used on race day. All core functionality works without internet access. Data generated during events will be stored in the local SQLite database. The data can then be uploaded to the cloud through the API/sync endpoint. The user manually triggers this via a button on the front end once they have an internet connection.

A manual database syncing version was chosen over an automated or time-based system to ensure reliability and avoid unexpected syncing errors. Without knowing when the user might connect to the internet, the best way is manual syncing. To do this, the user runs the docker image, navigates to the front end and clicks the sync database button. The syncing process includes logic to avoid any duplication and verifies data integrity. This makes the process user-friendly and dependable.

#### **5.4.6 Deployment and System Integration**

Docker containers encapsulate the backend server and the local SQLite instance. This ensures consistent deployment behaviour no matter the operating system and version. GitHub CI/CD pipelines are also used to automate Docker image builds; this allows easy updating in case of future work. A Nix flake was included to maintain consistent package versions across machines, and a single-click executable file was made to allow non-technical users to launch the full-stack web app without installing requirements like Node.js.

The backend is closely integrated with the firmware running on the ECUs. It has been designed to receive real-time data transmitted over a local wi-fi hotspot and dynamically discover devices on the subnet. The front end manages device-to-team assignments, whilst the back end accurately records assignments and scoring. The front end and firmware are seamlessly integrated and will respond accurately and responsively during events.

## 6 Next Steps

The system has been developed with modularity and extensibility in mind, providing a strong foundation for further development by EVolocity staff and future student teams. The architecture is designed to be adaptable, maintainable, and aligned with evolving competition formats, educational goals, and technological requirements. Several areas of enhancement have been identified:

### 6.1 User Roles and Access Control

Introducing a user authentication and role-based access control system would allow the platform to support multiple types of users. While the current system is designed for EVolocity officials, future iterations could introduce participant-facing views where student teams can access their own ECU data, performance analytics, and leaderboards. This would enhance engagement, transparency, and learning opportunities while ensuring sensitive administrative tools remain restricted to authorised staff.

### 6.2 Improved Data Storage

Currently, the microcontroller stores data in internal flash memory, which is a known point of wear over repeated write cycles. Migrating persistent storage to external SPI flash or an SD card would significantly improve the reliability and lifespan of the ECU hardware. It would also provide greater flexibility in how much data can be logged locally and could simplify offline usage in longer race scenarios.

### 6.3 Firmware Optimisation

The existing firmware meets all performance requirements using MicroPython, with a sampling rate of 125–200 Hz. However, porting critical portions of the codebase to C or C++ could further increase efficiency, enabling higher sampling rates and more accurate real-time energy calculations. This would also unlock hardware-level control features such as timers, and remove limitations imposed by the Python Global Interpreter Lock (GIL), allowing for more effective concurrency and improved responsiveness.

### 6.4 Hardware Refinement

The final version of the PCB included in this report incorporates a number of improvements over earlier prototypes, including more reliable component placement and support for microcontroller replacement via female headers. Future iterations could enhance this further by improving mechanical mounting options, reducing heat dissipation through improved power regulation layout, and integrating additional hardware diagnostics or status indicators for field debugging.

## Conclusions

The wireless data acquisition system is designed to measure the energy used by the electric vehicles designed and built by the competitors. The data for the measured energy usage is transmitted to EVolocity officials within the time required from EVolocity. A central database is used to store the transmitted database, which can be used by the EVolocity officials to manage the competition, monitor teams, and view real-time performance metrics using a user-friendly interface.

The project team is committed to respecting the values of Maori culture, and was actively engaged with the Maori community throughout the decision making process. The system is planned for long-term sustainability, and an eco-friendly solution is designed using components that are expected to last 10 years or more, to minimise environmental impact.

The PCB design was improved to attain a better accuracy for the data acquired. This was done by reducing the noise due to the environment, by adding a buffer on the voltage sensing, and another on the ADC reference voltage for the Raspberry Pi.

The firmware team has ensured that the values that the PCB measures can be properly captured by the Raspberry Pi, stored appropriately with the relevant calculations, and transmitted away so that a visual representation of the data can be created. A periodic sampling of both the Voltage, and Current, along with their timestamps are used to calculate the energy usage, and the average values. These values are prepared to be sent to the Software side by dividing them into batches. These batches are either stored to flash, or streamed to the server depending on the status of the server.

The software system was designed with simplicity, usability, and adaptability in mind to ensure there are no issues on race day. The database and user interface has been designed to be extremely straightforward to deploy and manage. In terms of database, SQLite was utilised for its simplicity and ease of use with little overhead. This allows a manual sync process with simple data uploads. The user interface was carefully designed with Te Tiriti and user-first approaches in mind. Finally, the testing suites with scoring, team assignment and end-to-end coverage ensured correctness throughout our development.

Overall, the project that was undertaken by the team creates a reliable solution that fully meets the requirements set by EVolocity. For the final result, the team has achieved the solution that meets the requirements laid out by EVolocity. The team also paid special attention to ensure that Maori values and cultures were upheld, and our designs were in accordance to that. On top of that, the team conducted a thorough review of the design and based on that suggested the ideas and improvements that can make the solution an even better product.

## References

- [1] Raspberry Pi Ltd, "RP2040 Datasheet," Raspberry Pi Ltd, Cambridge, UK, 2021. [Online]. Available: <https://datasheets.raspberrypi.com/rp2040/rp2040-datasheet.pdf>
- [2] Nichicon, "UVR Series Aluminum Electrolytic Capacitors," Nichicon Corporation, Japan, 2023. [Online]. Available: <https://www.digikey.co.nz/en/products/detail/nichicon/UVR2C100MPD/588902>
- [3] TE Connectivity, "ER Series Current Sense Resistors," TE Connectivity Ltd., Switzerland, 2022. [Online]. Available: <https://www.digikey.co.nz/en/products/detail/te-connectivity-passive-product/ER74R10KT/2365306>
- [4] Taiwan Semiconductor, "SR304 Schottky Barrier Rectifier," Taiwan Semiconductor Co., Ltd., Taiwan, 2022. [Online]. Available: <https://nz.element14.com/taiwan-semiconductor/sr304-r0/diode-schottky-3a-40v/dp/7278403>
- [5] Lite-On, "LTST-C191KRKT SMD LED," Lite-On Technology Corporation, Taiwan, 2022. [Online]. Available: <https://www.digikey.co.nz/en/products/detail/liteon/LTST-C191KRKT/386837>
- [6] ON Semiconductor, "LM324 Low Power Quad Operational Amplifier," ON Semiconductor, USA, 2022. [Online]. Available: <https://www.digikey.co.nz/en/products/detail/onsemi/LM324DR2G/918511>
- [7] STMicroelectronics, "L78L05ABUTR Voltage Regulator," STMicroelectronics, Switzerland, 2022. [Online]. Available: <https://www.digikey.co.nz/en/products/detail/stmicroelectronics/L78L05ABUTR/585705>
- [8] PCBWay, "PCB Assembly Services," PCBWay, China, 2023. [Online]. Available: <https://www.pcbway.com>
- [9] Raspberry Pi Ltd, "Raspberry Pi Pico W," Raspberry Pi Ltd, UK, 2022. [Online]. Available: <https://www.digikey.co.nz/en/products/detail/raspberry-pi/SC0918/16608263>
- [10] Yageo, "RC Series Chip Resistors," Yageo Corporation, Taiwan, 2022. [Online]. Available: <https://www.digikey.co.nz/en/products/detail/yageo/RC0805FR-0710KL/727535>
- [11] Samsung Electro-Mechanics, "CL21 Series Ceramic Capacitors," Samsung Electro-Mechanics, South Korea, 2022. [Online]. Available: <https://www.digikey.co.nz/en/products/detail/samsung-electro-mechanics/CL21B104KBCNNNC/3886661>
- [12] Keystone Electronics, "PCB Test Points," Keystone Electronics Corp., USA, 2022. [Online]. Available: <https://www.digikey.co.nz/en/products/detail/keystone-electronics/5003/362668>
- [13] J. Heath, "Working with op amps: tying down floating pins," *Analog IC Tips*, 2017. [Online]. Available: <https://www.analogictips.com/working-op-amps-tying-floating-pins/>

## Appendices

You may include up to twelve additional pages for appendices. However, your report should stand independently without a reader needing to look at these appendices. They will not be marked.

Appendices must start on a new page.

### Appendix A: Bill of Materials

The components can be bought from PCBWay [8], DigiKey [2] [3] [5] [6] [7] [9] [10] [11] [12] and Element14 [4]. The prices quoted are based on the websites of Digikey and Element14.

Table 2: Bill of Materials (BOM) for the ECU hardware components.

Item No.	Component	Part Number	Qty	Unit Cost
1	Op-Amp	LM324DR2G	1	\$0.64
2	Shunt Resistor	ER74R10KT	2	\$1.80
3	Linear Regulator	L78L05	1	\$1.37
4	Schottky Diode	SP304	1	\$0.95
5	LED	LTST-C191KRKT	1	\$0.20
6	RPi Pico W	SC0918	1	\$11.59
7	Test points	5003	5	\$0.26
8	Electrolytic Capacitors	TH	1	\$0.26
9	Ceramic Capacitors	0805 SMT	5	\$0.02
10	Resistors	0805 SMT	11	\$0.06
11	PCB	-	1	\$5.00
			<b>Total</b>	\$25.65

### Appendix B: ORing Simulation in LTSpice

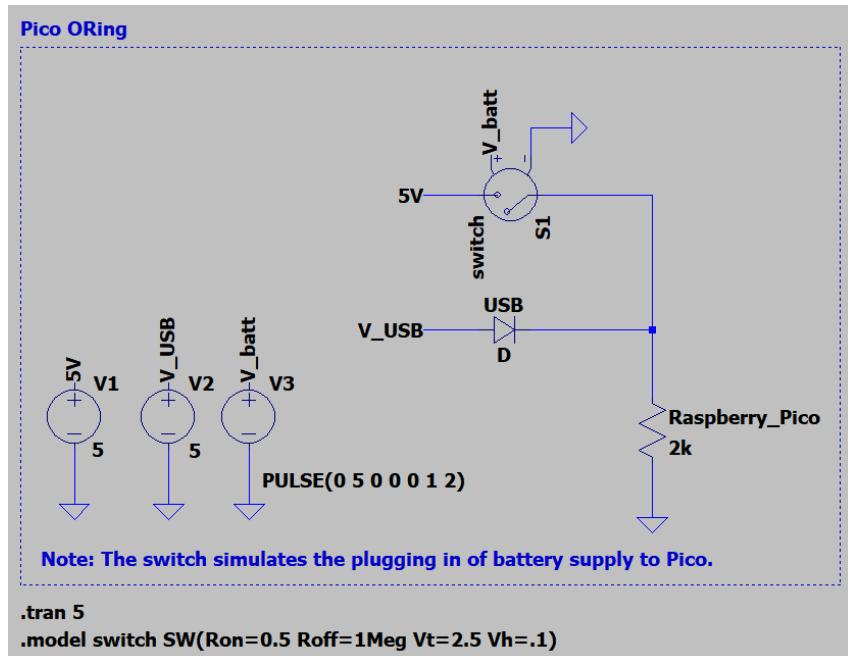


Figure 17: ORing Simulation in LTSpice

## Appendix C: Change bit weights to correct DNL error

```

firmware > dn1-correction.py > ...
  1  # Delta percentages from https://pico-adc.markomo.me/INL-DNL/#why-does-the-dnl-spike
  2  deltas = [
  3  ... 0.0000, # Bit 1 (MSB)
  4  ... 0.0000, # Bit 2
  5  ... 0.0083, # Bit 3
  6  ... -0.0084, # Bit 4
  7  ... -0.0085, # Bit 5
  8  ... -0.0084, # Bit 6
  9  ... -0.0084, # Bit 7
 10 ... -0.0084, # Bit 8
 11 ... -0.0086, # Bit 9
 12 ... -0.0071, # Bit 10
 13 ... -0.0070, # Bit 11
 14 ... -0.0073, # Bit 12 (LSB)
 15  ]
 16
 17 correction_factors = [1 + d for d in deltas]
 18
 19
 20 # Corrects DNL behaviour of the ADC
 21 def correct_adc_value(adc_12bit):
 22     corrected = 0
 23     for i in range(12):
 24         bit = (adc_12bit >> (11 - i)) & 0x1
 25         corrected += bit * (2 ** (11 - i)) * correction_factors[i]
 26     return corrected
 27
 28
 29 input_file = "_voltage_results.log"
 30 output_file = "_voltage_results_corrected.log"
 31
 32 with open(input_file, "r") as infile, open(output_file, "w") as outfile:
 33     for line in infile:
 34         if not line.strip():
 35             continue
 36         raw, actual = map(float, line.strip().split())
 37         raw_12bit = int(raw) >> 4
 38         corrected = correct_adc_value(raw_12bit)
 39         outfile.write(f"{corrected}\t{actual}\n")
 40
 41 print(f"Corrected values written to: {output_file}")
 42

```

Figure 18: Code used to change bit weights to correct DNL error

## Appendix D Current capture simulations in Wokwi

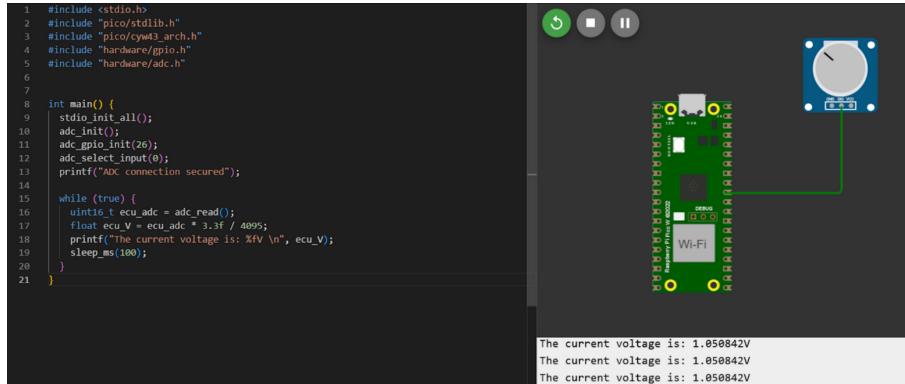


Figure 19: Current Capture simulations in Wokwi