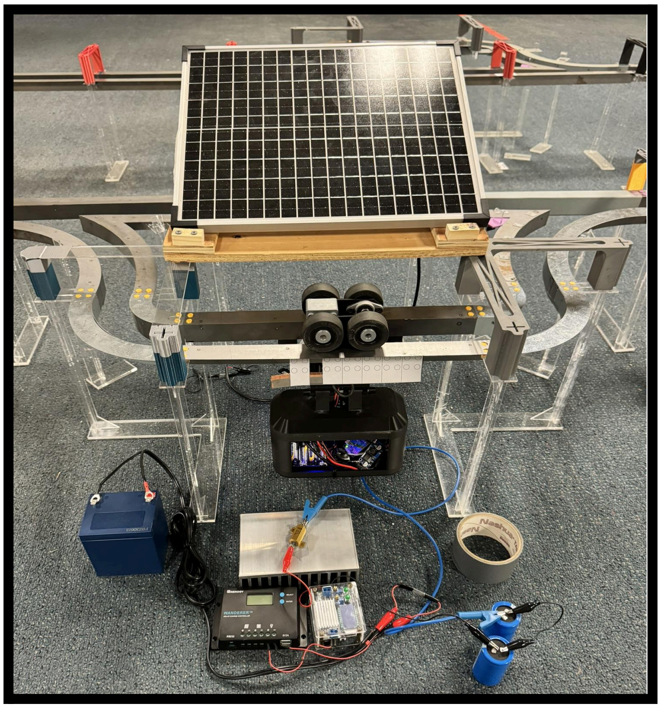
Energy Storage and Charging Team Spring 2024 Report



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I. Executive Summary

For our project, we developed a hybrid supercapacitor-lithium-ion battery energy charge and storage system that allows a small scale model of the Spartan Superway vehicle (Bogie) to operate on the demonstration model track. A key feature of the SPARTAN Superway (SSW) is the use of renewable energy. The solar energy received from the offline stations, flows through the third-rail carbon brushes, that's then transferred to our energy charge and storage system, which then continuously powers the Bogie. Through much research, many design iterations and consistently running the system through tests, we were able to develop a successful functional system. Our system initially could only output 5V at 0.1A to 0.2 A. This was barely enough for the small motors to draw from, but not enough for the motor on the Bogie to run. Our final design utilizes four supercapacitors and two lithium-ion batteries. The supercapacitors are set up with two sets of two supercapacitors in series and the pairs are put in parallel. This configuration along with the TP 4056, Pi Sugar Module and DC-DC Boost Converter allowed us to raise both current output of the system from 5V 0.2A to output 9V at 0.6A, which was enough to power the Bogie's motor.

II. Acknowledgments

We would like to express our utmost gratitude to:

Dr. Burford Furman for advising us on our project and sending helpful articles about supercapacitors, hybrid batteries, and supercapacitor systems.

Dr. Ping Hsu for pointing us in the right direction regarding our circuit design and meeting with us outside of office hours.

Ron Swenson for supervising, managing, and sponsoring the SPARTAN, along with providing helpful advice on our presentations.

SPARTAN Superway Core Team Members, especially Greg White & Khoa Lam for answering questions and providing tools.

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VI. Introduction and Project Description

A. Problem Definition

What is the SPARTAN Superway?

The SPARTAN Superway (SSW) stands for Solar Powered Automated Rapid Transit Ascendant Network. Furthermore, a transportation system powered by renewable energy can decrease carbon emissions and increase public safety, all while improving the quality of life within urban areas. Located in San Jose, California, the SPARTAN Superway was founded by Dr. Burford Furman and Ron Swenson in 2012, and it has been an ongoing project ever since. Currently, the superway is designed as a small-scale modular version that the team hopes to one day develop into a large-scale version.

Problems the SPARTAN Superway Addresses & Why the System is Needed

The SPARTAN Superway (SSW) is key to enhancing the quality of life and resolving various problems, from pollution to public safety. The issues that the SSW addresses are within the following sections:

Air Pollution Due to Gas-Powered Vehicles

Pollution causes about 9 million deaths globally, and 6.5 million are caused by air pollution (Fuller et al., 2022). Greenhouse gasses (GHGs), which include Carbon Dioxide (CO_2), Methane(CH_4), Nitrous Oxide (N_2O), Fluorinated Gases (F-gasses), and more, are the leading causes of air pollution, Global Warming, and Climate Change. Unfortunately, World 101 (2023) reports that the U.S. ranks #1 out of 10 countries for emitting the highest GHGs from 1850 to 2021. Today, in 2024, the U.S. is no longer the #1 emitter; however, we are still listed in the top 10 category and remain a leading contributor to this issue. Focusing on economic sectors, it's observed in **Figure 1** that Transportation makes up 38% of Carbon Dioxide emissions in the U.S., which is the largest out of all the economic sectors (Shirley et al., 2022). The second largest sector is the use of CO_2electricity to meet the electricity demand.

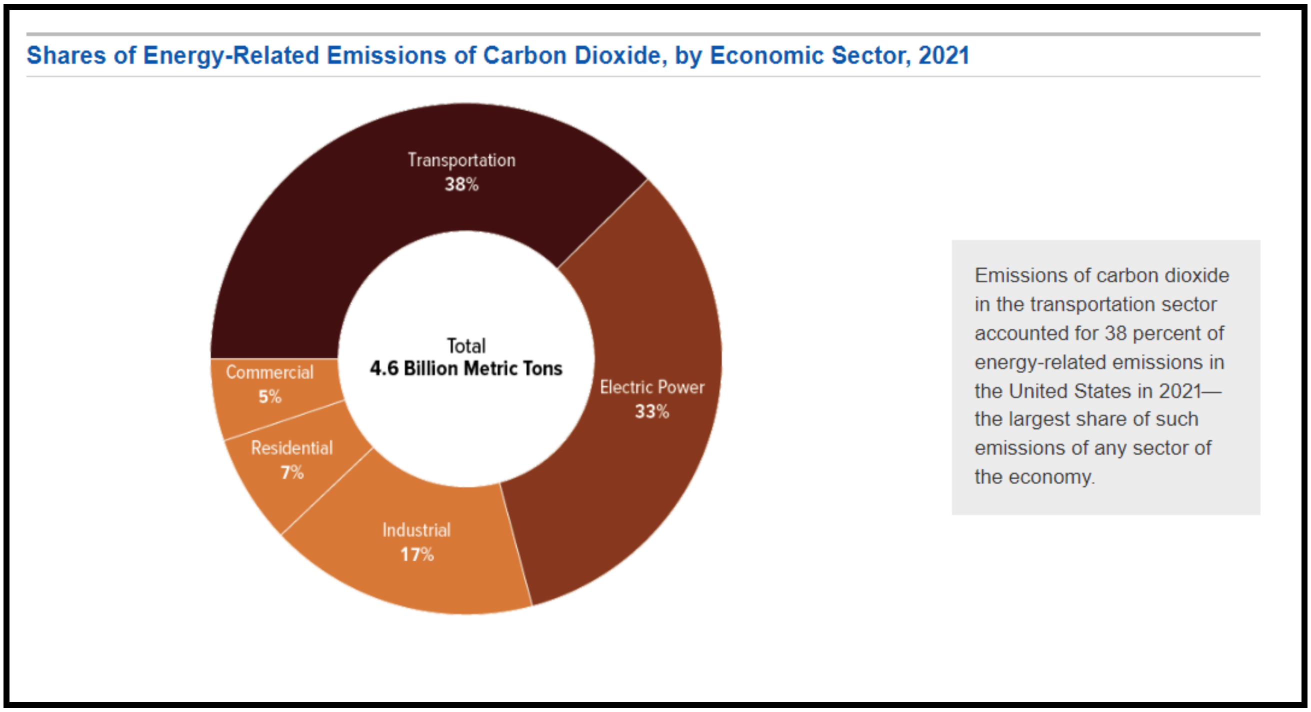

Figure 1. Carbon emissions from the Transportation and Electric Power sectors make up 71% of carbon emissions released into the air (Shirley et al., 2022).

Examining the amount of carbon emissions produced by the most populated state, California's Transportation sector is the largest producer of GHGs (Rozzelle & OEHHA, 2023). A detailed breakdown of sectors and percentages of GHGs produced in California is demonstrated in **Figure 2.**

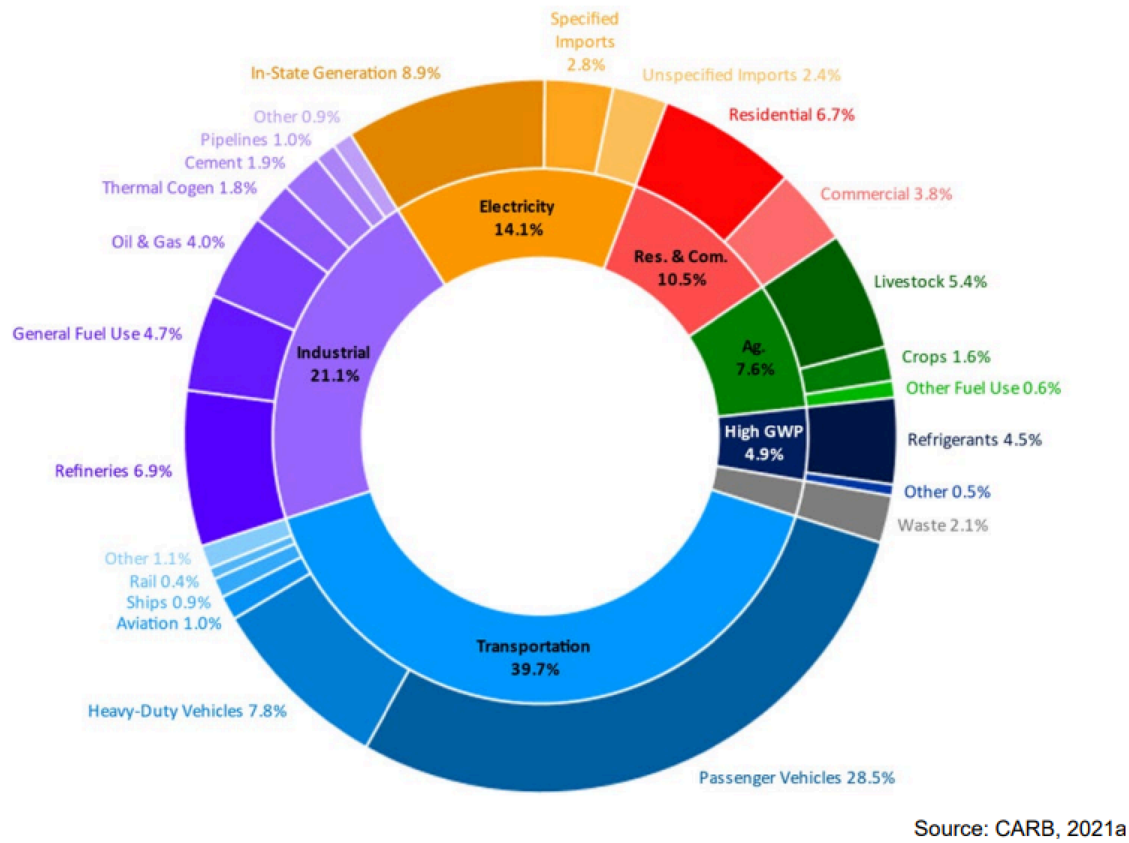

Figure 2. The Transportation sector in California is broken down into two major categories, with 7.8% as Heavy Duty Vehicles and 28.5% as Passenger Vehicles (OEHHA, 2023).

With the development of the SPARTAN Superways (SSW), the given percentage of carbon emissions from the Transportation sector will dramatically reduce because many people will decide not to drive (taking the SSW instead), which in return will reduce traffic congestion, which in turn will reduce the amount of GHGs released into the air.

Air Pollution Due to Electric Vehicles

To reduce the percentage of GHGs produced by the Transportation sector, California became the first in the world to ban the sale of gas-powered vehicles beginning in 2035 (Lopez, 2022). This regulation will then promote the use of electrical vehicles (EVs); however, EV owners will charge their vehicles, causing an even higher demand on the power grid. According to the California Energy Commission (2021), “electricity imports account for approximately 30 percent of total system electric generation (in California) each year.” Thus, the electricity demand is so high that California must import electricity from other states. If more people use EVs, then that will create an even higher demand to import electricity, and the other states may feel the need to burn more fossil fuels just to meet the electricity demand of their state and California.

The SPARTAN Superway can mitigate this issue. Since the system will be powered with solar energy, the SSW will not rely on the grid to supply electricity. California will not need to import electricity to power the Superway. In theory, people in the United States will not use their cars as often, or not use them at all, that is- if the SSW ideally expanded across the U.S. Thus, with the implementation of the SSW, Electric vehicles (EVs) owners will not charge their vehicles as frequently, which means less demand for electricity on the power grid; thus, less usage of fossil fuels to create more electricity.

Public Health and Safety

Both gas and electric vehicles cause traffic congestion; however, when many gas-powered vehicles are cramped up in one area, for instance, a backup on an arterial road, the concentrated release of pollutants can be very harmful, making it difficult for pedestrians walking on the sidewalk to breathe which is a public health concern. Air pollution from vehicle emissions causes asthma and other respiratory illnesses caused by long-term exposure. It causes those with Asthma to have Asthma attacks that could lead to death without immediate medical attention (e.g., an inhaler). Since the SPARTAN Superway runs on solar energy, it will not emit toxic pollutants. As mentioned earlier, it will clear up traffic congestion when people decide to use the SSW instead of driving their vehicles.

Another public health crisis is the amount of pedestrian accidents that occur. ABC 7 News reporter Lauren Martinez (2023) reports that as of April 2023, 10 people were involved in vehicle-pedestrian accidents in San Jose, CA, this year. This may not sound like a large number, but seven out of ten people died. It's a tragedy already when one person alone dies; there are most likely many more pedestrian fatalities in other Bay Area cities. To resolve this issue, the SSW will function above roads and sidewalks through a raised track design to prevent human collisions with the bogie (vehicle name for SSW). Thus providing safety for pedestrians and decreasing the number of vehicle-pedestrian accidents.

Quality of Life

In California's Bay Area, the main modes of public transportation consist of riding BART (Bay Area Rapid Transit) and catching the bus. Riding BART and catching the bus allow people to get to their destinations without traveling in a car; however, this is not the quickest way to travel. BART makes stops at every station even if people do not need to exit or enter the BART train. Using companies like AC Transit or VTA to catch the bus means that there may be an even longer wait time depending on the number of people waiting at each stop and the number of people that need to exit the bus. Additionally, sometimes both BART trains and buses break down, which can delay a commuter's trip even more and add stress to their daily lives. The SPARTAN Superway will improve the quality of life for commuters by decreasing the amount of stress since the Superway is a more efficient way of traveling. Founders Dr. Burford Furman and Ron Swenson (2023) point out that the Superway is a more efficient way of traveling since the SSW is "a network of guideways with stations located on offline track sections so that passengers can travel nonstop from origin to destination, much like a taxi." Traveling from point A to B without stopping is convenient and saves time. In addition, the SSW features fully automated bogies, which will allow the transportation network to run 24/7. The automation feature saves money, and the 24/7 operation time promotes travel safety, especially if people are coming from a party and want to get home safely at 2:00 am without drunk driving. Given all these features, the SSW will become the more desirable mode of transportation and improve the quality of life for people, especially commuters.

B. Project Objectives

One of our objectives is to design the vehicle of the SPARTAN Superway (SSW), also known as a Bogie, to run 24/7, and they must be charged and ready to go when people request them. This is where our team, the Energy Storage and Charge team, comes into operation. Our team was formed to improve the Bogie energy storage system for a small-scale modular demonstration model (SSW). The vehicle energy storage system will incorporate batteries and supercapacitors, remotely monitor the charging status, and ensure enough power is delivered to the motor to keep the Bogie running. Additionally, we implemented a third-rail charging system to charge the Bogie quickly when it reaches an offline station. Completing these tasks will allow a small-scale functional Bogie to operate with the other teams. Eventually, future students can design it on a larger scale that will evolve into a functional transportation system.

VII. Objectives

The main objective of our project is to reliably transfer power from the solar panel charging team's output power into the motor's team input power system–with an emphasis on the word "reliably." That means some constraints make this a more complex problem than initially thought. The complexity arises from using the solar panel team's output power to charge our team's power banks in less than a minute and operating a motor for a minimum of ten minutes. Is it feasible? If not, more importantly, can we repeat this process consistently? Reliably? Safely? Our team has been asking these same questions throughout the semester, a challenge we have been working relentlessly on. Suppose we can create an electrical system that can reliably, safely, and consistently charge in less than a minute and deliver power to a motor for a minimum of ten minutes. In that case, that's how we define our work as successful.

VIII. Project Specifications

The unique design challenges in our project result from some constraints we must work around. These constraints are mainly developed from outside our subsystem and come from two other teams: the solar panel and bogie teams. The solar panel team has a target for the amount of power they would be delivering to our team, and it is upon us to provide a consistent amount of power to the motor team. These target power ranges may vary from both teams, and a change in either can cause our team to reevaluate specific targets. As a contingency, we have set some minimum targets that we are working to achieve. As the neighboring teams' projects mature over the following semester, we can work towards fine-tuning these values as needed. The functional specs we have worked towards targeting are shown in **Figure 3 & Figure 4**. Further details about these functional specifications will be elaborated throughout the report.

Functional Specs	
Minimum Output Voltage	6 Volts
Minimum Output Current	3 Amp
Minimum Power Delivery	18 Watts
Charging Time	< 1 minute
Charging Type	Constant current
Stored energy	9.3 Joules per bogie
Stored Battery energy	1200mah
Input Power Absorbed	20 Watts

Figure 3. Functional specifications chart

Functional Specs		
Motor Output	Voltage	6 V -> 9V
	Current	3 A
	Power	18 W -> 27 W
Supercapacitor	Charging Time	< 1 min
	Charging Type	Constant Current
PiSugar	Input Voltage	5 V

Figure 4. Updated functional specification chart

IX. Literature Review

The idea of an ATN, commonly known as PRT (personal rapid transit), has been considered as far back as the 1950s. During that time, there was a vast push for advancing infrastructure in the United States due to the focus brought upon the matter by constructing the Interstate Highway System. The idea of a more personalized public transit system that could provide more convenient end-to-end service was attractive and, if successful, would mitigate some of the negatives of traditional public transportation. Multiple concepts were proposed throughout the 1960s, and companies worldwide began researching and developing prototypes. The first implementation of an ATN came to fruition in 1975 with the opening of the Morgantown PRT system at West Virginia University; one of these vehicles is shown in **Figure 5**. The system has been in operation for almost 50 years.

Figure 5. Morgantown PRT vehicle (Source: The Daily Athenaeum)

The Morgantown PRT would be the world's only ATN until around 30 years later, in 2005, when the city of Rivium in the Netherlands completed and commenced operation of their ATN system. Following this, four more ATNs have commenced operations worldwide: The Masdar City, UAE PRT in 2010, the London Heathrow PRT in 2011, the Suncheon PRT in South Korea in 2014, and the Chengdu Tianfu International Airport PRT in China in 2021 (ATRA, n.d.). The Morgantown PRT is still the world's most extensive ATN, with the longest guideway by length and the most geographical area covered.

Since 2012, the SPARTAN (Solar Powered Automated Rapid Transit Ascendant Network) Superway team has been developing an ATN system to remedy car dependency issues by creating a sustainable, convenient, and efficient transportation system. One of the system's main goals is to reduce the environmental impact as much as possible. To achieve this, it is an important goal of the Superway team for the system to be powered by renewable energy: part of this effort includes integrating a photovoltaic array into the Superway system. Since the beginning of the Superway project, multiple prototypes and scale models have been constructed (Spartan SuperWay, n.d.).

As the group in charge of the bogie's onboard energy storage and charging, our primary focus will be investigating the technologies behind supercapacitors and batteries and their potential applications that could help us develop our systems. The previous semester's teams have supplemented our team with a list of references and literature to catch up to speed, so the literature that our team will provide will build upon that and expand that library of knowledge. The culmination of the literature review will also help future group members learn more about the background research that drives our decision-making and processes.

UC Davis recently published an article investigating the applications of supercapacitors in hybrid and electric vehicles, which may provide some background on understanding the technology behind supercapacitor and battery vehicle systems. The vehicles observed in the study combined supercapacitors and some advanced batteries found in electric cars. Their comparison was made towards vehicles with lithium-ion batteries typically found in hybrid vehicles. Cars with supercapacitors replacing lithium-ion batteries performed more efficiently than their counterparts. Supercapacitor-equipped cars are physically faster, require less energy from the energy storage units, and have increased energy density efficiency (Burke and Zhao, 2015). This understanding of supercapacitors may prove helpful towards our supercapacitor integration into our bogie.

Depending on the use case of an electrically driven transportation system, there are benefits and drawbacks to implementing a battery or a supercapacitor exclusively in the design. Although supercapacitors can charge much faster than a battery, supercapacitors are less energy-dense and typically have lower capacities than an equivalently-sized battery (Zuo et al., 2017). To cover a given distance, a vehicle equipped with supercapacitors must be recharged around 10x as often as one equipped solely with a battery. To mitigate the drawback of an energy storage system composed solely of supercapacitors or solely of batteries, a "hybrid" energy storage system could combine the desirable characteristics of each storage medium. An energy storage system composed of supercapacitors and batteries would benefit the proposed operation of the Spartan Superway, as it would allow the bogie to be charged exceptionally quickly while retaining a large amount of energy in reserve. This would make the operation of the bogie more flexible, allowing it to make repeated uninterrupted traverses across the entire operational range, given a scenario where multiple passengers desire to travel from one end of a multi-mile track to another without stopping. There are numerous supercapacitor/battery system configurations, each serving a specific use case. A common trait of all "hybrid" supercapacitor-battery systems is an increased complexity over simpler systems utilizing only one type of energy storage technology. For example, extra circuitry may be required to ensure the system's smooth operation due to the possibility of overwhelming the battery with energy from the supercapacitor (Chia et al., 2015). This complexity would also take up more space than a more straightforward battery or supercapacitor-driven system, resulting in a larger overall bogie size or less room for passengers in a bogie's cabin. We must evaluate the pros and cons of implementing a hybrid supercapacitor/battery system and its benefits and drawbacks to the overall operation of the Superway.

X. Codes, Standards, and Design Constraints

The development of the Third Rail and our Energy Charge and Storage System for the Bogie involved several codes and standards that were important to adhere to.

Third-Rail

For instance, components of the Third-Rail design, which was previously planned to be 3D printed, would have followed the ASME 2018 standard Y14.5 ASME Dimensioning and Tolerancing, also known as Y14.5 Geometric Dimensioning and Tolerancing (GD&T). Y14.5 defines the guidelines for standard engineering drawings and models (ASME International, 2019). Following the rules, symbols, and design language defined in Y14.5 would have permitted an understanding of the Third-Rail design for engineers across the United States. Additionally, it was found that 56% of international companies use ASME Y14.5 for GD&T (Bemis, 2021). Thus, if we wanted to implement the SSW Third-Rail design worldwide, engineers in different countries could interpret the drawing correctly and produce the same design if we decided to 3D print the components. Instead of 3D printing, we changed the design of the Third-Rail and used carbon brushes and copper tape. DIN IEC 60136-3, IEC 60276 Ed. 2.0 b:2018 and DIN IEC 60413 are all standards related to dimensioning, physical properties, and definitions of carbon brushes (Carbon, 2013).

Relevant codes to follow for the Third Rail are from the National Electrical Safety Code 2023 (NESC). NESC Section 110A emphasizes that "[r]ooms and spaces in which electric supply conductors or equipment are installed shall be so arranged with barriers, such as fences, screens, partitions, or walls, to form an enclosure (IEEE, 2023)." This section, sections 314, 422, 431, and many other sections are all significant and helpful especially, for the future when developing the full-scale version of the Offline Stations.

Energy Charge & Storage System

Since our project relies heavily on a supercapacitor-battery hybrid system to interface a transit vehicle, it made sense to comply with and reference several standards by IEEE. For instance, the IEEE document *Safety Considerations when Designing Portable Electronics with [EDLCs]* provides several standards that detail the safety precautions to take when dealing with EDLCs, also known as supercapacitors (Walden et al., 2024). Furthermore, IEEE 1536, the "Standard for Rail Transit Vehicle Battery Physical Interface" recommends utilizing a proper battery holder and ensuring that there is enough space for the battery to remain at a normal temperature (IEEE V., 2003). Knowing this, we purchased a proper battery holder, instead of wrapping our battery in electrical tape as demonstrated in **Figure 6**.

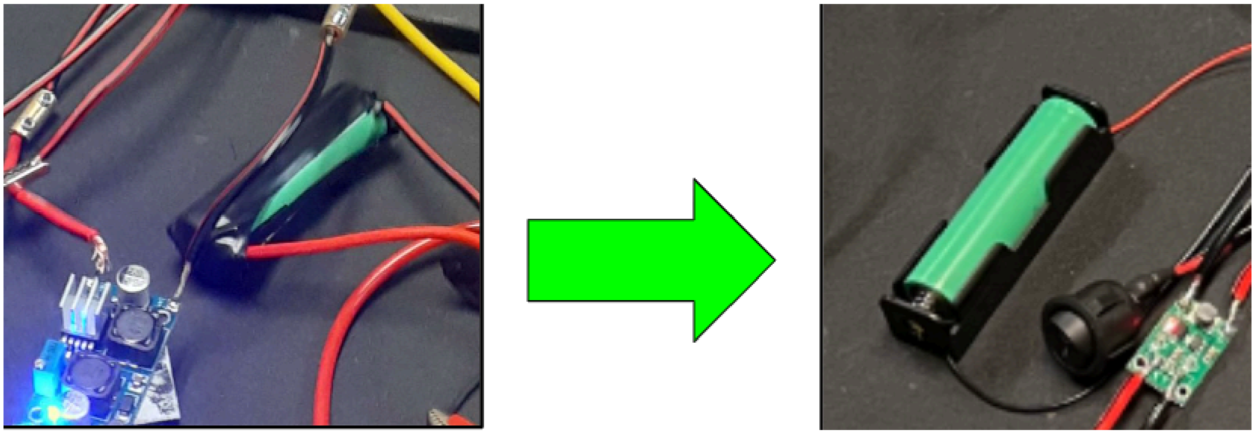

Figure 6. Electrical taped battery (left) replaced with a battery holder (right)

This improved our design and permitted proper circuit connection. IEEE 1725 & IEEE 1625 discusses overcharge and short circuit prevention, while the NFPA 70, 70B, 70E and NESC 110A provide codes to prevent fires and electrical hazards. After reviewing these codes and standards, we found that utilizing the TP 4056 and Pi Sugar Battery Module would be best suited for preventing electrical and fire hazards. More specifically, we selected these components to ensure the protection of the on board Lithium-Ion batteries. As for design constraints, our system initially could only output 5V at 0.1A to 0.2 A. This was barely enough for the small motors to draw from, but not enough for the motor on the Bogie to run. After adjusting and forming our final design, we were able to output 9V at 0.6A, which was enough to power the Bogie's motor, thus removing the constraints within our system.

XI. Team Work Plan

The project has been split into five components, each given to a team member tailored to their strengths. These five components represent the five critical physical parts that make up our project. **Figure 7** below shows that each project component is designated among five individuals, each individual being an "expert" within that particular part of the overall design.

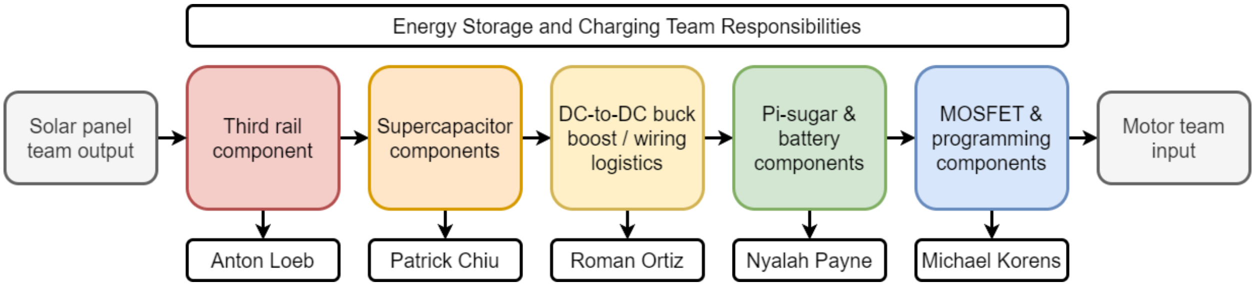

Figure 7. Delegation of team member responsibilities

Essentially, the physical components of the project have been split into equal one-fifth portions and delegated to a team member. By analyzing the chart, each team member has something to depend on and someone who depends on them. By having our team organized like this, we are not only required to communicate with each other constantly, but it also makes it easier to determine the progress of each group member. Throughout the semester, we have been working as an effective team to tackle some of the engineering challenges that we have faced. On another note, these delegated tasks and responsibilities are not strictly set. If an individual struggles with a component, we are more than willing to help each other understand our needs and goals better. An organized, fair, and highly communicative environment is critical to building an effective team.

XII. Concept Selection and Iteration

A. Prime Design

Our initial goal was to create a hybrid system that included supercapacitors and lithium-ion batteries to power the bogie, but this plan was too ambitious. After hours of research and having no luck finding some references to begin working off of, we decided to take a step back and reevaluate what we were doing.

The first step we took to get to our final design was figuring out how much voltage and current the supercapacitors could safely handle and the voltage and current the Solar Charging team could provide with their solar panel. We tested our circuit design with a variable power supply that could adjust the output voltage and current. This power supply made it simple to determine the values the supercapacitor could handle. The values we determined were safe to charge the supercapacitors at were 6-7 volts at around two amps of current. These voltage and current values are dangerous to plug directly into a lithium-ion battery, so we needed to find a way to step down these numbers.

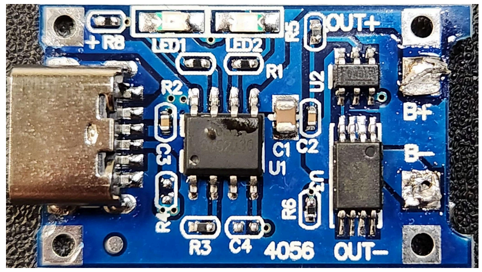

Figure 8. TP 4050 battery charging chip

To safely connect the supercapacitors to a lithium-ion battery, we used the battery charging chip called a TP 4056. The supercapacitors are wired to the chip inputs, and a battery is wired into the B+ and B- pins. The Outputs are then wired into a boost converter to output a consistent 5V. This is then wired into the PiSugar. The PiSugar is then able to output a consistent voltage of 5V. The 5V is insufficient to power a motor, so we wired it in a boost converter to output 9V.

The PiSugar checks whether the system is charging and monitors the battery's charge. With the 3.7V batteries, we cannot check whether the batteries are fully charged or depleted. The PiSugar could tell the ATN Vehicle to return to a charging station when the battery runs too low.

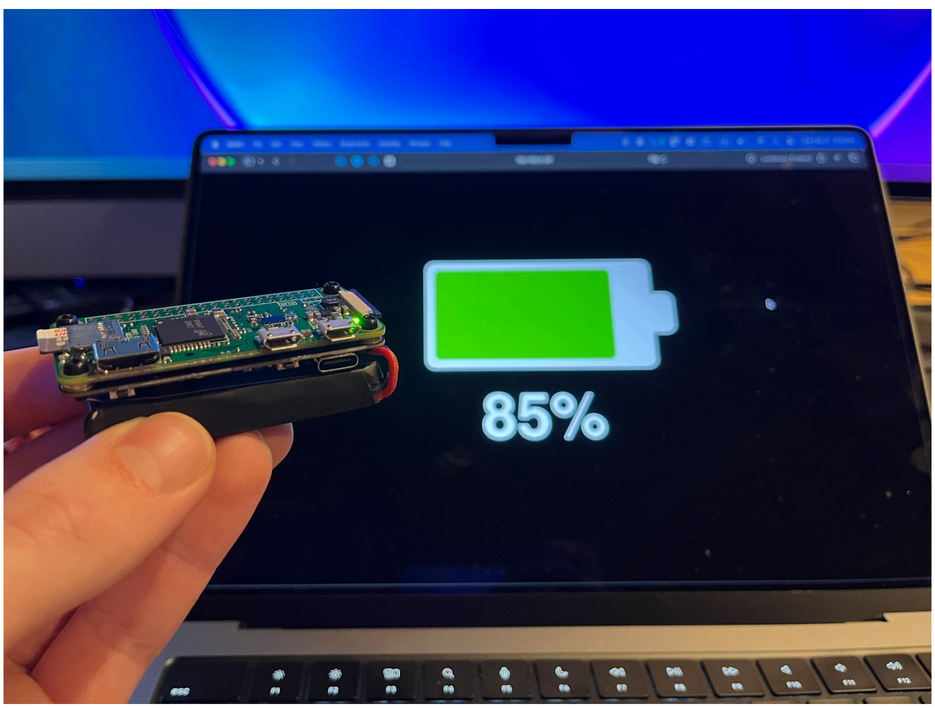

Figure 9. - PiSugar with wireless charge monitoring

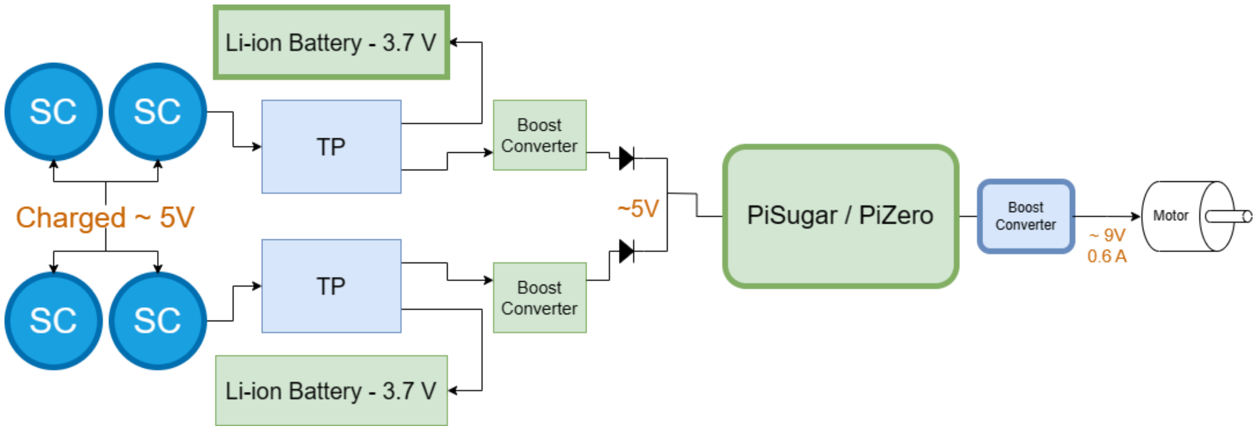

Figure 10. Hybrid Charging Circuit

The system works by having the energy storage system mounted on the ATN vehicle. The vehicle maneuvers into the charging station where graphite contacts, which are mounted and wired into the supercapacitors, come into contact with a third rail made of copper. The third rail constantly provides between 6-7 volts at around two amps. At this rate, the supercapacitors can fully charge in approximately 4-5 minutes. The TP chip begins to charge the 3.7 lithium-ion batteries separately. Through a series of calculations, it is estimated to take around 1 hour to charge these batteries fully, but fully charging at every stop is unnecessary. The reason for two separate TP chips, each with its battery, is to increase the output current due to a single 3.7V battery being unable to output enough to charge the PiSugar. The TP chip output is wired to a boost converter board to have the 3.7V be boosted to 5 V to charge the PiSugar battery. The PiSugar allows for charge monitoring, and the onboard protections allow for a more consistent output voltage. The PiSugar can output 5V, but with a boost converter, the output can be increased to around 9V. Testing the circuit to a comparable motor, we were able to provide around 9v and draw around .6 amps of current. These values allowed the ATN vehicle to run successfully.

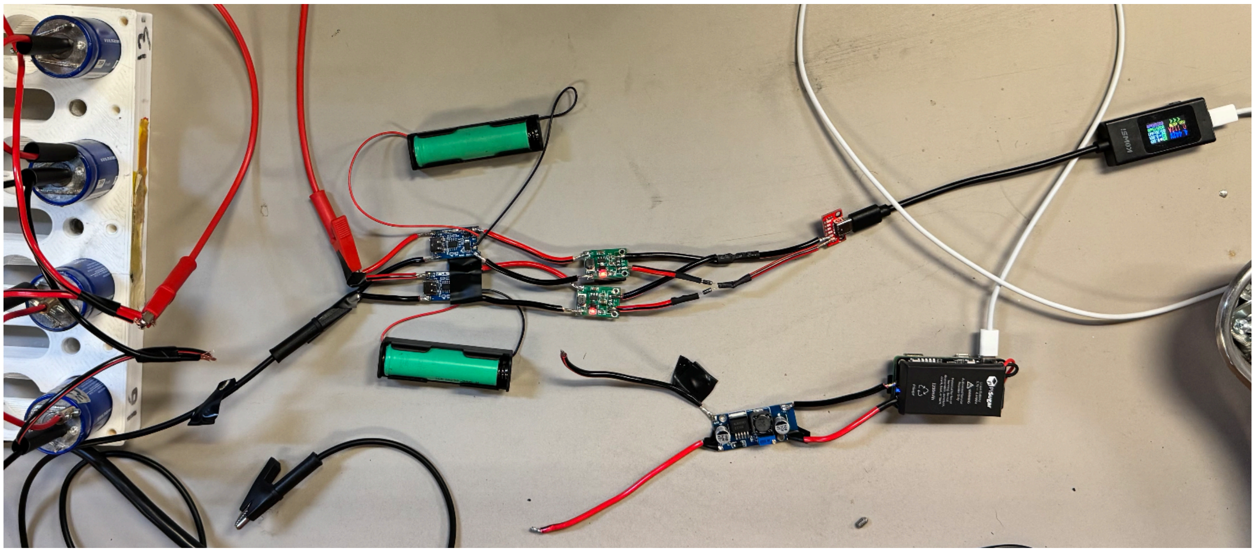

Figure 11. Energy Storage and Charging System components wired correctly

B. Alternate Concepts

For the design of the energy storage and charging system, we decided to begin working directly off the work done by the previous year's design. This plan was foiled after meeting with an Electrical Engineering Professor who pointed out the flaws of this design. **Figure 12** represents the circuit diagram from the previous team's project.

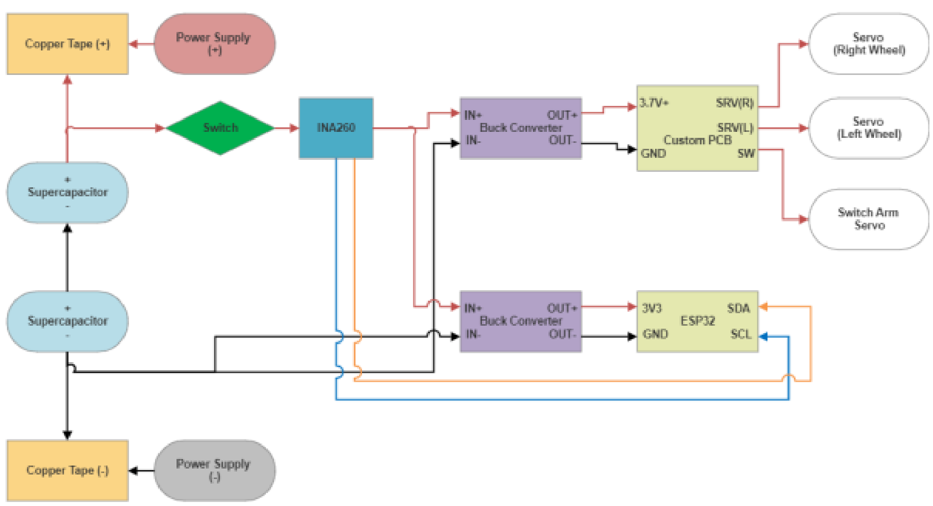

Figure 12. Previous year's energy storage and charging design

With our limited electrical engineering knowledge, we decided to seek advice from a professional. We met with a professional who pointed out why this design didn't use the supercapacitors efficiently. He mentioned that the setup of this circuit would likely be short and cause damage to the components or, at the very least, limit the lifespan of the supercapacitors.

We were advised to research a circuit already built and tested. With this advice, we began to study possible circuits that included both supercapacitors and lithium-ion batteries for our energy storage and charging system, but we got minimal results. The results were for applications that wouldn’t work for us or were too expensive and complex.

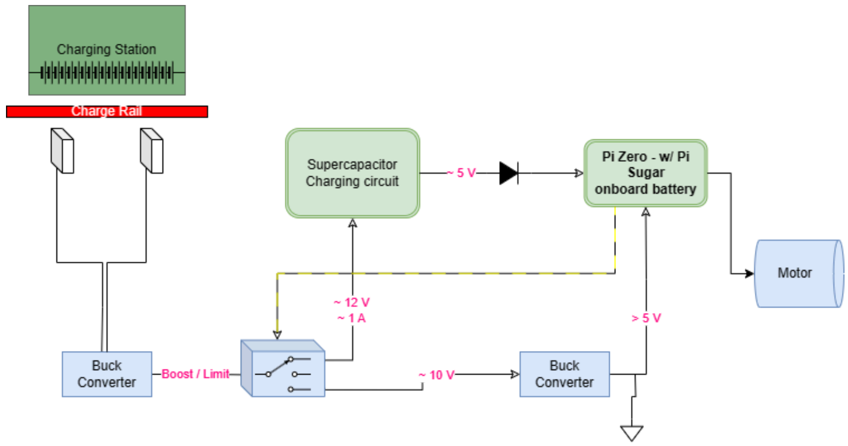

Figure 13. One of the first design concepts

One of the first designs we came up with, can be seen in **Figure 13** (above). With this first design we were thinking about using a relay to switch between charging the supercaps then switching to charging the PiSugar battery. This will prevent the supercaps from over charging but continue charging the PiSugar while it's still at the charging station. The issue with this design was trying to figure out when the supercapacitors were full and how to power the relay efficiently. Another issue we encountered with this design was having enough space. Our design has a final goal of being able to fit into the bogie but due to the number of components this design required it would be hard. The voltage values and current values were still too high for some of the components to handle so we had to stop and reconsider what we were doing.

C. Concept Selection

The choice to go with the current design plan came after a number of components were destroyed. The supercapacitors would output the voltage we were charging them at the issue though was the current. The current output was too high for any of the components so we needed to find a limiting source to prevent any more components from getting destroyed. We found the TP 4050 chip which would allow us to safely combine the Supercapacitors to the lithium ion battery. With this chip we still managed to fry some components but after days of testing and correcting the design configuration we were able to get a consistent voltage output.

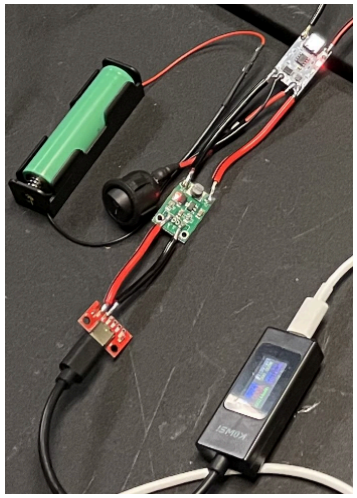

Figure 14. Working system unable to provide enough power

We tried connecting the system to the ATN motor but it wouldn't spin and will hardly power the motor. As an attempt to increase the current we simply doubled our system. Using two of the same circuits we combined the output and we were able to power the bogie successfully.

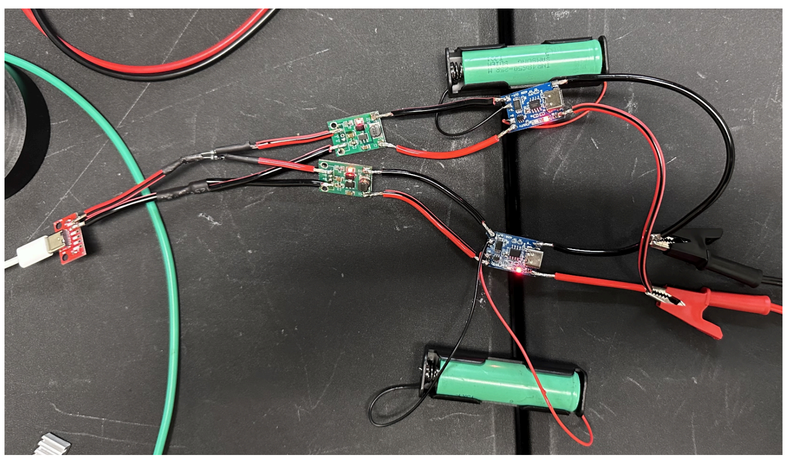

Figure 15. Final design concept

XIII. Theoretical Background and Analysis

A. Theoretical Background

1. Dwell In-Station (Charging) Time Estimation

The charging and operating behavior of the bogie is that an offline charging station will charge enough energy for the bogie to operate to the next offline charging station. The bogies are designed to store enough energy to operate station to station. Dwell time is the time that the bogie passes through the offline station, which allows the offline station to charge the energy storage. Details will be provided in the energy analysis section.

$$Time = \frac{Distance}{Max\ velocity}$$

2. Energy Consumption Analysis

The theoretical energy consumption calculation derived by Dr. Furman is provided below. The theoretical energy calculation is based on physics to calculate the energy needed to move the vehicle and subtract the resistance force. The parameters include station-to-station time, dwell-in-station time, max acceleration, jerks, wind resistance, auxiliary power, number of vehicles, mass of vehicle, friction resistance, elevation change, motor efficiency, regenerative recovery rate, etc.

Energy Calculation ¶

The governing equation for energy required for a station-to-station trip in t_s is (repeated):

$$E\left(t_s\right) = \frac{1}{\bar{\eta}}\left\{(1-R)n_t\frac{M_V V_L^2}{2} + \frac{1}{2}\rho C_D A_V\left[(V_L^2 + \langle V_w^2\rangle)D_s - \frac{V_L^4}{2a_m}\right] + n_T M_V\left[C_1 D_s + C_2 V_L\left(D_s - \frac{V_L^2}{3a_m}\right) + gz\right]\right\} + n_T P_{aux} t_s$$

The equation for t_s is:

$$t_s = t_D + \frac{D_s}{V_L} + \frac{V_L}{a_m} + \frac{a_m}{J_1} + \frac{a_m^3}{24V_L}\left(\frac{1}{J_2^2} - \frac{1}{J_1^2}\right)$$

Figure 16. Energy calculations need to travel station-to-station on the Superway track

3. Operating and Charging Energy and Power Analysis

To fulfill the design of charging enough energy in the bogie to operate to the next charging station, the ratio between operating time and dwell in station time (charging time) is directly proportional to the ratio of operating power and charging power. This calculation is extremely useful for determining the power specification and the relationship between operating power and charging power.

$$Ratio = \frac{Operating\ Time}{Dwell\ Time} = \frac{Operating\ Power}{Charging\ Power}$$

4. Alternative Electrical Energy/Power Consumption

The other practical way to calculate the actual energy consumption of the circuit is to add the power consumption from all electrical components. The energy could be replaced by power if needed for power calculation. For example, motors, actuators, microcontrollers, sensors, electromagnets, etc.

$$Energy = E_m + E_a + E_{MCU} + E_{sensor} + E_{magnet} + E_{external}$$

5. Choosing Appropriate Size - Supercapacitors

After determining the specification by the energy calculations, it is now time to choose the appropriate size of energy storage. In this project, supercapacitors serve as quick-charging energy storage devices that can be charged and power the vehicle at the same time. The energy stored in the supercapacitor can be calculated as:

$$E = \frac{1}{2}CV^2$$

Where,
E is energy (in Joules)
C is capacitance (in Farads)
V is voltage (in Volts)

However, using supercapacitors as energy storage, we were not able to use all the energy stored inside the supercapacitors due to the nature of electricity. More often, the circuit will only consume above a certain voltage from the supercapacitor. The available energy can be calculated as shown below:

$$E = \frac{1}{2}\left(V_{\text{max}}^2 - V_{\text{low}}^2\right) \cdot C$$

Where,
E is energy (in Joules)
V_{max} is the maximum rated voltage of a supercapacitor (in Volts)
V_{low} is the lowest operating voltage for the circuit (in Volts)

6. Choosing Appropriate Size - Lithium-Ion Batteries

Lithium-ion batteries are usually rated in mili-amp-hour. The derived energy equation can be calculated as shown below:

$$E = 3.6C_{\text{BAT}}V_{\text{rated}}$$

Where,
E is energy in Watts (J)
C_{BAT} is the battery capacity rating in mili-amp-hours (mAh)

V_{rated} is the rated voltage of the battery in volts (V)

7. Concept of Power Electronics

This project is related to power electronics, focusing on charging/discharging batteries and supercapacitors. Power electronics involves charging/discharging energy storage by providing the specified voltage and current to each component from charging power source (solar panel), supercapacitor/lithium-ion batteries (vehicle energy storage), and motor/MCU (vehicle mechatronics). The main challenge of this project is to

a. Supplying enough stall current/voltage to the motor
b. Parallel power cell
c. Voltage converters
d. Charging /discharging supercapacitor
e. Charging/discharging lithium-ion batteries

8. Supplying Stall Current/Voltage to the Motor

Stall current/voltage is the minimum current/voltage to start and move the motor. Each motor has its stall current and voltage in the datasheet. Designing a circuit must consider how much current and voltage you can provide from your power sources such as supercapacitors and lithium-ion batteries. Furthermore, knowing the discharging characteristics of supercapacitors and lithium-ion batteries to the motor is important for this project.

9. Parallel Power Cell

To start the motor, the energy storage needs to provide a surge of current. The power cells (supercapacitor/lithium-ion battery) are connected in parallel to add the current. For example, when the motor needs more current, based on Kirchhoff's current rule (KCL), connecting 2 or more power cells in parallel will multiply the current by the number of cells.

10. DC-DC Voltage Converters

Each power source (power supply, solar panel, supercapacitor, lithium-ion batteries) and electrical component has a different voltage and current rating. The voltage converters serve a crucial role in converting one voltage to another. For this application with supercapacitors and motors, having a high current rating (>3A) or adding a heat-dissipating solution prevents overheating and melting wire.

11. Charging /Discharging Supercapacitor

The characteristics of the supercapacitor based on its nature are low energy density and high power density, which means it charges/discharges fast and stores low energy with a high self-discharge rate. Because of its fast discharging rate, it is extremely dangerous to short a supercapacitor as it could release a lot of energy at once. Ensuring that there is no risk of shorting a supercapacitor at all times is essential for safety.

To charge a supercapacitor, the simplest way is to connect the terminals of the supercapacitor directly to the power supply, in other terms, shorting it. This method may sound dangerous, but this is the only working solution to charge the supercapacitor. A supercapacitor can be charged at its max charging/discharging current at its voltage rating (i.e. Maxwell BCAP0350 35A, 2.7V). Supercapacitors have a unique charging/discharging behavior in constant current and constant voltage respectively:

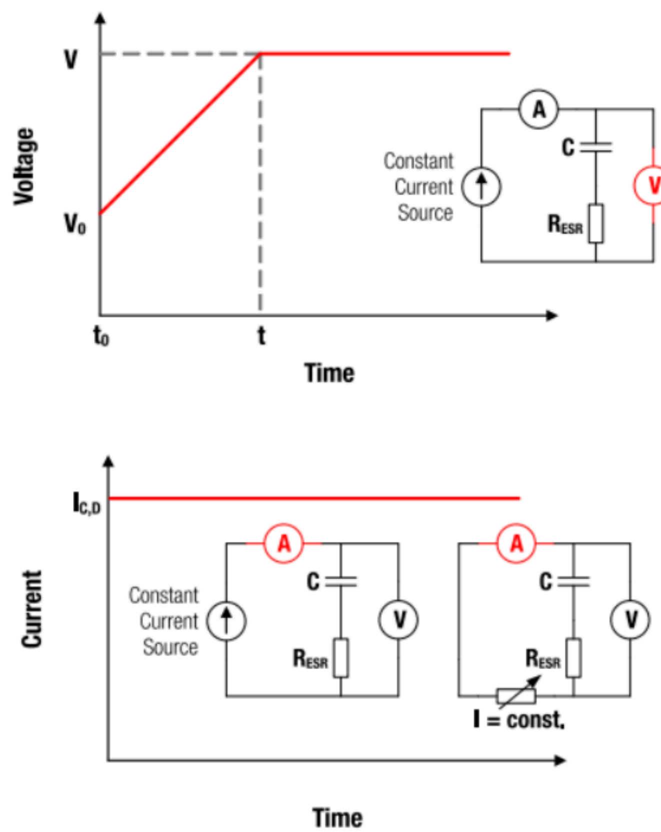

Figure 17. Voltage and current during constant current charging

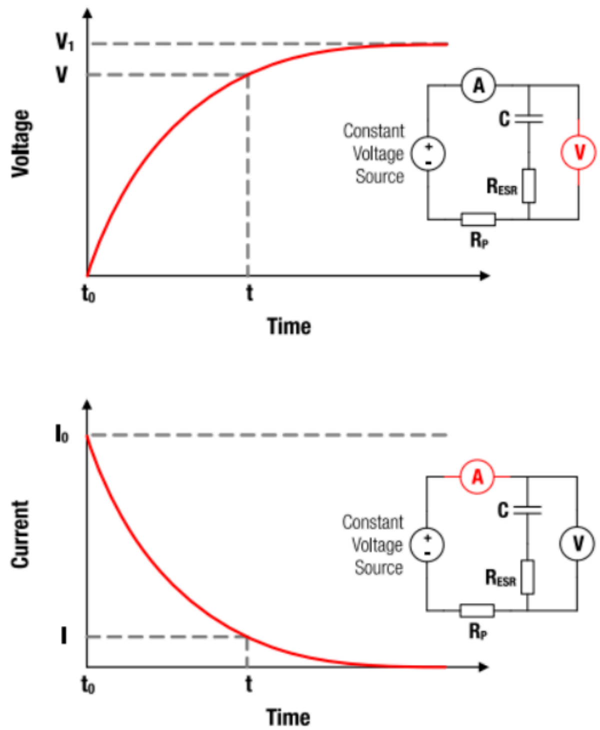

Figure 18. Voltage and current during constant voltage charging

According to the investigation, constant current charging is faster than constant voltage charging. The constant current charging time and constant voltage charging time equations are shown below:

Constant Current (CC) Charging/ Discharging Time

$$t = (V - V_0) * \frac{C}{I_C}$$

where V is the final voltage (in Volts)

V_0 is the initial voltage (in Volts)

C is the capacitance of the capacitor (in Farads)

I_C is the charging/discharging current (in Amperes)

Constant Voltage (CV) Charging Time

$$t = ln(\frac{V_1}{V_1 - V)} * (R_{ESR} + R_P) * C$$

where $R_{ESR} + R_P = (V_1/I_{max})$

V is the voltage at time t (in Volts)

V_1 is the charging voltage (in Volts)

C is the capacitance of the capacitor (in Farads)

12. Charging/Discharging Lithium-Ion Batteries

The characteristics of lithium-ion batteries are the opposite of supercapacitors. It has high energy density and lower power density, which means it charges/discharges slower and stores a lot of energy with a low self-discharge rate. The estimated charge and discharge times are usually specified in the datasheet.

CAUTION: DO NOT CHARGE THE LITHIUM-ION BATTERY DIRECTLY FROM THE SUPERCAPACITOR!!! THE BATTERY WILL BE PERMANENTLY DAMAGED WITH OVERCURRENT!!!

To charge lithium-ion batteries, a charging module is required. Lithium-Ion batteries require extreme care to not exceed the maximum rated voltage or below the minimum rated voltage as they could damage the batteries or cause an explosion hazard.

TP4056 charging module provides overcharging, over-discharging, overcurrent, and short-circuit protection. The charging current is programmable. There is also an option of implementing an external power-sharing feature allowing the circuit to charge the batteries and deliver power simultaneously.

13. Benefit of Hybrid Supercapacitor and Lithium-Ion Battery

The supercapacitor has the benefit of charging fast. The lithium-ion battery has the benefit of storing energy. Combining the benefits of supercapacitors and lithium-ion batteries will greatly improve the energy density of supercapacitors and power density of lithium-ion batteries.

	Charge Time	Stored Energy
Supercapacitor	**Fast**	Low
Lithium Ion Battery	Slow	**High**

Table 1. Supercapacitor vs Battery charging and stored energy comparison

B. Analysis

1. Dwell Time Estimation (Expected Bogie Behavior)

To calculate minimum dwell time, time, distance, and average velocity are required. The max speed from the 2022-2023 energy storage team was 0.2826 m/s. The 2023-2024 small-scale track team designed a 7.3-meter track. The offline station was about 1.44 meters long. The minimum dwell time was:

$$Time = \frac{Distance}{Max\ velocity} = \frac{1.44\ m}{0.2826\ \frac{m}{s}} = 5.10\ seconds$$

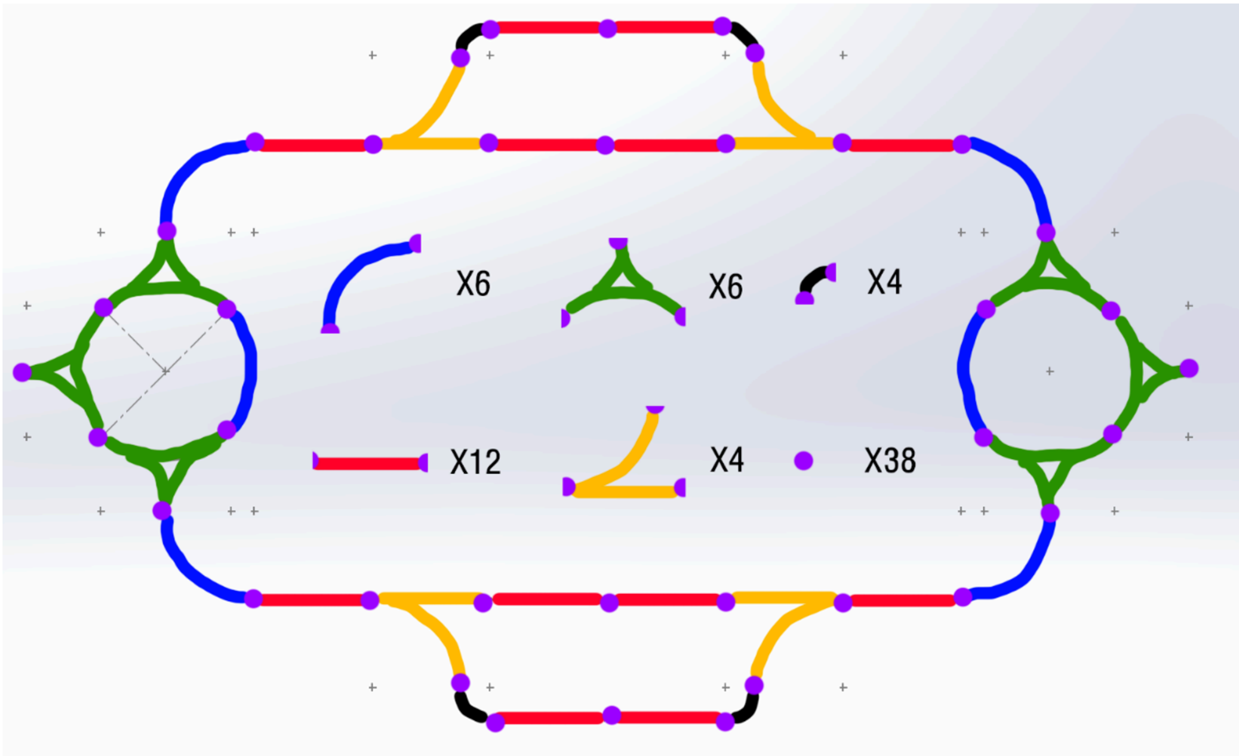

Figure 19. Track schematic from 2023-2024 small-scale track team

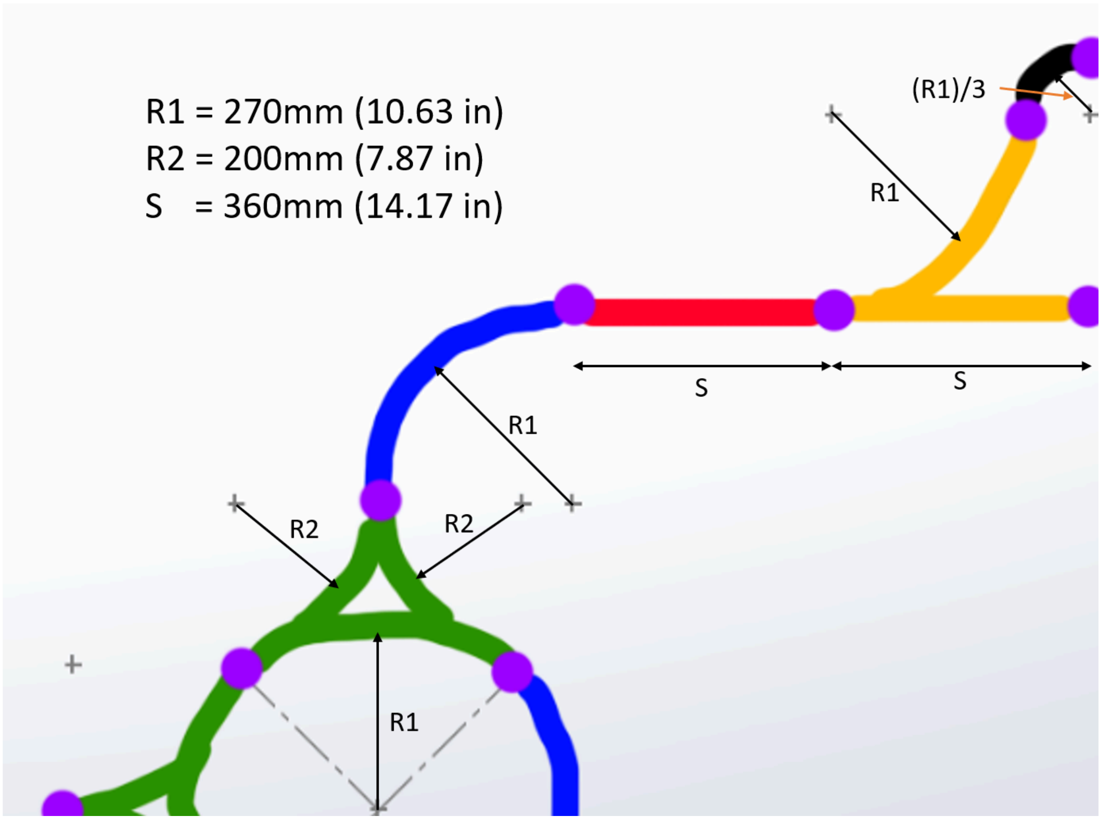

Figure 20. Track dimension from 2023-2024 small-scale track team

2. Energy Consumption Analysis

Using the energy calculator Python code provided by Dr. Furman, we can estimate the ideal energy consumption of the bogie. Parameters in the equation are further discussed in the appendices. Assuming dwell time is 5.10 seconds, the ideal energy consumption for a single bogie operating on a 7.3-meter track with one charging station is approximately 9.30 Joules. The average trip time is 34.5 seconds. The average operating power is 0.269 Watts. The Python code is included in the appendices.

Energy Calculation ¶

The governing equation for energy required for a station-to-station trip in t_s is (repeated):

$$E(t_s) = \frac{1}{\bar{\eta}}\left\{(1-R)n_t\frac{M_V V_L^2}{2} + \frac{1}{2}\rho C_D A_V\left[(V_L^2 + \langle V_w^2\rangle)D_s - \frac{V_L^4}{2a_m}\right] + n_T M_V\left[C_1 D_s + C_2 V_L(D_s - \frac{V_L^2}{3a_m}) + gz\right]\right\} + n_T P_{aux} t_s$$

The equation for t_s is:

$$t_s = t_D + \frac{D_s}{V_L} + \frac{V_L}{a_m} + \frac{a_m}{J_1} + \frac{a_m^3}{24V_L}\left(\frac{1}{J_2^2} - \frac{1}{J_1^2}\right)$$

Figure 21. Energy calculations need to travel station-to-station on the Superway track

3. Operating and charging energy and power analysis

To fulfill the design of charging enough energy in the bogie to operate to the next charging station, the ideal charging power is 6.76 times larger than the operating power based on the operating time and dwell/ charging time. The ratio between operating and dwell is

$$Ratio = \frac{Operating\ Time}{Dwell\ Time} = \frac{34.5\ seconds}{5.10\ seconds} = 6.76$$

The ideal energy consumption is 69.9 times less than the actual operating energy consumption from the 2023-2024 bogie mechatronics/motor team from station to station. In the ideal calculation, the ideal energy is approximately 9.3 Joules, the ideal operating power is 0.269 Watts, and the ideal charging power is 1.82 Watts. In the proposed system, the operating energy is 621 Joules, the operating power is 18 Watts, and the charging power is 122 Watts. The charging power of 122 Watts is considered a lot in our scale and scope. Lowering the motor power or operating/dwell time ratio is suggested. Detailed calculations are provided in Appendix B.

4. Alternative Electrical Energy Consumption

$$Energy = E_m + E_a + E_{MCU} + E_{sensor} + E_{magnet} + E_{external}$$

$$Energy = 18J + 10J + 2J + 1J + 0.5J = 32J$$

i.e. Energy = 18J +10J + 2J +0.5J+1J +0.5J = 32J

5. Choosing Appropriate Size - Supercapacitors

i.e. For a Maxwel BCAP0350 supercapacitor single cell,

$$E = \frac{1}{2} * C * V^2$$

$$E = \frac{1}{2} * 350F * 2.7V^2 = 1276J = 0.35Wh$$

The following calculations assume three of the same type of supercapacitors are connected series. The available energy is calculated by finding the difference between the charged and minimum operating voltage levels. The available energies are greater than 621 Joules, and all supercapacitors on the list will fulfill the design specifications. The voltage is limited from 6.0 volts to 8.1 volts for the lowest motor operating voltage, and the maximum voltage connects three 2.7 volts in series.

$$E = \frac{1}{2} * ({V_{max}}^2 - {V_{low}}^2) * C$$

where:

$V_{eq} = 8.1\ V$

$V_{motor} = 6.0\ V$

3 cell supercapacitors in series

The spreadsheet and equations are included in the appendices.

Capacitance (F)	Total Energy Stored (J)	Available Energy (J)
500	5467.5	2467.5
3000	32805	14805
5000	54675	24675
325	3553.875	1603.875

Figure 22. Super Capacitor Comparison Chart

6. Choosing Appropriate Size - Lithium-Ion Batteries

$E = 3.6 C_{\text{BAT}} V_{\text{rated}}$

Where,

E is energy in Watts (J)

C_{BAT} is the battery capacity rating in mili-amp-hours (mAh)

V_{rated} is the rated voltage of the battery in volts (V)

i.e. for an INR18650-25R lithium-ion rechargeable cell battery

$E = 3.6 * 2500mAh * 3.7V = 33300J = 9.25Wh$

7. Concept of Power Electronics

Power electronics is a specific field in electrical engineering related to circuitry, electronics, and control systems. This project mainly focuses on DC-DC power interface between different types of power cell. The following section will further analyze the concept of power electronics and its applications.

8. Supplying Stall Current/Voltage to the Motor

2023-2024 bogie mechatronics team used the double shafts 12V DC motor (634JSX32-31ZY). The following datasheet showed that the stall current is 6100mA at 12V.

Type (Double Shafts)	Gear Box								Motor	
	Reduction Ratio	Rated Torque (Kg-cm)	Stall Torque (Kg-cm)	No-Load Speed (rpm)	Rated Speed (rpm)	No-Load Current (mA)	Rated Current (mA)	Stall Current (mA)	Rated Volt (v)	No-Load Speed (rpm)
634JSX634-31ZY	1:634	12	37/34	3	/	70	130/150	380	12	1750
634JSX505-31ZY	1:505	15	45	5	/	100	370/380	900	12	2250
634JSX634-31ZY	1:634	40	/	10	/	200	1400/1280	2700/2800	12	5000
634JSX101-31ZY	1:101	7	17/20	60	41	250	1400/1320	3600/3500	12	6000
634JSX32-31ZY	1:32	2	8/10	250	198	400	1400/1260	6100/5900	12	8000

Figure 23. Datasheet from 634JSX32-31ZY motor

9. Parallel Power Cell

Parallel power cell is an application of Kirchhoff's current rule where $\sum I_i = 0$ or $I_{in} = I_{out}$. For example, a motor is drawing 6A of current. However, 1 lithium ion battery can supply 3A maximum. Therefore, 2 lithium ion battery are connected in parallel to supply enough current to the motor.

$I_1 = I_2$

$I_1 + I_2 = I_3 = 6A$

$I_1 = I_2 = 3A$

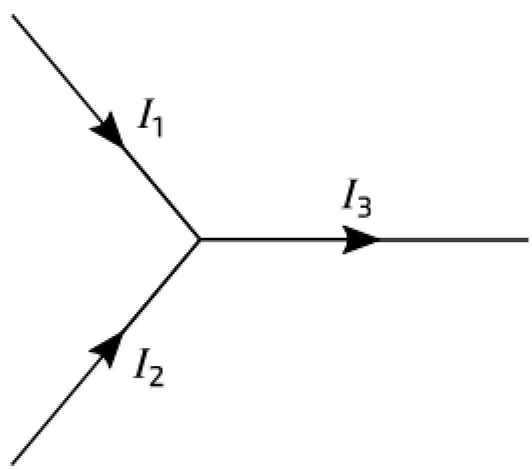

Figure 24. Concept of Kirchhoff’s Current Rule

10. DC-DC Voltage Converters

For example, the DC 12V motor needs at least 6V, 6A to start the motor. One 18650 lithium ion battery could supply 3A, 3.7V with the range between 2.5V-4.2V. Therefore, a DC-DC voltage converters that can handle 6A and convert 2.5V-4.2V to 6V shall be designed or purchased.

11. Charging /Discharging Supercapacitor

Constant current charges the supercapacitors faster than constant voltage charging. The analysis in the spreadsheet shows that 3 supercapacitors in series charge faster with constant current. The constant current and voltage charging time ratio is 19.2%, which indicates that constant current takes ⅕ of the time to charge with constant voltage. The spreadsheet analysis is in the appendices.

Capacitance (F)	CC Charging Time (s)	CV Charging Time (s)
500	700	3645
3000	420	2187
5000	438	2278
325	5	24

Table 2. Capacitor vs Charging Time values

12. Charging/Discharging Lithium-Ion Batteries

For example, INR18650-25R specified the charging voltage at 4.2V. For rapid charging, 4A will take 60 minutes to charge fully. For standard, 1.25A will take 180 minutes to charge fully. Using a TP4056 chip connect to a 5V voltage source will charge the lithium battery safely.

3.0. Nominal specifications

Item	Specification
3.1 Nominal discharge capacity	2,500mAh Charge: 1.25A, 4.20V,CCCV 125mA cut-off, Discharge: 0.2C, 2.5V discharge cut-off
3.2 Nominal voltage	3.6V
3.3 Standard charge	CCCV, 1.25A, 4.20 ± 0.05 V, 125mA cut-off
3.4 Rapid charge	CCCV, 4A, 4.20 ± 0.05 V, 100mA cut-off
3.6 Charging time	Standard charge : 180min / 125mA cut-off Rapid charge: 60min (at 25℃) / 100mA cut-off

Figure 25. Partial datasheet of INR18650-25R lithium ion battery

13. Benefit of Hybrid Supercapacitor and Lithium-Ion Battery

In 2022-2023 report, the supercapacitor powered the motor, and Li-ion will power the microcontroller for stability. The 2022-2023 energy storage team report pointed out the microcontroller shutdown because the voltage level is not stable using a supercapacitor as the energy storage. Due to the unique chemistry between supercapacitors and lithium-ion batteries, the voltage level of the supercapacitor declines while discharging. The voltage level of the lithium-ion battery does not decrease until the end of discharging. The need of DC-DC voltage converter is emphasized again to keep the voltage stable. Lithium-ion battery will be an ideal power for microcontroller while it might not be able to supply enough current to the motor. If lithium ion battery is powering a motor, the parallel cell design will be applicable. Supercapacitor's declining voltage required a DC-DC converter that is capable of converting any input voltage within supercapacitor's nominal voltage to the desired voltage in order to power both motor and MCU.

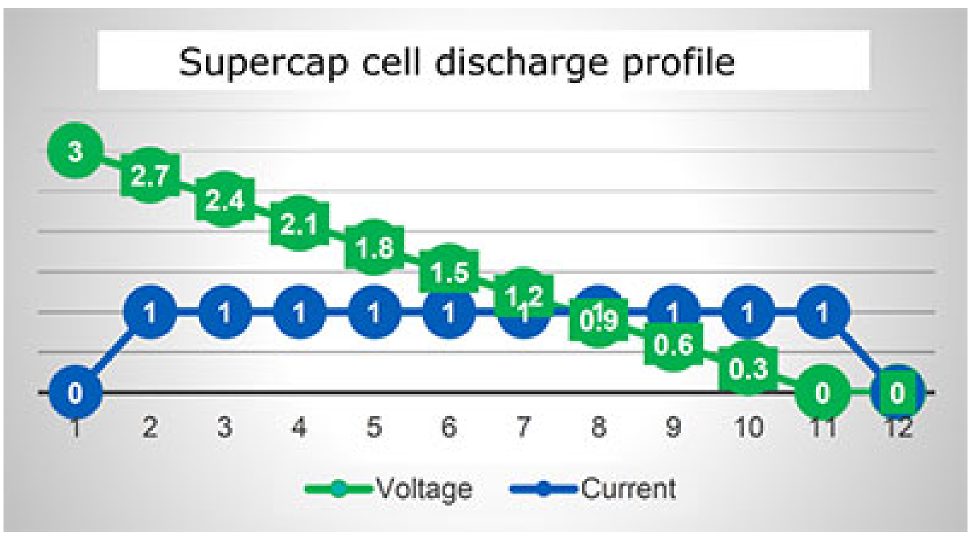

Figure 26. Supercapacitor cell discharge profile with a declining voltage level

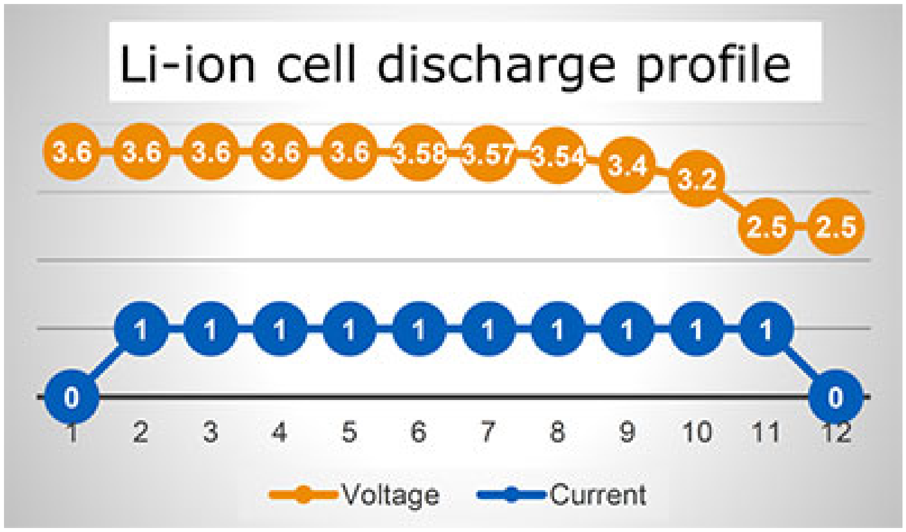

Figure 27. Lithium-ion battery discharge profile will almost steady voltage level

XIV. Documentation and Bill of Materials

A. Documentation

1. Charging Behavior of Supercapacitors

In the experiment, charging a 500 Farad supercapacitor directly from a DC power supply does not match the constant current charging behavior. The experiment directly connected one supercapacitor to the DC power supply. The MyDAQ monitored the voltage level from National Instruments using LabVIEW. Then the data was imported to Google Sheets to create the graph. Instead of the linear profile, the testing data behaves similarly to the RC charging profile. The experimental result was not expected. The potential error could be that a proper supercapacitor charging circuit was missing. A supercapacitor charging circuit protects the supercapacitor from overcharging, undercharging, and overheating, especially for scaling the system up. The spreadsheet and experiment procedure are included in the appendices.

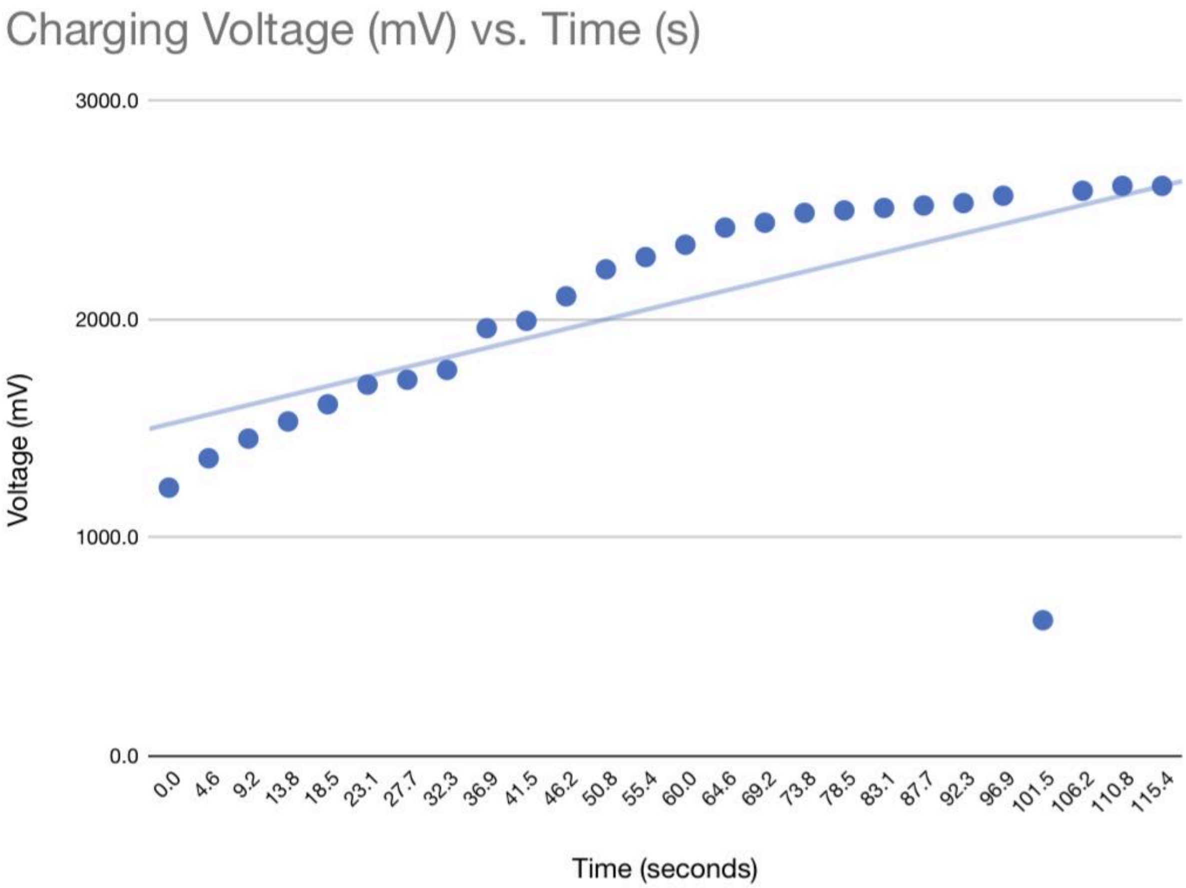

Figure 28. Charging voltage in millivolts versus time in seconds for charging a 500 Farad supercapacitor

B. Bill of Materials and Cost Analysis:

Part Name	Part No.	Quantity	Source	Price
Maxwell Supercapacitors	BCAP0350 E270 T11	4 *x # of bogies*	SPARTAN SUPERWA Rise Above	**$ ~**
Lithium-Ion Rechargeable Cell	INR18650-25R	2 *x # of bogies*	SPARTAN SUPERWA Rise Above	**$ ~**

Lithium Battery Charging and Protection Board	TP4056	*2 x # of bogies*	amazon	$8.99
Pi Sugar 3	Pi Sugar 3	*1 x # of bogies*	amazon	$49.99
Boost module	Newzoll DC 1V-5V to 5V Boost Module Board	*2 x # of bogies*	amazon	$8.99/5 pack
Pi Zero W	Pi Zero W	*1 x # of bogies*	amazon	$5.00
16 Gauge Wire	VIABRICO 16 Gauge Wire 100 ft	1 roll	amazon	$12.00
Battery enclosure	10 Pack generic holder	*2 x # of bogies*	amazon	$8.00
DC-DC 5V Out boost		*2 x # of bogies*	amazon	$8.00
Graphite Contact	Helwig Carbon Brushes 30-317441	*2 x # of bogies*	ebay	$15.00/4 pack
Copper Strip	N/A	*2 x # of charging stations*	SPARTAN SUPERWAY Rise Above	?

Power Supply	Wanptek 300W	1x	amazon	$69.99
Micro SD Card	SanDisk Ultra 128GB	1x	Best Buy	$15.93
			Total ≈	$200.92

Table 3. Bill of Materials used for the Vehicle Charging team

The components were mainly external parts needed to form the “buffer” system between the Supercapacitors and the Batteries. The lithium battery protection board is essential since there is a level of voltage that must be maintained to charge the batteries safely—the largest part of our budget, the Misc. Expenditures allow us to provide power to our circuit, clip components together using alligator clips, buy resistors, and replace damaged parts due to our testing. If our design goes into production, these costs will increase in the budget, assuming we want to power a life-sized bogie and not a small-scale bogie since the lithium battery charging and protection board would have to be replaced with stronger parts. The battery components would have to be upgraded to hold more energy, and the wires would probably need to be thicker to withstand higher power consumption. The basic idea with our small-scale implementation would remain the same, but the components would have to be upgraded to scale with the increased power consumption and requirements.

XV. Prototyping

A. Prototyping Methods

For the prototyping process our most important tool was a variable power supply. With the power supply we were changing the voltage and current to test our components at different voltages and current ranges.

In our prototyping we tried to be overly cautious to avoid any mishaps. To ensure safety we would first test every component separately at the ranges that each component would with output or need for an input. This process took a bit of time and didn’t prevent mishaps. There were times while testing where boost converters would work sporadically and cause voltage spikes burning some components. This would require us to resolve every component again and try another method. For this reason we used alligator clips to easily swap out components and try new configurations.

The design and the different components we used changed a number of times throughout the semester. We would research possible designs for the charging and energy storage system and then physically try them unsuccessfully. We would constantly go back to the start and have to think of a new design. When we arrived at our final design to work we soldered everything together and made things semi-permanent.

B. Assembly of the Final Prototype

1. Supercap setup

The system uses 4 supercapacitors total. The Supercaps are set up with 2 sets of 2 Supercaps in series and the pairs are put in parallel. This configuration allows for one set of connections to be the contact point at each end. Image below shows the way we wired our setups. Accidentally shorting the supercapacitors by touching the positive and negative terminals with something conductive is extremely dangerous. To avoid any issues with the wires slipping out and touching ,we used screw in connectors to secure the wires.

Figure 29. Screw in connectors for securing wires to the Supercapacitors

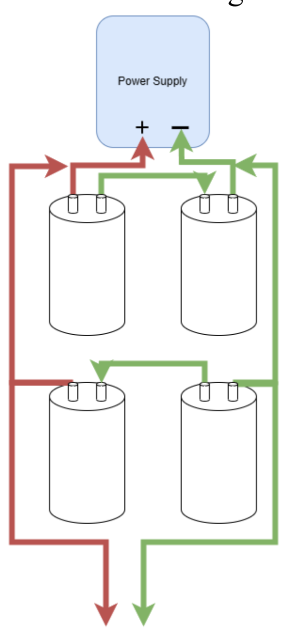

Figure 30. Supercapcitor wiring setup

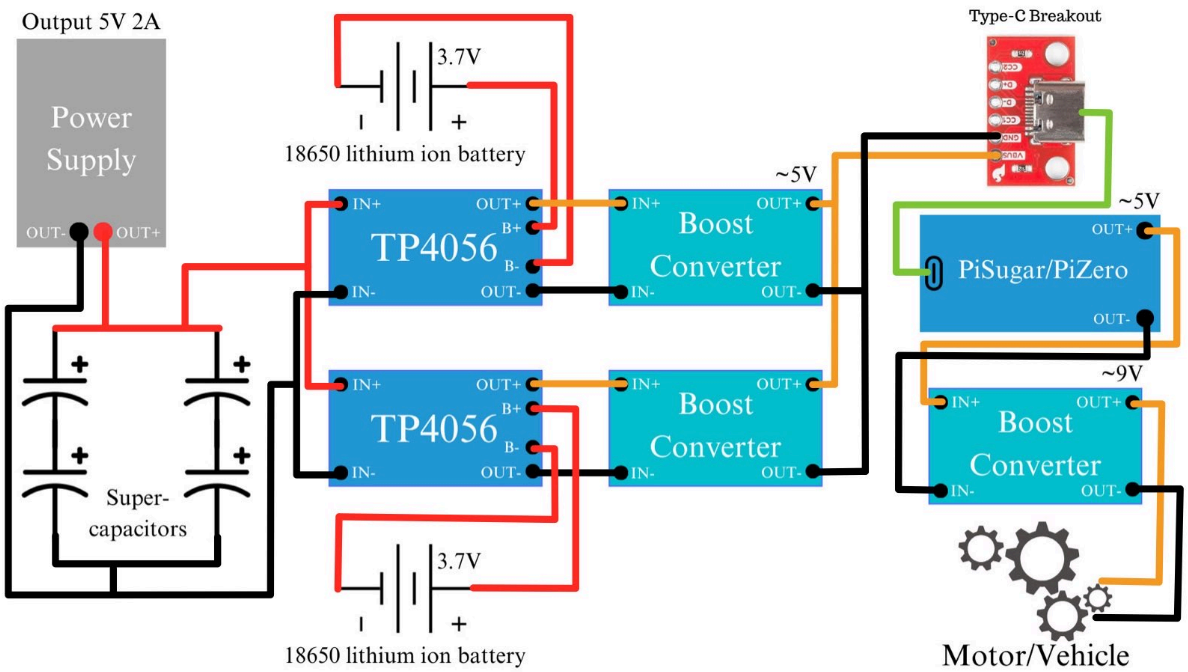

Figure 31. Detailed circuit diagram of he charging system

2. TP4050 Setup

The wiring setup of the TP chip is pretty straight forward. The TP chip has a positive input and a neutral input. We soldered wire leads that attach to the supercapacitors.
We attached the battery in the correct orientations to B+ and B-. Out + and Out - lead out to the boost converter.

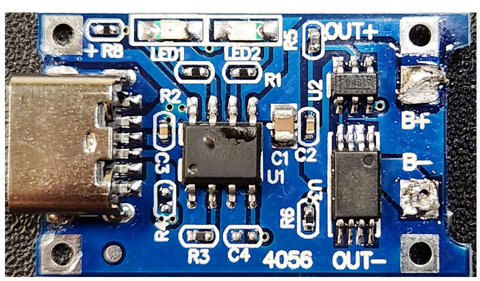

Figure 32. TP charging module

The boost converter we used was a constant voltage boost converter to boost from 1-5v to a constant 5V. It is wired into a USB-C breakout board so we can connect to the PiSugar.

3. PiSugar Setup

The PiSugar comes pre-built with its own charge protection so not much has to be done. The last thing is to wire in a boost converter and adjust the output the voltage required but that the Sugar can safely handle.

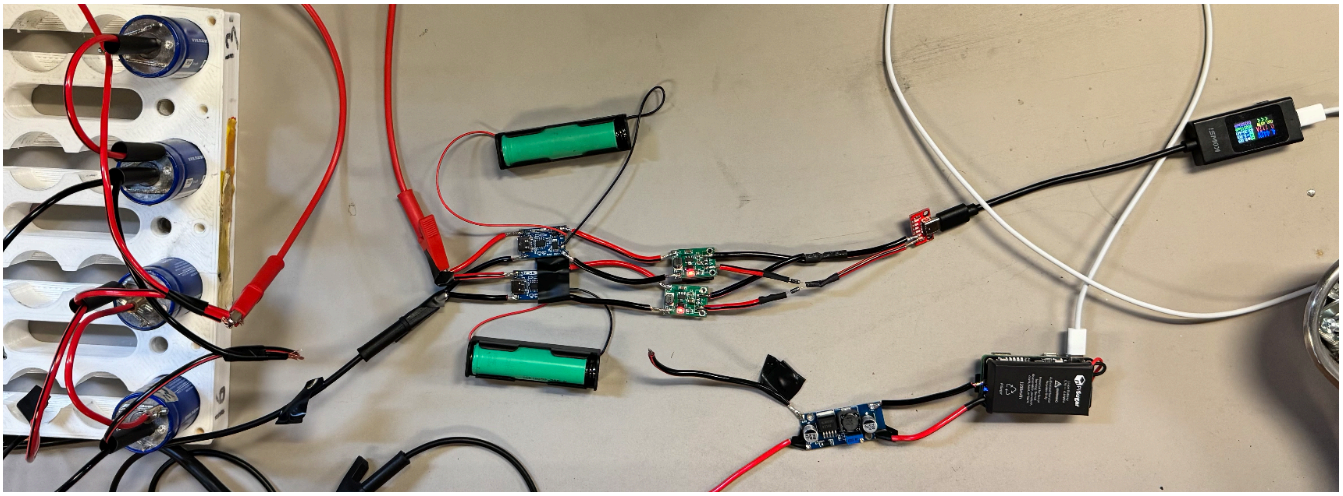

Figure 33. Charging and Energy Storage Final Setup

XVI. Testing and Validation

A. Overall Testing Setup, procedure, and results

For testing of our setup we relied heavily on the use of our variable power supply. With this device we are able to supply our desired voltage and adjust the desired current before connecting all the components together. We used a multimeter to verify the voltage output at important points and would only connect components if the output values seemed reasonable. We also made use of this component in the figure below that would detect the voltage and current passing through it. This made testing the output easy and saved us some time during the testing portion of the project.

Figure 34. Voltage and current monitor

Once we got our design to work we were able to begin testing with the components of the other teams. We started with the solar charging team. They were in charge of getting power from the sun using a solar panel and providing enough power to quickly charge the system.

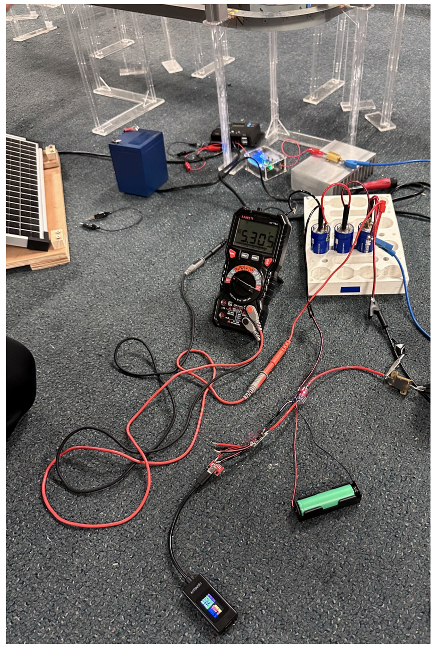

Figure 35. Testing the solar charing

The solar charging team was successful and was able to charge our supercapacitors in a timely manner. After we confirmed that the system was working and could be charged safely we tested the contacts on the third rail. The third rail was two strips of copper tape attached to the charging station. One rail is powered and the second is ground. Attaching the supercapacitors to the graphite foot and bring them into contact while powering the system was effective in charging the system.

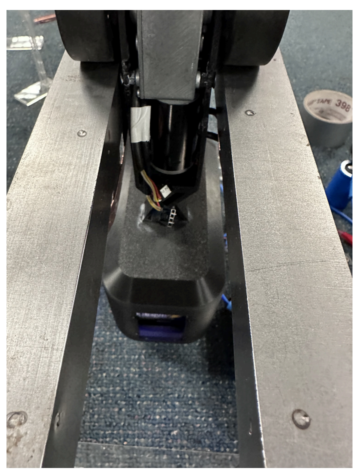

Figure 36. 3rd rail with graphite contacts

Overall the system was able to charge, store energy, and power the bogie with enough power. After weeks of testing and struggling to get things to work together we were successful.

XVII. Societal Impacts

The results of our project are vital for developing a 24/7 ATN network, one of the most essential components in realizing that goal. An efficient energy management system must be implemented within the bogie and throughout the network. To convince more individuals to ditch their cars, we must make our ATN system compelling, accessible, and reliable. By developing a hybrid power management system and proving it works, we can provide a foundation for future projects to iterate on and expand upon our concept. If we can fully utilize solar power to quickly, reliably, and safely charge the bogies, we can show the world that we don't need fossil fuels to power a fully functioning ATN system. Our project is the basis for this.

XVIII. Conclusions and Next Steps

Going into this project, we weren't sure if a supercapacitor and battery hybrid system would work. Some research was done on the subject, but the field of study wasn't as extensive as we would have hoped. However, our work has proven that a hybrid system is not only possible but can also be beneficial if implemented. Our design, analytical calculations, and prototyping support our argument that a hybrid system configuration is possible. In terms of meeting specifications, we almost achieved our complete goal. The only two components we couldn't fully achieve but came close to hitting were the output current and minimum power delivery. It doesn't mean that the bogie couldn't operate because of a lower power limit; it was more than capable of operating and glided along the modular tracks just fine. So, from one perspective, the target output was a relative measurement given to us by the motor team; however, if future teams require more energy in their motors or more components to power, a larger power budget must be considered. The power spec was not reached because of the amount of current output by the PiSugar. One component that could be upgraded to achieve a more reliable output current is upgrading the PiSugar to the PiSugar 3 Plus. This model is more expensive and would have taken us well over budget, but it does allow a higher current output budget, going from 2.5 Amps to 3 Amps. Our conclusion from our teamwork is that, even though our project has nearly met the functional specifications in its entirety, there is still room for improvement in all aspects of the project, which includes but is not limited to optimizing cable management, building custom PCB boards to reduce size and complexity, testing other battery management chipsets on the market to increase efficiency potentially, and having an alternate design component that includes current reading modules for testing purposes. Based on our cost analysis, hindsight is always 20/20. There are components that we purchased that we did not need in the final result but ended up buying as a result of early prototyping. One of the most vital components of testing the completed circuit is having a proper power supply and enough cables, resistors, supercapacitors, and tools to assemble the envisioned circuit. Some expenses were also spent on replacing the TP4056 chips and the PiSugar battery since we had a few incidents where we fried both components from high voltage spikes. These were costly mistakes, but they were good mistakes since they strengthened the outcome of our design. Given our explanations, documentation, and data analysis, the main aspect of the project's next iteration is optimizing the design and improving efficiency. We recommend investigating all the chip components used in our design and seeing if better alternatives may yield faster battery charging times, improved thermal performance, higher power deliveries, higher current yields, and more. These improvements sound nice on paper; however, it is important to keep safety in mind, and sometimes safety should be the deciding factor over performance. For example, the Supercapacitors can handle high currents, but the rest of the design cannot. We fried many TP4056 due to high current outputs from the Supercapacitors. Keep this recommendation in mind for the next two semesters, and we cannot wait to see what the next iteration of the vehicle charging system looks like!

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XX. Appendices

A. Detailed calculations of analyses

Operating and charging energy and power analysis

Governing equation:

$$Energy = Power * Time$$

$$Time = \frac{Distance}{Max\ velocity}$$

Operating:

$$Ratio = \frac{Operating\,Time}{Dwell\,Time} = \frac{Operating\,Power}{Charging\,Power}$$

$$Energy = E_m + E_a + E_{MCU} + E_{sensor} + E_{magnet} + E_{external}$$

$$Operating\ Energy = Operating\ Power * Operating\,Time$$

$$18\,W * 34.5\ seconds = 621\ J$$

$$Actual\ Operating\ Power = Voltage * Current$$

$$6\,Volts * 3\ Amps = 18\,Watts$$

$$Ideal\ Operating\ Power = \frac{Ideal\ Energy}{Operating\ Time}$$

$$\frac{9.3\ J}{34.5\ seconds} = 0.269\,W$$

Charging:

$$Actual\ Charging\ Power = \frac{Actual\ Energy}{Dwell\ Time}$$

$$\frac{621\ J}{5.10\ seconds} = 122\,W$$

$$Ideal\ Charging\ Power = \frac{Ideal\ Energy}{Dwell\ Time}$$

$$\frac{9.3\ J}{5.10\ seconds} = 1.82\,W$$

Supercapacitor Comparison and Analysis

SCs Compare (6V motor voltage)

Name						HS/HSL1016-3 R8306-R	
Notes						Hybrid Supercaps	
Capacitance (F)	500	500	3000	5000	325	30	1
Equivalent C (F)	166.667	166.667	1000.000	1666.667	108.333	15.000	0.333
ESR (mOhm)	48	?	17	12	1.9	550	48
Voltage (V)	2.7	2.7	2.7	2.7	2.7	3.8	2.7
Equivalent Voltage (V)	8.1	8.1	8.1	8.1	8.1	7.6	8.1
Nominal Current (A)	0.25	?	1	1.5	30		0.25
Max Continuous Current (A)	0.5	3	5	8	49	0.15	0.5
Peak Current (A)	1.2	?	10	15	270	2.7	1.2
CC Charging Time (s)	700	117	420	438	5	?	1
CV Charging Time (s)	3645	607	2187	2278	24	?	7
Total Energy Stored (J)	5467.5	5467.5	32805	54675	3553.875	433.2	10.935
Low State Energy (J)	3000	3000	18000	30000	1950	270	6
Available Energy (J)	2467.5	2467.5	14805	24675	1603.875	163.2	4.935
URL Link	500F Supercapacitor Link	500F Supercapacitor (Different Brand) Link	3000F Supercapacitor Link	5000F Supercapacitor Link	325F Supercapacitor Link	30F Supercapacitor Link	1F Supercapacitor Link
CC/CV ratio	0.192	0.192	0.192	0.192	0.192	#VALUE!	0.192
Available Energy ratio (J)	0.451	0.451	0.451	0.451	0.451	0.377	0.451

Average CC charge Power (W)	3.525	21.15	35.25	56.4	345.45	#VALUE!	3.525
Discharging time (sec)							
Average CV charge power (W)	3.525	21.15	35.25	56.4	345.45	#VALUE!	3.525
	If the motor operates at 6V, we will need at least 3 SCs in series.						
	assuming C is the equivalent capacitance of 3 SCs in series, which is C/3						
	Ic is assumed to be max continuous current.						

Constant Current (CC) Charging/ Discharging Time

$$t = (V - V_0) * \frac{C}{I_C}$$

where V is the final voltage in Volt

V_0 is the initial voltage in Volt

C is the capacitance of the capacitor Farad

I_C is the charging/discharging current in Ampere

Constant Voltage (CV) Charging Time

$$t = ln(\frac{V_1}{V_1 - V}) * (R_{ESR} + R_P) * C$$

where $R_{ESR} + R_P = (V_1/I_{max})$

V is the voltage at time t in Volt

V_1 is the charging voltage in Volt

C is the capacitance of the capacitor in Farad

Total Energy Stored in Supercapacitors (SCs)

$$E = \frac{1}{2}CV^2$$

Low State Energy

$$E = \frac{1}{2}CV_{low}^2$$

Available Energy

$$Available\ energy = Total\ energy - Low\ state\ energy$$

CC/CV Ratio

$$CC/CV\ ratio = CC\ time/CV\ time$$

Available Energy Ratio

$$Available\ energy\ ratio = \frac{Low\ state\ energy}{Total\ energy}$$

Average CC Charging Power

$$Average\ CC\ charging\ power = \frac{Available\ energy}{CC\ chargingtime}$$

Average CV Charging Power

$$Average\ CV\ charging\ power = \frac{Available\ energy}{CV\ chargingtime}$$

Constant Current Charging & Discharging Test and Report

Discharging data and spreadsheet

discharging.xlsx

Time (s)	Voltage (mV)				
0	2519.758641		Estimated Time (s)		
4.47	2519.758641		7min	420sec	Time interval 420/94=4.47sec
5.47	2519.758641				
6.47	2519.758641				
7.47	2519.758641				
8.47	2519.758641				
9.47	2519.758641				
10.47	2519.758641				
11.47	-11.571825				
12.47	-0.321468				
13.47	2306.001846				
14.47	2294.751488				
15.47	2283.501131				
16.47	2249.750058				
17.47	2193.49827				
18.47	2170.997554				
19.47	2170.997554				
20.47	2159.747197				
21.47	2148.496839				
22.47	2125.996124				
23.47	2103.495409				

24.47	2092.245051				
25.47	2080.994693				
26.47	2069.744336				
27.47	2069.744336				
28.47	2047.243621				
29.47	2024.742905				
30.47	2024.742905				
31.47	2002.24219				
32.47	1990.991832				
33.47	1979.741475				
34.47	1979.741475				
35.47	1968.491117				
36.47	1957.24076				
37.47	1923.489687				
38.47	1912.239329				
39.47	1878.488256				
40.47	1867.237898				
41.47	1855.987541				
42.47	1844.737183				
43.47	1833.486826				
44.47	1822.236468				
45.47	1810.98611				
46.47	1810.98611				
47.47	1799.735753				
48.47	1799.735753				
49.47	1777.235037				
50.47	1765.98468				
51.47	1743.483965				
52.47	1709.732892				
53.47	1709.732892				
54.47	1630.980388				
55.47	1608.479673				
56.47	1597.229315				
57.47	1585.978958				
58.47	1574.7286				
59.47	1552.227885				
60.47	1540.977527				
61.47	1518.476812				

62.47	1507.226454				
63.47	1495.976097				
64.47	1484.725739				
65.47	1473.475382				
66.47	1473.475382				
67.47	1462.225024				
68.47	1462.225024				
69.47	1428.473951				
70.47	1417.223593				
71.47	1417.223593				
72.47	1405.973236				
73.47	1383.472521				
74.47	1360.971805				
75.47	1349.721448				
76.47	1338.47109				
77.47	1327.220732				
78.47	1315.970375				
79.47	1304.720017				
80.47	1293.469659				
81.47	1259.718587				
82.47	1248.468229				
83.47	1180.966083				
84.47	1180.966083				
85.47	1169.715726				
86.47	1158.465368				
87.47	1113.463937				
88.47	1135.964653				
89.47	1113.463937				
90.47	1102.21358				
91.47	1090.963222				
92.47	1079.712865				
93.47	1045.961792				
94.47	1034.711434				
95.47	1023.461076				
96.47	1012.210719				

Charging data and spreadsheet (2 min charging, 3A, 4.6s per click)

charging.xlsx

Clicks	Time (s)	Voltage (mV)
0	0.0	1225.967514
1	4.6	1360.971805
2	9.2	1450.974666
3	13.8	1529.72717
4	18.5	1608.479673
5	23.1	1698.482534
6	27.7	1720.983249
7	32.3	1765.98468
8	36.9	1957.24076
9	41.5	1990.991832
10	46.2	2103.495409
11	50.8	2227.249343
12	55.4	2283.501131
13	60.0	2339.752919
14	64.6	2418.505422
15	69.2	2441.006138
16	73.8	2486.007568
17	78.5	2497.257926
18	83.1	2508.508283
19	87.7	2519.758641
20	92.3	2531.008999
21	96.9	2564.760071
22	101.5	618.448202
23	106.2	2587.260787
24	110.8	2609.761502
25	115.4	2609.761502

ME120 Term Project Report

ME120 Term Project Report (Patrick Chiu & Aaron Francis Lerma)

The project report begins on the next page!

Table of Contents:

- Add a Write to Measurement File Express VI
- Wire everything like in Figure 2

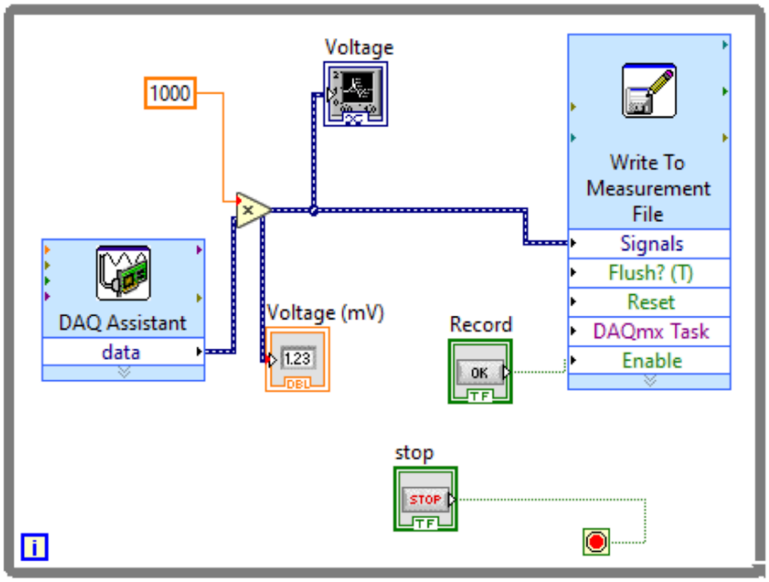

Figure 2: Block Diagram

For the first part of data collection we will be charging our 2.7V 500F supercapacitor. First, we took the supercapacitor and made sure it is discharged as much as we can by hooking it up to a LED or a DC motor to deplete it. Then, we ran the code. Next, we hooked up the positive and negative alligator clips, connected to the power supply, and connected it to the positive and negative parts that stick up on the supercapacitor. Quickly after this, we put the positive and negative multimeter test leads on to the positive and negative parts that are on the supercapacitor and rapidly pressed record on the front panel on LabVIEW. We did this until we got to its max constant voltage then stopped the code. Doing this, we get our data points of the voltage for each time we clicked the record button while it was charging.

For the second part of data collection we discharged the supercapacitor. First, while keeping the same setup from charging the supercapacitor, we disconnect the supercapacitor from the power supply and connect both a LED and a DC motor to the supercapacitor to start discharging the supercapacitor. Next, we rapidly hit the record button like last time except that we do it until the voltage goes under 1000mV since the time to discharge the supercapacitor is significantly longer than charging it. After this stop the code and disassemble the apparatus for clean up. We now get another graph which shows the rate that the fully charged supercapacitor discharges.

References:

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Chaves, C., et al. (2023). Design and Fabrication of Network Scale Energy Storage and Charging Station of the SPARTAN Superway.

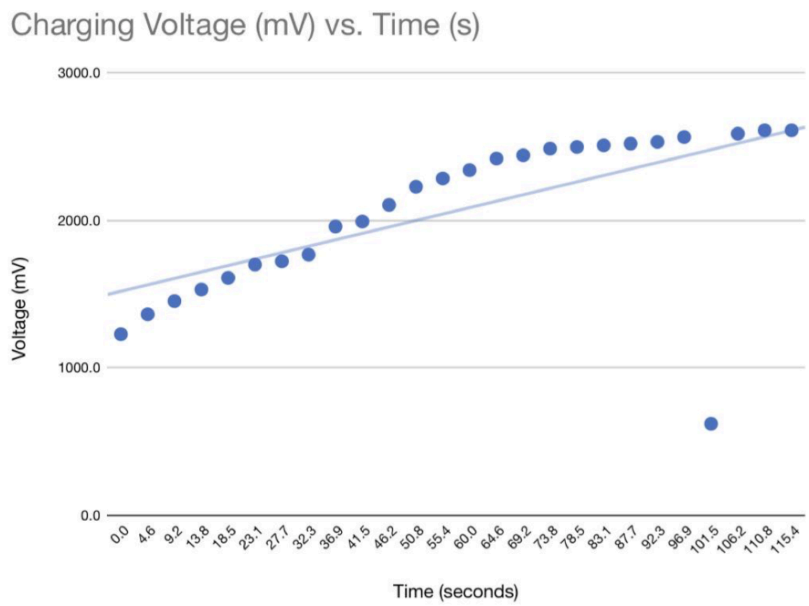

Figure 3: charging voltage in millivolt versus time in second

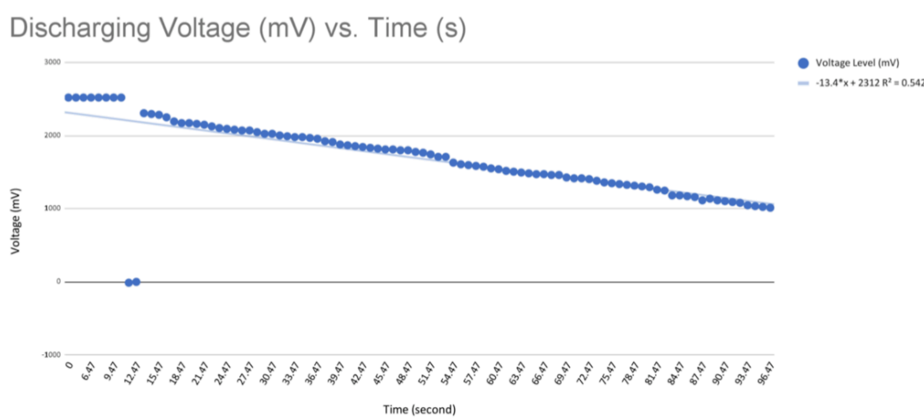

Figure 4: discharging voltage in millivolt versus time in second

Theoretical constant current charging governing equation:

$$t = (V - V_0) * \frac{C}{I_C}$$

B. Detailed simulation results and Algorithms

2-bjf-energycalculation-patrick-5

December 9, 2023

1 Table of Contents

Version 2016-06-30 2009

2 Notebook setup

[1]:
```
# Imports from __future__ in case we're running Python 2
from __future__ import division, print_function
from __future__ import absolute_import, unicode_literals

# Imports from IPython
from IPython.display import Image

# Our numerical workhorses
import numpy as np
import scipy.integrate

# Import pyplot for plotting
import matplotlib.pyplot as plt

# Magic function to make matplotlib inline;
# other style specs must come AFTER
%matplotlib inline

# This enables SVG graphics inline.
# here is a bug, so uncomment if it works.
```

```
# %config InlineBackend.figure_formats = {'svg',}
```

3 Nomenclature

Nomenclature from *Transit Systems Theory* by J. E. Anderson

References

t_s = station-to-station time (s)

t_D = dwell in station time (s)

$E(t_s)$ = average power consumption from t=0 to t=t_s

t_{0L} = time to reach line speed (s)

a_m = maximum acceleration [0.125*g for standing, 0.25*g for sitting; m/s^2]

J_1 = jerk associated with acceleration profile (m/s^3). See Figure 1.

J_2 = jerk associated with acceleration profile (m/s^3). See Figure 1.

V_L = line speed (m/s) [Expected to be about 13.4 m/s (30 mph)]

V_w = wind speed (m/s)

D_s = distance traveled in time t_s (the distance between stops) (m)

D_{0L} = distance traveled to reach line speed (m)

n_T = number of vehicles in a train (vehicles that are joined together)

P_{aux} = auxiliary power consumed per vehicle (W)

M_v = mass of vehicle (kg)

F_{sr} = static rolling resistance (N)

F_{sr_m} = static rolling resistance per unit of mass (= C_1, see below) (N/kg)

F_{dr} = dynamic rolling resistance (N-s/m)

F_{dr_m} = dynamic rolling resistance per unit of mass (= C_2, see below) (N-s/kg-m)

g = acceleration due to gravity (9.81 m/s^2)

z = elevation change (m)

A_v = frontal area of vehicle (m^2)

C_D = coefficient of drag [A conservative value is probably about 0.51, same as the Volkswagen Westfalia camper van]

ρ = motor efficiency

R = regen recovery factor (55% - 70%)

$\bar{\eta}$ = average efficiency of the electric motor. [Simplifies the computation for energy if the motor efficiency is a strong function of velocity.]

W = M*g = weight of vehicle (N)

C_{rr} = Coefficient of rolling resistance (dimensionless)

C_1 = static rolling resistance per unit of mass (N/kg) (See the table below)

C_2 = velocity dependent rolling resistance per unit of mass (N-s/m-kg) [Note: Often cited for determination of rolling resistance for rail vehicles is the Davis equation: R = A + BV + CV^2, where R is the rolling resistance (lbf) per ton (mass) of vehicle. Davis used B=0.045 lbf/(ton-MPH). Modern rail vehicles use better equipment than was used when Davis developed his empirical equation, so his value for B is conservative. A conservative value for B is therefore 4.935×10^{-4} N/(kg-m/s). (Reference: the AREMA Manual for Railway Engineering, Chapter 16, p. 16-2-3)]

f1 = coefficient of rolling resistance (without velocity dependence) (m). At 3 mph:

F_{sr} = rolling resistance = f1*N*R (N is load on the wheel, R is wheel radius) (N). To get F_{sr_m}, divide F_{sr} by the vehicle mass.

4 Governing Equation for Energy

The governing equation for energy required for a station-to-station trip in t_s is given by Anderson (1978)*:

$$E(t_s) = \frac{1}{\bar{\eta}}\left\{(1-R)n_t\frac{M_V V_L^2}{2} + \frac{1}{2}\rho C_D A_V\left[(V_L^2 + \langle V_w^2\rangle)D_s - \frac{V_L^4}{2a_m}\right] + n_T M_V\left[C_1 D_s + C_2 V_L(D_s - \frac{V_L^2}{3a_m}) + gz\right]\right\} + n_T P_{aux} t_s \quad (1)$$

* The equation (2.6.6) as printed in Anderson (1978) was missing the right parenthesis after the $\langle V_w^2\rangle$ term

The equation for t_s is:

$t_s = t_D + \frac{D_s}{V_L} + \frac{V_L}{a_m} + \frac{a_m}{J_1} + \frac{a_m^3}{24V_L}\left(\frac{1}{J_2^2} - \frac{1}{J_1^2}\right)$ where J_1 and J_2 are the ‘jerks’ (derivatives of the acceleration) in the acceleration profiles as shown in Figure 1.

<img src = “Transit Systems Theory/fig2-1_Accel_profile.PNG”,width=400,height=200>

Figure 1. Acceleration profile

5 Calculation of Static Rolling Resistance

From Transit Systems Theory

First, define a function, Fsr(), that computes the static rolling resistance given a normal force for the wheel on the guideway, the radius of the wheel, and the coefficient of rolling resistance, an experimentally determined value for specific wheel-guideway materials at a relatively low speed (3 MPH). See the article from Plant Engineering: http://tinyurl.com/go8yfr8

```
[2]: # Calculation of Fsr, the static rolling resistance
def Fsr(M, R, f1):
    """
    Compute the rolling resistance, Fsr.

    Parameters
    ----------
    M : Mass of load supported by wheel rolling on surface (kg)
    R : Radius of wheel (m)
    f1 : Coefficient of rolling resistance (m)

    Returns
    -------
    output : Fsr, static rolling resistance (N)

    Notes
    -----
    .. Returns the static rolling resistance for the given normal force,
        wheel radius, and coefficient of rolling resistance

    """
    # Return the calculated value of Fsr

    g=9.81   # m/s^2

    return f1*M*g/R
```

Use the definition and some values to calculate the static rolling resistance.

```
[3]: M = 1  #(kg) Mass of fully loaded ATN vehicle
g = 9.81  #(m/s^2) Acceleration due to gravity
Weight = M*g  #(N) Normal force of wheel on guideway
R = (1.75/2)*0.0254 # (m) Radius of wheel
print("Weight =",Weight,"N")

f1 = 0.057  # (in) Coefficient of rolling resistance:
# Cast iron on steel = 0.021 in;
# Polyurethane on steel = 0.03 - 0.057 in.<--
f1 = f1*0.0254 # (m) Coefficient of rolling resistance
Fs_roll=Fsr(M,R,f1)
Fsr_m = Fs_roll/M
C_rr = Fsr_m/g
print("Fsr = {:.3f} N (= {:.3f} lbf)".format(Fs_roll,Fs_roll/4.448))
print("Fsr_m = {:.3} N/kg (= {:.3} lbf/kg)".format(Fsr_m,Fsr_m/4.448))
print("C_rr = {:.3}".format(C_rr))
```

```
Weight = 9.81 N
Fsr = 0.639 N (= 0.144 lbf)
```

```
Fsr_m = 0.639 N/kg (= 0.144 lbf/kg)
C_rr = 0.0651
```

There should be also accounting for the rolling resistance of the switching wheels and the wayside pickup shoes. According to (http://www.mstelektroteknik.com/en/portfolioview/thirdrailshoegears/), side-running collector shoes have contact forces of about 70 N. Measurements of friction on pantograph strips by Dinh, et. al., 2012 found the coefficient of friction at zero current to be about 0.22, which is the 'worst case', as passage of electrical current actually lowers the coefficient of friction. Given this information, it is anticipated that the drag force from the current collectors will be about 0.22x70 N = {{0.22*70}} N. Thus, adding about 10% to Fsr will conservatively account for friction from the collector shoe.

More detailed force analysis is needed to determine the normal forces on the switching wheels. Assume for the purposes of this analysis that they add about the same order of magnitude as the collector shoes. Thus, the calculation of the rolling resistance will apply a 'fudge factor' to increase the static rolling resistance by 20%.

The value of C_2 will be taken as the value for B in the Davis equation, which is 4.935×10^{-4} N/(kg-m/s) (AREMA, 2010).

[4]:
```
C2 = 0.0004935   # N/(kg-m/s)
V_L = 0.2826   # m/s
Fd_roll = M*C2*V_L
(print("Dynamic rolling resistance at line speed = {:.7f} N (= {:.7f} lbf)"
       .format(Fd_roll,Fd_roll/4.448)))
```

```
Dynamic rolling resistance at line speed = 0.0001395 N (= 0.0000314 lbf)
```

6 Energy Calculation

The governing equation for energy required for a station-to-station trip in t_s is (repeated):

$$E\left(t_s\right) = \frac{1}{\bar{\eta}}\left\{(1-R)n_t\frac{M_V V_L^2}{2} + \frac{1}{2}\rho C_D A_V\left[(V_L^2 + \langle V_w^2\rangle)D_s - \frac{V_L^4}{2a_m}\right] + n_T M_V\left[C_1 D_s + C_2 V_L (D_s - \frac{V_L^2}{3a_m}) + gz\right]\right\} + n_T P_{aux} t_s \quad (2)$$

The equation for t_s is:

$t_s = t_D + \frac{D_s}{V_L} + \frac{V_L}{a_m} + \frac{a_m}{J_1} + \frac{a_m^3}{24V_L}\left(\frac{1}{J_2^2} - \frac{1}{J_1^2}\right)$

7 Daily Energy Use

Consider what the daily energy need will be. The maximum capacity might occur for 4 hours during the day, M - F, and in one direction (commute direction).

[5]:
```
n_bar = 0.80  #  average efficiency of the electric motor
g = 9.81  # acceleration due to gravity, m/s^2
a_m = 0.25*g  # maximum acceleration for seated passengers
J1 = a_m  # jerk starting from rest
J2 = a_m  # jerk approaching line speed
R_regen = 0  # regenerative braking recovery efficiency
n_t = 1  # number of vehicles in a 'train'
M_v = 1 # vehicle + bogie mass, kg
W_v = M_v*g  # weight of vehicle and bogie
V_l = 0.2826 # line speed, m/s
V_w = 5 # average wind speed, m/s
rho = 1.275  # density of air, kg/m^3
C_d = 0.51  # coefficient of drag (0.42 for a solid hemisphere)
A_v = 0.02  # frontal area of a vehicle, m^2
D_s = 8  # distance between stations, m
R_wheel = (1.75/2)*0.0254 # Radius of wheel (assuming 12 in. diameter), m
f1 = 0.057  # Coefficient of rolling resistance, in.:
# Cast iron on steel = 0.021 in; Polyurethane on steel = 0.03 - 0.057 in.
f1=f1*0.0254 # Coefficient of rolling resistance, m
C1 = Fsr(M_v,R_wheel,f1)/M_v  # static roll resist per unit mass, N/kg)
C2 = 0.0004935  # dyn roll resistance (depends on velocity). N/(kg-m/s)
z = 0.10  # elevation change from start to the end of the trip, m
P_aux = 0.0  # auxilliary power, W (see Wikipedia for auto air con)
f_unk = 1.0  # extra factor for collector shoe and switching wheel drag
t_d = 5.10  # dwell time in station, s
# last year max speed is 0.2826 m/s. this year track length is 7.3 m.
# the station is 1.44 m long.
# minimum dwell time is 1.5/0.2826 = 5.31 sec.
# round it to 5.5 sec.
t_s = t_d + D_s/V_l + V_l/a_m + a_m/J1 + \
   (a_m**3/(24*V_l))*(1/J2**2 - 1/J1**2)

regen_loss_comp = (1/n_bar)*(1-R_regen)*n_t*(M_v*V_l**2)/2
air_drag_comp = (1/n_bar)*0.5*rho*C_d*A_v*((V_l**2 + V_w**2)*D_s - \
    V_l**4/(2*a_m))
rolling_res_comp = (1/n_bar)*n_t*M_v*(f_unk*C1*D_s + C2*V_l*(D_s - \
    V_l**2/(3*a_m)))
elev_comp = (1/n_bar)*n_t*M_v*(g*z)
aux_comp = n_t*P_aux*t_s
sum_comp = regen_loss_comp + air_drag_comp + rolling_res_comp + \
 elev_comp + aux_comp
E_ts = sum_comp
P_avg = E_ts/t_s

print("** Energy per vehicle **")
print("Energy required, E(t_s) = {:.4e} J".format(E_ts))
print("Average trip time, {:.3f} seconds".format(t_s))
```

```
print("Average power, P_avg = {:,} W\n\n".format(P_avg))

print("STOP HERE. FIRST STAGE FINISHED.")
print("")
print("")
# Calculation of the maximum number of vehicles
L_g = 0.0073  # length of the network, km
headway = 5.0  # minimum headway, s
head_dist = V_l * headway  # minimum headway distance, m
slots_max = round(L_g*1000 / head_dist)
# print(slots_max)  # how many slots are available?
slots_70 = round(0.70 * slots_max)  # 70% utilization is the practical max
n_v = slots_70  # maximum number of vehicles
pax_veh = 3.0  # average number of passengers per vehicle
pax_hr = round(pax_veh * 3600 / headway)

#  Park and Ride Data from Spring 2016
n_RMS = 44.0 #  max
n_2RMS = 2*n_RMS

hrs_year = 24*365

print(">> Energy per",n_v, "vehicles (70% of theoretical max cap)<<")
print("Passengers per hour = {:,} (assuming {:.1f} pax/veh)".format(pax_hr,␣
 ↪pax_veh))
print("Energy required, E(t_s) = {:.3e} J".format(n_v*E_ts))
print("Average trip time, {:.1f} minutes".format(t_s/60))
print("Average power, P_avg = {:.5e} W\n\n".format(n_v*P_avg))


print(">> Energy per 2x",n_RMS, "vehicles (RMS hourly Spring 2016 Park and Ride␣
 ↪data)<<")
print("Energy required, = {:.3e} J".format(n_2RMS*E_ts))
print("Power, P_avg = {:.2e} W".format(n_2RMS*E_ts/t_s))
print("Yearly energy required = {:.3e} kWhr\n\n".format((hrs_year*n_2RMS*E_ts/
 ↪t_s)/1000))


(print("KE loss = {:.2e} J ---> {:.1f}%".format(regen_loss_comp,
        100*regen_loss_comp/sum_comp)))
(print("Air drag loss = {:.2e} J ---> {:.1f}%".format(air_drag_comp,
    100*air_drag_comp/sum_comp)))
(print("Rolling resistance loss = {:.2e} J ---> {:.1f}%".
       format(rolling_res_comp,100*rolling_res_comp/sum_comp)))
(print("Elevation loss = {:.2e} J ---> {:.1f}%".format(elev_comp,
        100*elev_comp/sum_comp)))
(print("Aux power loss {:.2e} J ---> {:.1f}%".format(aux_comp,
```

```
        100*aux_comp/sum_comp)))
```

```
** Energy per vehicle **
Energy required, E(t_s) = 9.2989e+00 J
Average trip time, 34.524 seconds
Average power, P_avg = 0.2693469642095929 W


STOP HERE. FIRST STAGE FINISHED.


>> Energy per 4 vehicles (70% of theoretical max cap)<<
Passengers per hour = 2,160 (assuming 3.0 pax/veh)
Energy required, E(t_s) = 3.720e+01 J
Average trip time, 0.6 minutes
Average power, P_avg = 1.07739e+00 W


>> Energy per 2x 44.0 vehicles (RMS hourly Spring 2016 Park and Ride data)<<
Energy required, = 8.183e+02 J
Power, P_avg = 2.37e+01 W
Yearly energy required = 2.076e+02 kWhr


KE loss = 4.99e-02 J ---> 0.5%
Air drag loss = 1.63e+00 J ---> 17.5%
Rolling resistance loss = 6.39e+00 J ---> 68.7%
Elevation loss = 1.23e+00 J ---> 13.2%
Aux power loss 0.00e+00 J ---> 0.0%
```

8 References

Anderson, J. E. (1978). Transit systems theory. Lexington, Massachusetts: Lexington Books (D.C. Heath and Company).

Ding, T., Chen, G., Li, Y., He, Q., & Xuan, W. (2012). Friction and wear behavior of pantograph strips sliding against copper contact wire with electric current. AASRI Procedia, 2, 288-292.

Manual for railway engineering (2010). Lanham, Maryland: American Railway Engineering and Maintenance-of-Way Association. Retrieved from https://www.arema.org/publications/mre/

Back to Nomenclature

C. Component Datasheets

Part Name	Datasheet Link	Link to Purchase
Pi Zero W	https://datasheets.raspberrypi.com/rpizero/raspberry-pi-zero-w-reduced-schematics.pdf GPIO Pins https://images.theengineeringprojects.com/image/main/2021/03/raspberry-pi-zero-5.png	https://www.amazon.com/Raspberry-Zero-Bluetooth-Compatible-Connector/dp/B0C4XKQ6F2/ref=sr_1_1_sspa?crid=1AFU088C1IVOO&keywords=pi+zero+w&qid=1701147922&sprefix=pi+zero+w%2Caps%2C143&sr=8-1-spons&sp_csd=d2lkZ2V0TmFtZT1zcF9hdGY&psc=1
Pi Sugar 3	https://github.com/PiSugar/pisugar-documents/tree/master/datasheet	https://www.amazon.com/dp/B09MJ8SCGD
Power Supply 0-30V 0-10A	https://www.amazon.com/dp/B08HYK2ZW3 (scroll to bottom for Datasheet)	https://www.amazon.com/dp/B08HYK2ZW3
DC 1V-5V to 5V Boost Module Board	https://www.amazon.com/dp/B01MQG3T7V (scroll to bottom for Datasheet)	https://www.amazon.com/dp/B01MQG3T7V
Adjustable DC-DC Buck Boost Converter XL6009 DC to DC 5-32 V to 1.25-35 V Voltage Module	https://www.haoyuelectronics.com/Attachment/XL6009/XL6009-DC-DC-Converter-Datasheet.pdf	https://www.amazon.com/gp/product/B07NTXSJHB/ref=ppx_yo_dt_b_asin_title_o05_s00
TP 4056 Lithium Battery Charging Module	https://dlnmh9ip6v2uc.cloudfront.net/datasheets/Prototyping/TP4056.pdf	https://www.amazon.com/dp/B0B639FVR4?psc=1&ref=ppx_yo2ov_dt_b_product_details
USB Type-C Breakout Board Serial Basic Breakout Female Connector Type PCB Converter Board	https://www.amazon.com/DIANN-Type-C-Breakout-Connector-Converter/dp/B0BLSN5PR8?th=1 (Scroll to bottom for Datasheet).	https://www.amazon.com/DIANN-Type-C-Breakout-Connector-Converter/dp/B0BLSN5PR8?th=1
Maxwell BCAP0350 Supercapacitor	https://www.mouser.com/datasheet/2/257/Maxwell_BCSeries_DS_1017105-4-1179684.pdf	From the core team
Samsung INR18650-25R Lithium Rechargeable Battery	https://www.imrbatteries.com/content/samsung_25r_2.pdf	From the core team
diymore USB C Tester Power Meter	https://www.amazon.com/dp/B0CCJ4C1RB?th=1 (scroll to the bottom for Datasheet)	https://www.amazon.com/dp/B0CCJ4C1RB?th=1

16 gauge copper wire		
Alligator Clips		https://www.amazon.com/dp/B0881KQWRP
Alligator Clips with wire		https://www.amazon.com/dp/B083K7PXYY?th=1

D. Information for Future Work

More information about the upgrade to the PiSugar 3, the PiSugar 3 Plus, can be found in the GitHub documentation at this link: https://github.com/PiSugar/PiSugar/wiki/PiSugar-3-Series

E. Miscellaneous Future Investigation and Suggestion

1. Hybrid capacitor

Hybrid capacitor is a unique type of capacitor that behave like a capacitor with slightly more energy density. This type of capacitor was not fully investigated in this report. It is a potential candidate for for vehicle energy storage but requires testing on its behavior and energy storage characteristics.

2. Regenerative braking systems

Regenerative braking systems are common used in electric vehicle to restore energy by collection energy through braking. Supercapacitor is a perfect energy storage for restoring a lot of energy in a short period of time.

3. TP4056 power-sharing modification (charging and powering simultaneously)

The overvoltage protection are designed to stop charging when charging curren is below 100mA. However, charging and powering simultaneously will confuse the charging current reading which the overvoltage protection will not work, causing potential overcharge hazard. The internet has more information to implement power-sharing mechanism to allow TP4056 charges 18650 battery safely and power the motor at the same time.

4. TP4056 modification to increase charging current

TP4056 charging current is programmable by switching the proper resistor as specified in the datasheet. Since 18650 battery fast charging current is 4A, TP4056 could be modified to provide 4A with heat sink preventing overheat.

5. Heating solution (overheating circuit)

Powering motor and using supercapacitor involve high current application. Most circuit are not designed for high current purposes. Therefore, adding heat sink or other heat solutions is necessary to keep the circuit cool.

6. Scalable Charging System

In this project, the supercapacitor and 18650 lithium ion battery is scalable to a larger load by adding the number of cell. Be aware of how each cell is connected to each other. In the next section, we will discuss balancing battery cell later.

7. Balancing supercapacitor (more than one cell)

Balancing supercapacitors is important when the number of cells increases. Due to different internal resistance in supercapacitors from the factory, each cell charges slightly differently. Therefore, balancing circuits for supercapacitors is needed to avoid overvoltage or undervoltage. The unbalanced voltage in supercapacitors are more obvious when they are connected series.

8. Balancing Lithium Ion Battery (more than one cell)

Similar to supercapacitors, lithium ion batteries need to be balanced when there is more than one cell to prevent overcharge or undercharge. The unbalanced voltage in lithium ion batteries is more obvious when they are connected series.

9. High Current Solderless Breadboard

One of the main challenges in this project is a normal solderless breadboard cannot handle more than 1000mA. For high current system, we have to use alligator clips and soldering 16 gauge wire to the circuit, which is time consuming and unorganized. If future students can develop a high current/power solderless breadboard will increase the developing efficiency for supercapacitor charging system testing.

10. Custom PCB Voltage Converter

In this project, there are a lot of trial and error to find the appropriate voltage converter. Once we are more familiar with the voltage converter, we began to think about designing a custom voltage converter to match our. For example, 3 super capacitors connected in series has 8.1V. Having a custom voltage converter that can convert 1V-8V input to constant 5V output will help the energy efficiency significantly that we use most of the energy stored in supercapacitors.

11. Measuring Power, voltage, current sensor (energy status monitoring system)

By implementing power/voltage/current sensor, all the power data could be visualize in laptop by microcontroller. In this project, we were using multimeter to measure current and voltage. However, moving multimeter back and forth around the circuit is inefficient. Having power sensor will allow students to monitor power data in every location at the same time without tempering with the circuit.

12. Implement a fuse to protect the circuit

Implementing a fuse to protect the circuit from overcurrent and overvoltage is important. We damaged many components overheating/overvoltage during our testing. To reduce the cost, it is crucial to implement a fuse in different locations of the circuit.

13. High current testing

The finalized circuit design is functional but need further testing, including high current testing. So far, we were able to charge the supercapcitors at 5V 2A. For future students, we suggest to replicate and understand the circuit for first testing. Doing electrical engineering from mechanical engineering is difficult, but it is doable.

14. Independent Power Supply

This year we work independently with the solar charging and mechatronics bogie team. It is important to have a stable power supply. We struggled for the first semester for not investing in a new power supply. Once we got a power supply everything works.