Electric Conversion of a 1972 Triumph Spitfire

A Major Qualifying Project Report submitted to the faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the degree of Bachelor of Science

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Abstract:

Our team converted a student-owned 1972 Triumph Spitfire (MK IV) from a gasoline powered, internal combustion powertrain to a fully electric powertrain. Electric Vehicles (EV) have in recent years exploded in popularity with developments in embedded systems and battery technology. This has been compounded as more manufacturers focus on making environmentally friendly vehicles. To do this conversion, our team removed the internal combustion engine, and implemented an electric motor and motor control unit, a 24-kWh battery unit, user interface, and sensor suite. There is still work to be done, however initial test drives of our converted EV are promising. Final testing on efficiency and performance is still underway, but our team has successfully implemented the 24-kWh battery pack, manual-electric drivetrain, and supporting equipment. The goal of this project is to show that converting a car to an EV can increase its performance, efficiency, and reliability, while being more budget friendly than a combustion car.

Acknowledgements:

We would like to thank our project advisors, Professor Nick Bertozzi, Professor Rick Brown, Professor Joshua Cuneo, and Professor Craig Putnam, for their extensive guidance and insight throughout the academic year. We are grateful to the Sprunger family for providing our team with a workplace, advice, and equipment which we used to renovate the car. Our team received incredible generosity through fundraising as well and would like to express our gratitude to all the supporters of the project, especially: Liz Magnotta and John Connell. Additionally, we would like to thank all the people and organizations who have worked with us by supplying materials, and mentorship. We are grateful for their help along the way: Rodrigo Donascimento and Josh Mallette in Washburn Laboratories, Ilyas Salhi and Evelyn Maude in the WPI Electric Formula SAE team, Jeremy Trilling, Coastal Equipment Corporation, and Wray and Charlie at Pro Shaper Workshop. Without everyone’s hard work and dedication, this project would not have been possible.

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Introduction:

Fossil fuels have been the primary means of mobile energy storage across the world for hundreds of years. While being a highly energy-dense fuel, the engines that burn this fuel are highly inefficient and release carbon dioxide as a byproduct, a known greenhouse gas. “In 2020, greenhouse gas emissions from transportation accounted for about 27% of America’s total greenhouse gas emission, making it the largest contributor of greenhouse gas emissions in the United States” (Sokona, 2022).

An electric drive system has the potential to be a greener and more efficient alternative to gasoline engines, primarily due to having a smaller recurring carbon footprint. This characteristic is due to the fact that electric motors have an average of 80% or higher efficiency compared to around 40% for an internal combustion engine (Boloor, 2019). In this project, we hope to show that converting an antique car such as this 1972 Spitfire MkIV to a fully electric system can be a practical solution to increasing the reliability and efficiency of a currently gas-powered system.

We expect this conversion to offer greater reliability and enhanced longevity for this particular vehicle, while improving performance and efficiency. We believe the Triumph Spitfire is a particularly good candidate for this conversion as it offers numerous advantages such as ample space, a lightweight chassis, and a simple structure. Besides improving performance and reliability, we have also placed a priority on the budget of the project. Since this is a student funded MQP, we only have limited funds to complete the project. With these priorities in mind, our goal is to produce a functioning electric vehicle with reasonable range and performance capabilities.

Team Structure:

Our team is composed of engineers from a variety of disciplines. There are four mechanical engineers: Grace Magnotta, Blaise Pingree, Wynn Roberts, Bradley Sprunger; two computer scientists: Shane Donahue and Sean McMillan; one robotics engineer, Patrick Flanigan; and one electrical engineer, Rachael Smith. In order to work efficiently, we divided the project into a number of core components including: Motor and Electronic Control Unit (ECU), Accumulator and Wiring, Transmission, Rear Drivetrain, and UI/Sensors/Software. To foster interdisciplinary work, we had everyone work on 2-3 of these teams. Initially, this created sub teams of 4-5 people which made it difficult to coordinate schedules and meet. After a short time, we switched to a system where two people were the project lead on each component. The mechanical and robotics engineers mainly focused on the motor and ECU, transmission, rear drivetrain work, and accumulator design. On the other hand, the computer scientists and electrical engineers worked on the battery pack and wiring, UI/software, and sensor integration design.

Scope of Project:

The summarized goal of the Electric Triumph Spitfire MKIV (1972) Major Qualifying Project is to convert a Triumph Spitfire from an internal combustion engine (ICE) and its related peripherals to a fully electric powertrain with updated peripherals (dashboard, UI). This project can further be divided into several main objectives, including the implementation of an electric drive motor, battery unit, ECU, sensor suite, and comprehensive user interface (UI).

In addition, we hope to maintain street legality throughout this build. Some general practices to ensure its legality are getting the car reinspected (the same inspection a regular ICE goes through) and, although we do not expect to have to do this, potentially re-registering the vehicle because of the radical transformation (*Can I Convert My Car to Electric? (Everything You Need to Know)*, 2021) (Martynyuk, 2022). Getting the car inspected would ensure everything is working correctly from a mechanic's perspective. However, it is ultimately up to the local DMV to decide what they look for in an inspection and what needs to happen in order to qualify the vehicle as street legal.

General Goals:

The project's goals begin with an analysis of the current capabilities of this specific vintage car. Once we have analyzed the current donor car, our project aims to design and then integrate the capabilities offered by a modern electric drivetrain into the preexisting automotive infrastructure of our donor car.

By doing this, the team is hoping to challenge the common stereotypes related to electric vehicles when compared to ICE vehicles, including but not limited to, cost and incomparable range to an ICE, while simultaneously developing creative and cost-effective engineering solutions. In addition, we hope to promote the argument that electric conversions can be an alternate path to an electric future, rather than that of building new, mass produced modern electric cars.

To judge the success of our project in a quantitative manner, preliminary goals have been set for the functional Electric-Converted Triumph Spitfire, planned for completion in C-23. These goals relate to the car's core characteristics, and the 1972 Triumph Spitfire MKIV published specifications. In addition, metrics commonly used to compare cars during their use have been assessed and added to our goals. We have set stretch, achievable, minimum, and OEM specification standards (pictured below in Table 1) to drive our project as well as assess our progress throughout the year.

Technical Goals:

Table 1 shows our technical goals for the vehicle in regard to distance, maximum speed, acceleration, and weight. Note the OEM Specifications and how they compare to the other goals. The team's achievable goals, based on calculations, hopefully will be easily attainable. These numbers were chosen due to the power of the accumulator, average amperage drawn from the motor, and other factors.

Technical Goal:	Stretch Goal	Achievable Goal	Minimum Requirement	OEM Specification
Range	100 Miles	60 Miles	10 Miles	295 Miles
Max MPH	110 MPH	65 MPH	30 MPH	97MPH
0-60	8s	15s	25s	16s
Weight	1650lbs	1850lbs	2200lbs	1850lbs

Table 1. Technical Goals.

Qualitative Goals:

In addition to the technical specs of the project, some goals cannot be assigned a quantitative value. As discussed above, it is a core goal of our team to rework the common stereotypes related to electric vehicles. Simultaneously, we believe that by converting a common, low-cost Triumph Spitfire, we will be increasing the lifespan of this specific donor car. We hope our conversion will propose the possibility, and practicality, of an electric conversion. Perhaps, in addition, by documenting our work we may inspire other people that they might have the skills and capabilities to undertake a similar project of their own.

To demonstrate the practicality of such a vehicle, it is a requirement for our car to have the capabilities to function the same as any other vehicle on the road. For example, the car should start without issue, while the battery should be chargeable in a manner that mimics other electric vehicle options and is not a chore. Common maintenance such as brake and tire services should be uninhibited by our modifications. In addition, our modified UI should be user friendly, and unobtrusive in order to allow the vehicle's driver to concentrate on the road. Although these goals cannot be assigned a distinctive value, it is important that the vehicle retains these functions after its conversion, and these goals are tracked and documented throughout the course of the project.

Problems/Gaps:

This project contains challenges across several disciplines, as well as integrating modern day technology into a vehicle from 1972. Most of our team members have limited experience working on cars, which created a knowledge gap. Due to this, members of our team encountered problems outside of our knowledge base or respective engineering discipline and needed to be broadly knowledgeable in several aspects of engineering simultaneously. This required constant learning through research. Based on our technical goals, we had predictable challenges such as the integration, compatibility, and packing of physical components into the vehicle *(motor, ecu, battery, sensors, etc.).* For example, the electric motor needed to be coupled to the transmission requiring a custom coupler. Other challenges included part compatibility when sourcing equipment from different vendors and ensuring the successful integration of software.

Due to the Spitfire's age and the complexity of this project unexpected problems naturally arose. These often could take many forms as it is impossible to know the complete history of any car and the wear on any one of its thousands of components. However, through proactive measures including leeway in both our time allocation as well as our prepared budget we were able to mitigate these issues before they became too large.

Budget:

Creating a Budget/Bill of Materials

One of the most important aspects of a large project is a detailed and thorough budget. Without a budget, funds are not guaranteed to be distributed properly among the many parts needed for this project. If this happens, it is also likely that the project will run over its intended budget, which also causes problems as essential aspects of the project may not be purchased. There are many key aspects of formulating a budget, many of which must happen prior to the development of an official budget.

The first aspect of creating a budget is the discussion and documentation of everything that will need to be purchased in the project. In this project, the largest expense is parts for the vehicle. This includes parts such as the electric motor, batteries, and transmission. Some expenses can be hidden but still need to be addressed, such as shipping costs, software costs and raw materials such as wire which is used for electrical connections. These costs are often overlooked but contribute to a decent portion of costs when all added up.

The next step is to understand the total budget you are working with, and to allot which parts are a priority to the project and are thus given the most percentage of the budget. This makes sure that when you begin spending your budget, you are more likely to run out of money on less important aspects of the project which won't hinder the final deliverable as much. For this project, the most important aspect for the car is the electric motor and batteries. Without these two, clearly the project wouldn't get far, so it is important to take this into consideration when creating a budget.

Finally, in addition to the original budget containing all the expected costs, a parallel budget containing the actual costs should be created to keep track of whether the expected budget is being followed or not. In a perfect world actual costs would equal the expected costs, however in many cases prices fluctuate, and unknown costs show up later. By keeping track of every cost, you can more accurately gauge whether you will meet your maximum budget or not.

Funding

Typically projects like this take significant time and money. An electric conversion could range anywhere from $7,500 to $95,800 (Martynyuk, 2020) In order to fund our project, we had three methods of income. The current owner of the car, and a member of the project team, Patrick Flanigan will be personally funding around $9,000 for this project. Another teammate, Blaise, created a GoFundMe where we have currently raised $2,525. Additionally, varying by academic major, WPI provides a budget per student for MQP work. With eight people on this project, our ‘school billable funding’ sums to roughly $1,500 which can be spent on tooling, research, and some consumables. As it stands at the moment in total, our project budget is $11,525 with an additional potential for $1500 of school funding.

Bill of Materials

Total Electric Spitfire Budget			
Project Budget W/ Gofundme:	$11,525	Current Cash Left in Bank Account:	*$182.00*
Current GoFundMe Funds:	$2,525		
Expected Gross Costs:	$10,871		
Expected School Billing:	$1,828		

Group Name	Budgetted	Expected Gross Costs: (Project + School $)	Expected Gross School Billable	*Already Spent* School Billable:	Total Cash Spent:	Cash to be spent
Motor / ECU	$3,300	$3,728	$17	$0	$3,611	$118
Transmission	$700	$852	$121	$121	$852	$0
Accumulator	$3,200	$4,614	$819	$591	$4,564	$50
Differential	$400	$0	$0	$0	$0	$0
Lane Assist	$100	$0	$0	$0	$0	$0
Dashboard	$300	$581	$200	200	$537	$44
Wiring	$200	$1,096	$671	412	$1,096	$0
	Total Budgeted:	Total Expected Costs:	School Billable:	Spent School Billable:	Spent Cash:	Cash to be spent:
	$8,000	$10,871	$1,828	$1,828	$10,660	$211

Figure 1. Bill of Materials as of April 18th, 2023

Above in Figure 1 is the overview slide of the current bill of materials (as of April 18th) set for the Electric Spitfire project. It contains the six main aspects of our project which will need materials, along with an allotted amount of the budget for each aspect. There are also tabs made specifically for each aspect of the project, which gives more detail of how the budget is being used for that part of the project. Note that the Motor/ECU as well as the Accumulator take up a majority of the budget due to their importance to the project (as evident in Figure 1 and 3).

In the first term of the project, a decision by the group was made that while a total of $9,000 had been budgeted, and $1,000 had been donated in addition, a maximum budget of $8,500 was established such that when extra costs arise, such as shipping costs or price fluctuation, a buffer was maintained to make sure the absolute maximum would not be breached.

By the end of the second term of the project , the most critical and expensive components needed for the project were purchased. This included the AC motor, inverter, DC-DC charger, lithium-ion cells, and raw materials. As a result, our budget was less forward-looking and less volatile. At this time, the project was projected to end with $1,900 unspent. However, it is worth noting that in the event of difficulties while processing school reimbursements of $1800, we did not want the project to run out of funds. As a result, we are also bearing in mind that in the unlikely event that we are unable to be reimbursed by the school for any equipment, we would end the project with $400 unspent.

By the end of the third term, all parts required for the project were purchased. This was also a key term where many components were manufactured in Washburn laboratories. Thus, the project left a total of $900 unspent. The process to bill the school began in the beginning of the fourth term, as consumables and the Advanced Driver Assistance System (ADAS) were being purchased. This left the project with very few funds towards the final few weeks of the project, which was anticipated.

Figure 2 highlights one of the specific tabs, the Accumulator tab, which goes into detail as to how the budget is being split up for this part. It is split into the part itself, a description of the part, a link to be able to find the part online, notes, priority rating, quantity, individual cost, and finally total cost. The first item on the list contains the battery cells, which provide a total power of 4 kilowatts each. The individual cost for each battery is $500 and with a quantity of 4 the total cost towards the budget is $2000. In addition to this, we expect to add an additional pair of batteries for a combined price of $500. This sums to six battery modules, or 24 kWh, for $2500. Once adding in the outlet, charger, and converter among other necessities, the budget for the accumulator is projected to be roughly $200 more than what is budgeted for this component.

	A	B	C	D	E	F	G	H	I	J
1	Part	Description	Link	Notes	Has this been purchased yet?	Quantity	Ind. Cost	Tax + Shipping	Total Cost	School Billable
2	Brick of Cells	4 KWh each, Provided by Jeremy.			Y	4	$500	$0	$2,000	$0
3	Optional additional cells for $250 each	4 KWh each, Provided by Jeremy.		Would have to purchase in pairs	N	2	$250	$0	$500	$0
4	BMS (Daly) 250 Amp, 27S		Link		Y	2	$334	$42	$710	$0
5										
6	Female J1772 Outlet		Link		N	1	$88	$0	$88	$0
7	AC-DC EV Charger	7 Amps	Link	Not CAN enabled	N	1	$209	$15	$224	$0
8	AC-DC EV Charger	30 Amps	Link	CAN enabled	N		$419	$165	$0	$0
9	AC-DC EV Charger	10 Amps	Link	CAN enabled	N		$686		$0	$0
10	AC-DC EV Charger	12 Amps	Link	Not CAN enabled	N		$650		$0	$0
11	J1772 Communications Producal Device (AVC2)		Link		N	1	$45	$15	$60	$0
12									$0	$0
13–16	DC-DC Converter		Link		Y	1	$150	$0	$150	$0
17										

Figure 2. Accumulator BOM

As the group continued purchasing parts, the rows were highlighted blue to indicate an item had been purchased. As of October 13, we had ordered roughly 85% of the parts needed for the project. Critically, this included several items with extensive lead times.

In addition to the overall and team specific pages, we've put together graphs and charts to better visualize the project's current, expected, and maximum spending, as well as spending by teams (below in Figure 3, 4, 5, and 6).

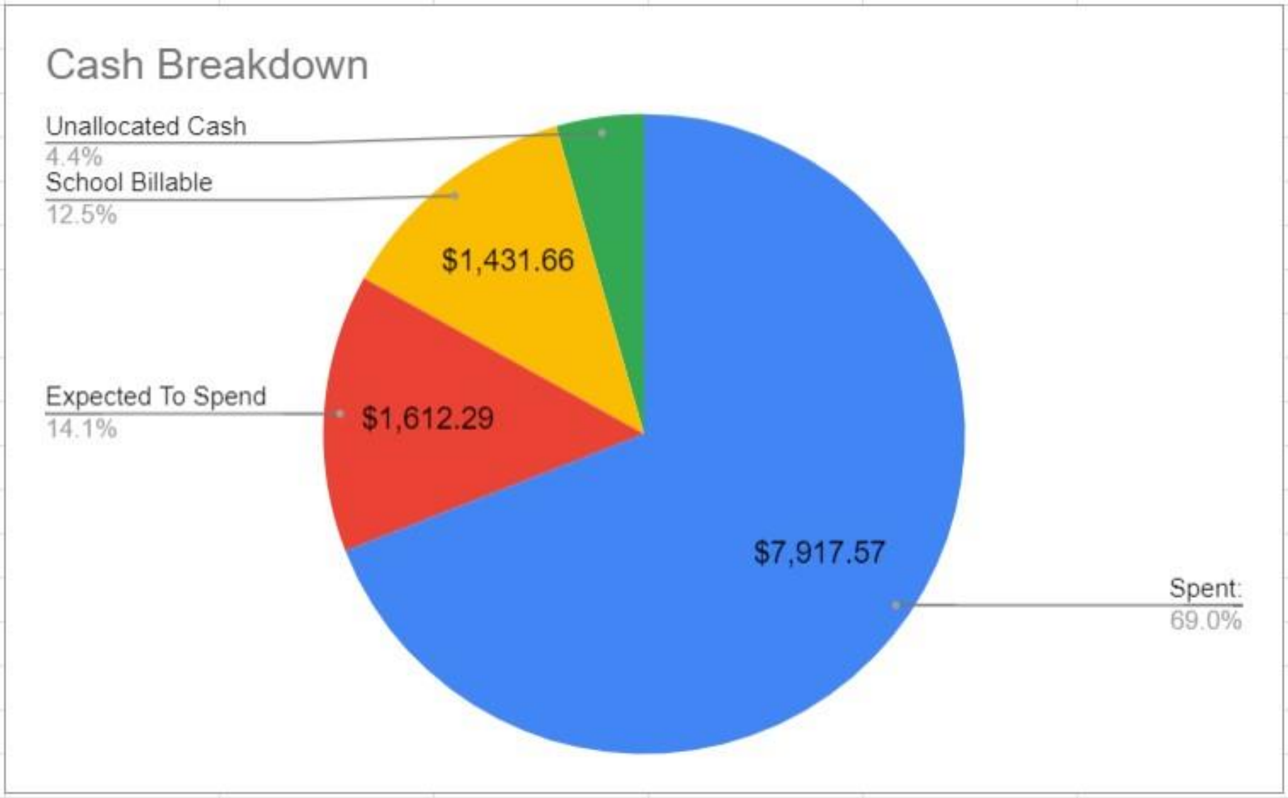


Figure 3. Breakdown of funding as it would have looked in the middle months of the project.

Overview:	
Spent:	$7,917.57
Expected Left to Spend:	$1,612.29
School Billable:	$1,431.66
Left After Delta:	$507.05

Figure 4. Budget overview as it would have looked during the middle months of the project.

Spending By Team	
Motor & MCU	$3,728
Accumulator	$4,614
Transmission	$852
Wiring	$1,096
Dashboard & Software	$581
Differential	0
Lane-Assist	0

Figure 5. Spending by team at the end of the project (4/27/2023).

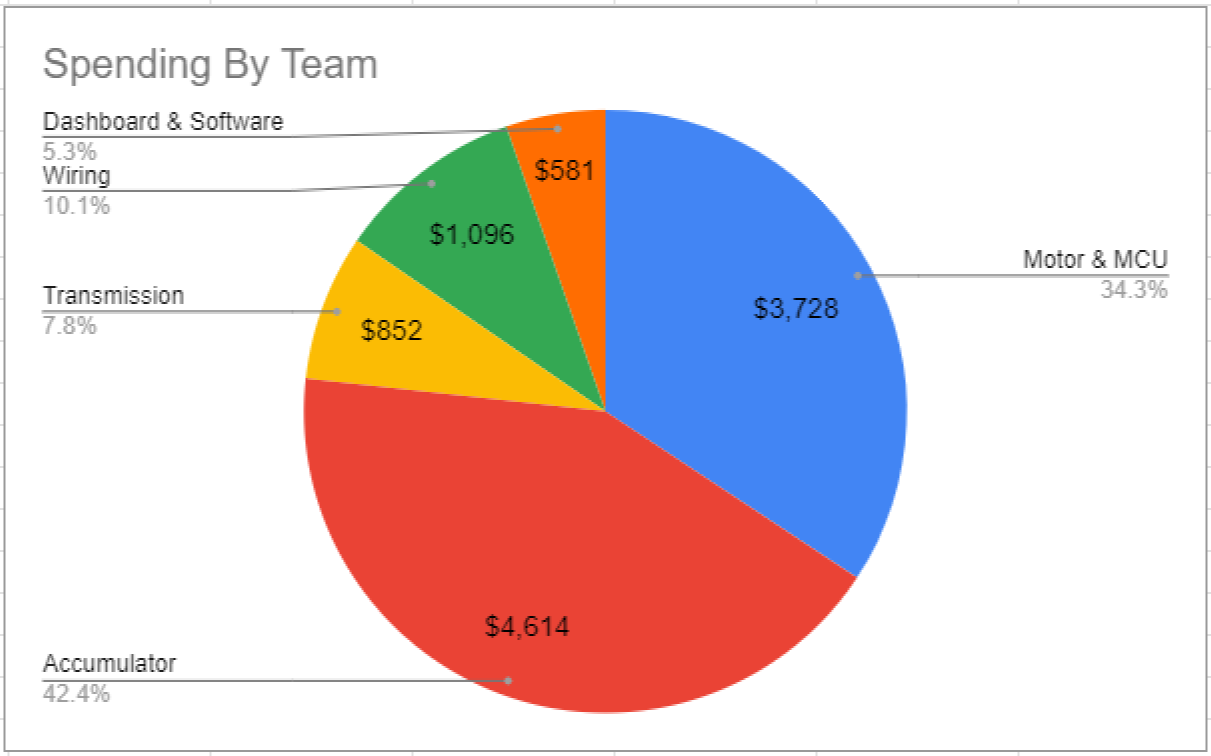


Figure 6. Spending by team at the end of the project (4/27/2023).

Timeline:

A timeline is a critical aspect of any large project. Similar to the budget, a timeline seeks to split the project into its most important parts. From there, deadlines are created, and a schedule is developed to make sure effort is spent at the right time for the right aspect of the project. Without a timeline, the project can easily fall into disarray, with people working on aspects of the project which cannot be achieved until earlier pieces of the project are finished. There are many ways to document a timeline, but the most common way is a Gantt chart. This creates a timeline for the project, as well as the specific aspects of the project which need to be completed at any given time. It is also incredibly easy to add and subtract deadlines or project pieces to keep an accurate log of the time spent on the project.

Figure 7. Project Gantt Chart

Note. Timeline of project

Our Gantt chart, depicted in Figure 7, is split into main themes of the project, such as Project Setup, Early Research and Planning, as well as others. Below these main themes contain more specific parts of the project and their respective deadlines. On the chart, the series of cascading tasks fall into the “research and design” section. This is broken down into six respective categories, each pertaining to a different part of the project. An example of this is the Battery and Wiring Integration Planning banner, which is then split into four specific aspects of this part of the project. These all contain deadlines which are expected to be met but can be changed if needed depending on the problems we may run into as we advance further into this project.

Our team utilized a Gantt chart during the terms which required the most planning, specifically during A term and through the end of B term. In C and D terms our team switched to a 'critical path analysis' style to stay on top of tasks. This allowed our team some of the same goal and process driven benefits that the Gantt chart provides, while being more dynamic, promoting collaboration, and requiring less time maintain. Similar to the Gantt chart, our goals were separated by team (Accumulator, Wiring, Mechanical, etc). However instead of following a timeline like on the Gantt chart, our goals were color coded to differentiate the urgency and progress of the goal. For example, pink means urgent, yellow means somewhat urgent, and orange means it can be done later. Once progress has been made on that goal, the square changes color to indicate that. Green indicates completed and blue indicates a separate list of goals. Figure 8 is an example from our critical path analysis board. (See Appendix E for links to Gantt Chart and Critical Path Analysis Board)

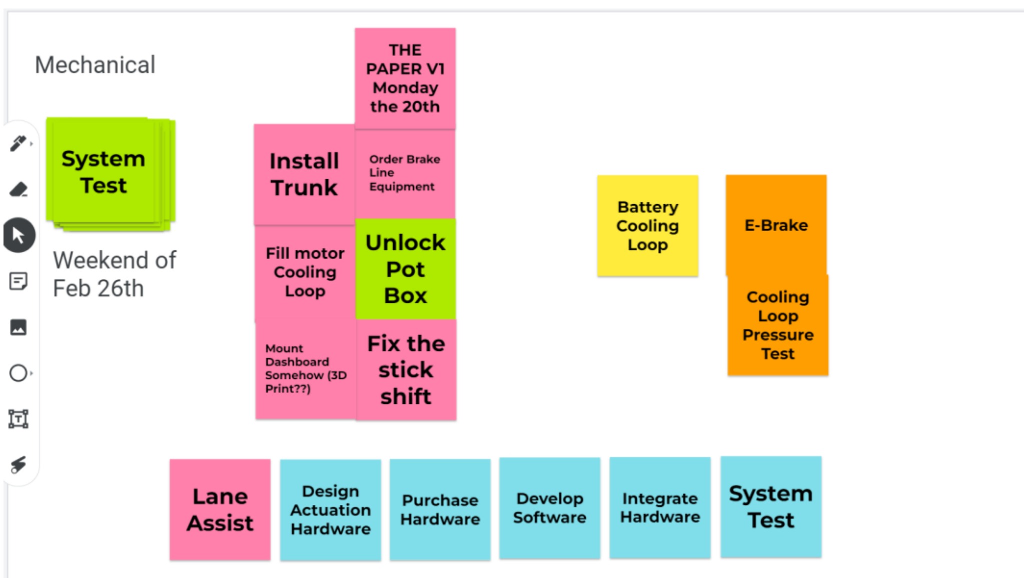


Figure 8. Project Critical Path Analysis Board

Component Selection and Physical Design:

Accumulator:

Overview:

Designing an accumulator from scratch poses a number of challenges. Our team had a few priorities in mind; primarily we looked to maximize the range and output power of our battery pack while minimizing the cost of development and implementation. In addition, we had to strongly consider development time and finally, strongly prioritized minimizing complexity. In order to achieve the optimal outcome we considered a number of different battery types and selected our battery type based on cost, ability, and accessibility. We then considered the different locations we could place these batteries in the car and what it would look like to integrate them successfully. Following this we designed housings and electronics integrations such that the accumulator could be integrated into the car successfully.

Battery Cell Types

Our team considered a number of battery types and designs. The most common styles of batteries in EVs are lithium-ion 18650 or 21700 type cells, LiFePo4 (Lithium Iron Phosphate), and lead acid batteries. Lead acid offers the worst energy density per weight and size, and thus were quickly decided to be our worst candidates, although they do offer a relatively low cost per watt hour of electricity (Anuphappharadorn et al.). Lithium Ion cells offer increased energy density with respect to both size and weight. Of Lithium Ion cells, 21700 type cells are capable of higher discharge and capacity, and are generally preferred to 18650 cells. Finally, LiFePo4 cells offer a greater lifetime cycle and massively increased capacity over the lithium ion cells, although they operate at a low voltage of 3.2V per cell.

18650 'Beta' Battery Banks

In our project, we had the opportunity to purchase pre-owned 'banks' of 18650 cells that were housed in a fire retardant material known as GrafGuard. When we purchased them, these cell banks were spot welded with industry-standard nickel tabs, but did not have integrated battery management or cooling systems. These banks contain 13 groups of cells wired in series, with each group containing 24 cells wired in parallel, for a grand total of 312 18650 type cells. This configuration resulted in each unit having the characteristics of operating at 48 Volts and 84 Amp Hours each, with a maximum discharge rate of 240 Amps. At a price of $500 a brick, and a total capacity of 4032 Wh per, this option would cost us $0.124 per watt. For comparison, a lead acid battery, the cheapest alternative, typically costs around $0.17 per watt hour. Other options can be significantly more expensive: 21700's cost roughly $0.34/watt, and LiFePo4 type cells typically cost roughly \$0.20/watt. With a battery system targeting 24 kWh of stored energy, these price differences scale significantly. Photos and CAD models of a “Beta Pack” and the GrafGuard cell retention material can be seen below in Figure 9, 10, and 11.

Figure 9. A Single “Beta Pack”, housed in a machined plastic housing.

Figure 10. The GrafGaurd Cell retention material in a “Beta Pack”.

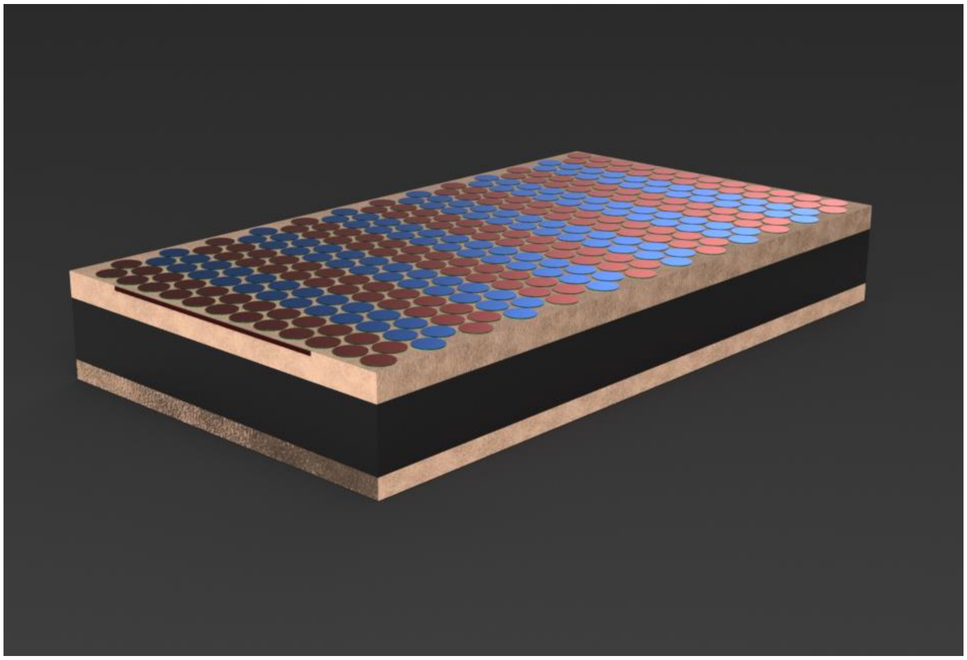


Figure 11. A CAD model of the "Beta Pack" used for further development.

Design Considerations using 18650 Type Cells:

18650 type lithium ion cells are common and well-studied. Our specific type of cell is manufactured by LG and has the model number MJ-1. These cells have been rigorously tested and had their capabilities and limitations studied extensively. In order to guarantee safe and continuous operation, the cells have to stay within a number of specified parameters including temperature ranges, electrical configurations as well as common and less common use cases.

The Requirements we must meet with these types of cells are as follows:

- The cells must not leave the specified temperature thresholds depicted in Table 2

Short Term Storage (< 1 Month)	-20 – 60 ℃
Average Storage (< 3 Months)	-20 – 45 ℃
Long Term Storage (< 1 Year)	-20 – 20 ℃
Minimum Temp while charging	0 ℃
Maximum Temp while charging	45 ℃
Minimum Temp while discharging	-20 ℃
Maximum Temp while discharging	60 ℃

Table 2. Battery Cell Temperature Threshold

Link

- The cells must never leave their specified maximum and minimum voltage thresholds
- The cells must never leave their specified maximum current thresholds
- The cells may never short circuit
- The cells must never be overcharged or over discharged
  - Any charging and discharging systems must have built in limits
- The cells may never be punctured, submerged, wetted, or allowed much physical strain
- Cells strung together in series must remain ‘balanced’ relative to each other. That is the voltage level and/or relative capacity must be nearly even.

Due to these criteria, in the case of long-term storage, for instance, the car would most likely have to live in a temperature-controlled garage. However, it is worth noting that these storage criteria are to minimize chemical degradation of the cell. This is typically measured as maintaining 90% of the capacity of the cell. This means that operating or storing the cells outside of this specified range typically is not necessarily a failure criterion, but will chemically degrade the cell, resulting in diminished cell life.

Beta Pack Configurations

Mainly driven by our project budget, we initially planned to purchase four such units of batteries. By using 48V pre-assembled battery packs, we were limited in our battery structure to either 48V, 96V, or a 192 Volt system. As a result, we are limited in our configurations to:

- All four packs in series: 192 Volts, 84 Amp Hours
  - 240 Amps maximum discharge rate
- Two packs in series, two in parallel: 96 Volts, 168 Amp Hours
  - 480 Amps maximum discharge rate
- All four packs in parallel: 48V, 336 Amp Hours
  - 960 Amps maximum discharge rate

We decided to wire the ‘bricks’ of batteries both in series and in parallel. By configuring the batteries in this way, we would be able to obtain an output of 96V and 168 Ah to feed into our motor, with a maximum discharge rate of 440 Amps. We chose to run this setup for a number of reasons. Primarily, 96 volts requires half the amperage for the same amount of power as a 48 volt system. With the size and capability of our batteries, we would lose too much power to inefficiencies in the motor, ECU, and conduits at the higher amperages (M.S. Chen et. al.). On the other hand, a 192 Volt system is far less common than the 96V system and requires equipment rated to double the voltage; typically, this increases sourcing difficulties and installation hazards as well. By running the 96V system we are able to discharge 440 Amps for a total power peak of 38.4 Kw, which we consider adequate for our project, as well as offering increased safety and accessibility. As a result, during the initial designs of our battery pack, we expected our batteries to be wired as depicted in Figure 12.

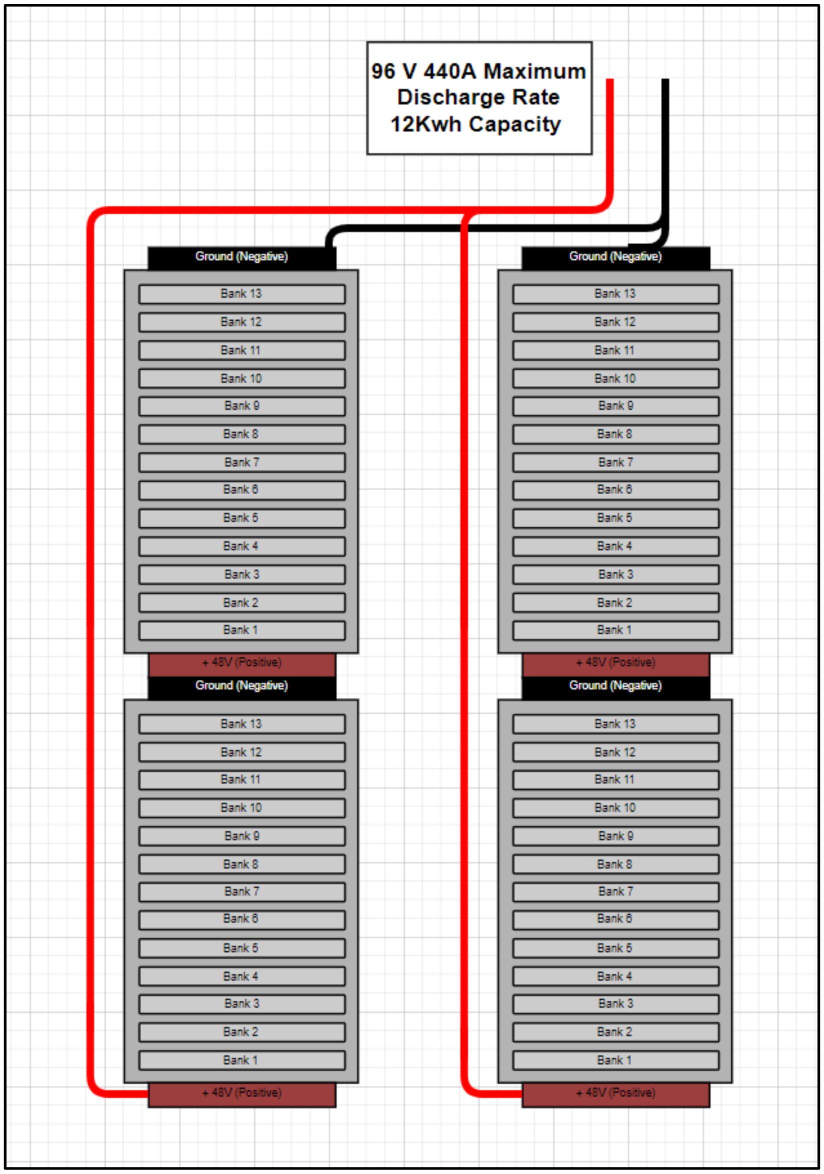


Figure 12. Accumulator Wiring Diagram

By mid-November we had developed the project, and therefore our budget such that we had the opportunity to buy a third pair of battery modules. By doing this we were able to up our total capacity from 16 kWh and our maximum amperage output from 480 amps to 720 amps. This led us to a final configuration that was exactly the same as in figure 12 but with a third pair of batteries.

Accumulator Management Systems Overview

When building a battery consisting of hundreds of smaller Lithium-Ion cells, it is absolutely necessary to ensure the individual cells are protected from operating outside of their designed ranges. These ranges include temperature, voltages, current draw, and charging rates. Each one of these plays a critical role in ensuring the safety, and long lifespan of each 18650 cell. To accomplish this, a battery management system (BMS) may be programmed to limit the rate of charge and discharge, as well as monitor temperature and cell balancing (Gabbar et al.). If the system notices any imbalances or readings outside of the acceptable range, it must be capable of tripping a fuse or contactor to isolate the battery from further usage and imbalances. In addition to this, the BMS calculates the charge remaining for each battery which can be displayed through the EVMS (electric vehicle monitoring system).

Accumulator Management Design

We considered a number of Li-Ion BMS systems. Early in the project, we decided it would be outside the scope of this project to design and implement our own BMS. These systems are design and research intensive and therefore would require a massive lead time to develop. As a result, we were limited in our selection to COTS (Commercial off the Shelf) items. Of these, the system we selected is the Daly manufactured BMS system. We were able to obtain these systems for roughly $230 per BMS, resulting in a full BMS system cost of $700.

Daly is a Chinese electronics manufacturer that sells a line of battery management systems. These systems range in monitoring ability for battery units consisting of 0 to 27 banks of 18650 cells in series. In addition, these systems range in current capabilities from 0 to 500 Amps. This system offers programmable monitoring against over current charge and discharge, over and under voltage, temperature, and cell balancing. In addition to this, the BMS is capable of communicating over CAN, UART, and Bluetooth. A screenshot of the Bluetooth readout can be seen below in Figures 13 and 14.

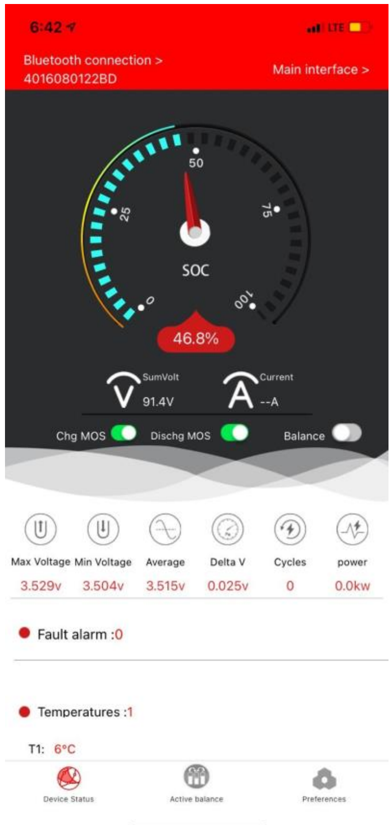


Figure 13. First Page of Readout from one of the three Daly BMS systems.

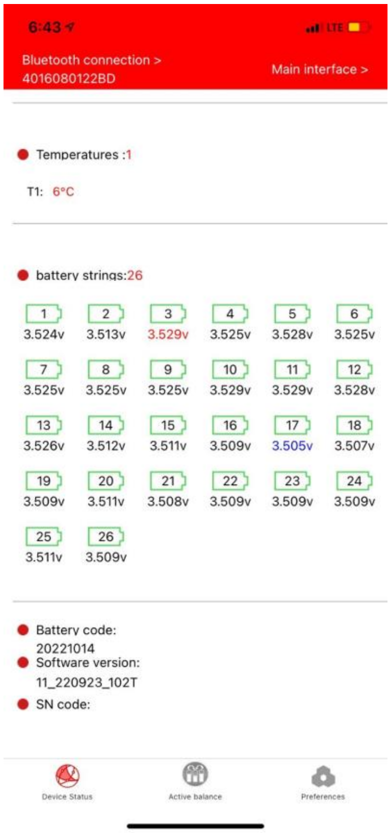


Figure 14. Second Page of Readout from one of the three Daly BMS systems.

Accumulator Management Configuration

Due to the high amperage demands of the motor, we would expect to run three of these BMS modules in parallel, to split the current demands between them. We have confirmed that it is possible to install the packs in parallel as long as the bricks are balanced upon installation, and remain balanced through charging and discharging cycles. As a result, the Accumulator with the Daly BMS system is shown below in Figure 15.

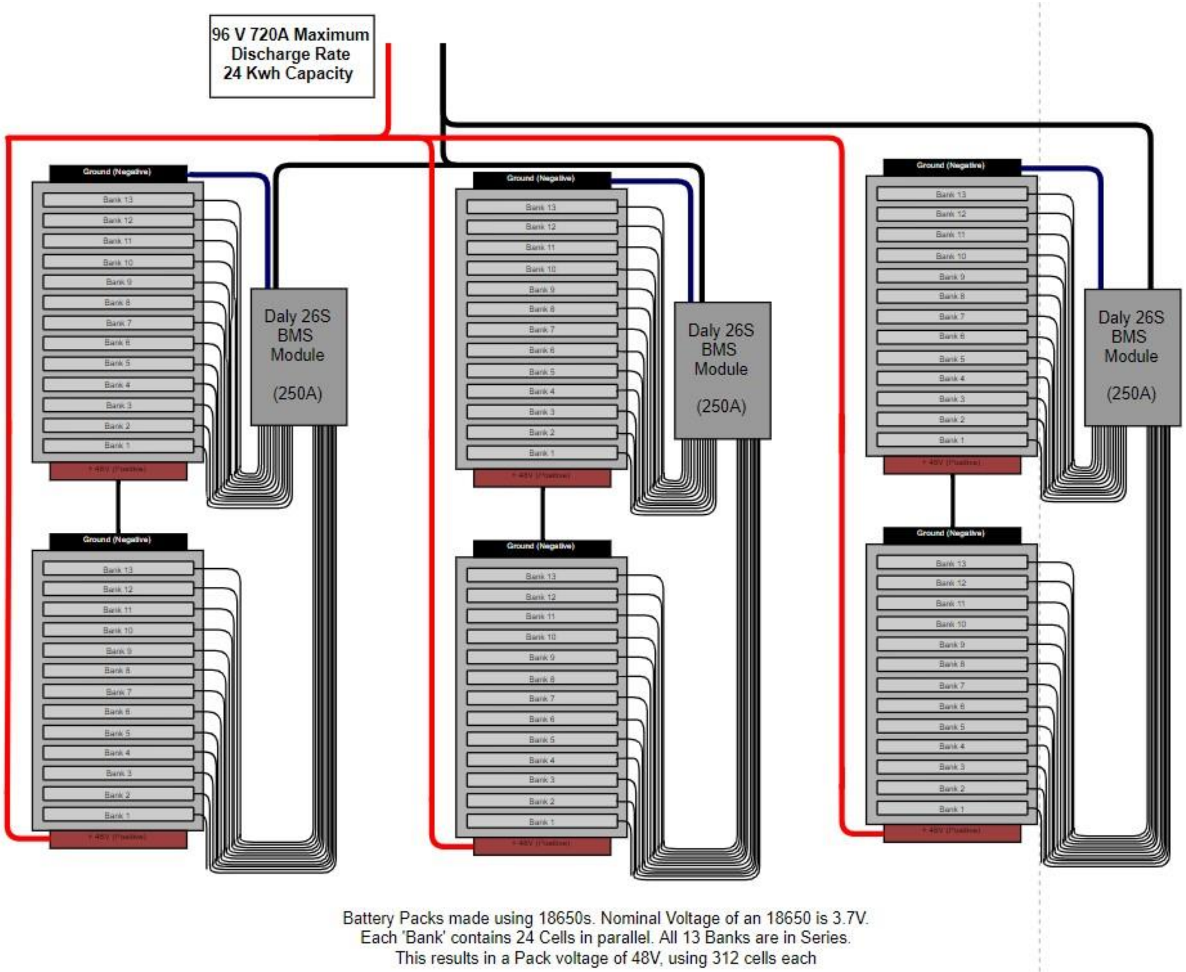


Figure 15. Accumulator and BMS Wiring Diagram

Accumulator Location Considerations:

We considered a number of possible locations for our accumulator system. The considered potential locations included under the hood, under the car in a 'skateboard' integrated battery-frame build, in the trunk, the previous location of the fuel tank, and in the cabin of the car itself. After serious consideration, we decided on two of the best locations: under the hood and in the trunk.

By placing the accumulator unit in the previous location of the fuel tank we would see significant environmental advantages. This would allow us to easily protect the system from vibrations, temperature fluctuations, and debris, as well as provide protection in the event of a collision from any direction. Unfortunately, our batteries are substantially larger than the size of the OEM fuel tank. As a result, this location consideration quickly became both the fuel tank location as well as a considerable portion of the trunk space. This area combined would provide a suitable location for us to build in our accumulator unit. Of course, there are a few challenges as well that would be presented by this placement. In this location, the accumulator would be nearly six feet of linear distance from the motor and inverter. By snaking any cables and cooling tubes along the frame or interior of the car, we expect the length of these cables to be in excess of 10 feet. In order to operate without significant voltage drop in the wires or head loss in the cooling tubes, the diameter of these conduits would be significantly larger than if the accumulator was closer to the motor and inverter. At first, the favorite of these locations was to mount the accumulator system in the trunk. As a result, we lidar scanned the trunk and fuel tank locations, and began early design on a potential system (Figures 16, 17, and 18).

Figure 16. A photo of the car with the trunk lid and fuel tank removed

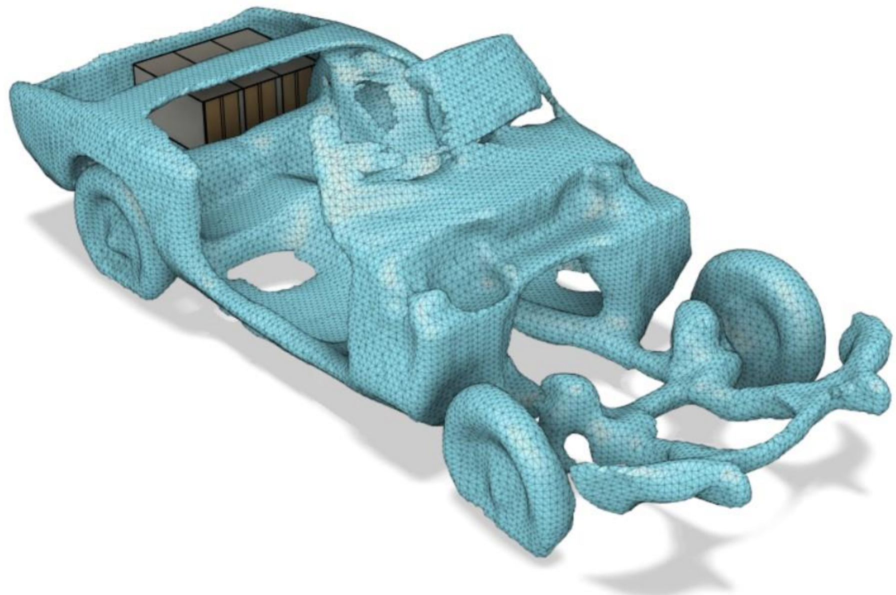


Figure 17. A Lidar scan of the car with an early accumulator design in the trunk location.

Figure 18. A close up photo of the trunk with the trunk lid removed

However, after further consideration we realized some of the disadvantages of the trunk-mounted battery unit, as well as some of the advantages that a front-end mounted battery pack could provide. One of the strongest considerations was that despite offering such great environmental protection, the trunk has no frame underneath it. This means in the event of a rear-ended crash there is very little protection for the battery unit. Advantages of placing the battery unit under the hood are fairly numerous as well, for one it would require far less conduit (both linearly and cross sectionally) and would suffer fewer losses due to the inefficiency of transmitting high amperage over long distances. The primary driving factor in the decision, however, was the resulting weight distribution. The accumulator unit amounts to roughly 260lbs. By placing this weight in the trunk, we calculated that the Triumph would be roughly balanced about the rear wheels. This would result in a lack of steering and braking capabilities at the front of the vehicle. We considered this to be absolutely unacceptable, and as such decided to place the accumulator unit under the hood. Unfortunately, this location does present challenges as well. We knew it would be difficult to create and maintain a stable environment for the battery units in the exposed area of the engine bay and, in addition, we bore in mind the results of a potential front-end collision throughout the design process. Finally, and perhaps most challenging, we were extremely pressed for space under the hood. All in all, our accumulator unit will have to fit in an area roughly 20” x 24” x 10”. As a result, we lidar scanned the front of the car and began initial development of configurations which might fit all six battery units.

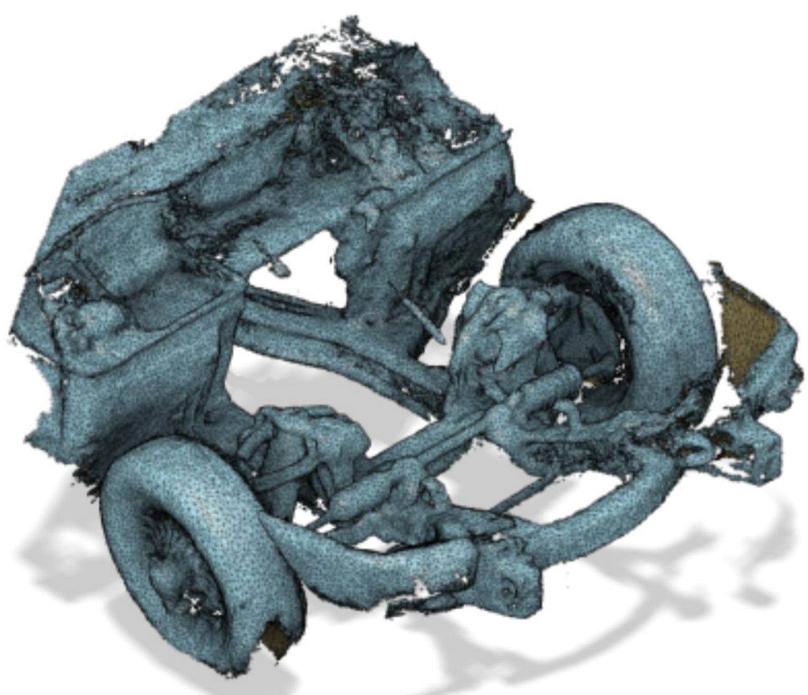


Figure 19. Lidar Scan of the front end of the car

Figure 19 shows a lidar scan of the front area of the car with the hood removed. These lidar scans proved to be critical in development as they gave us an in-depth assessment of the location of all of the OEM equipment. In addition to using these lidar scans, we were able to rapidly determine potential positions for our battery units. Figures 20 and 21 show two potential configurations that we did not end up using due to packaging challenges.

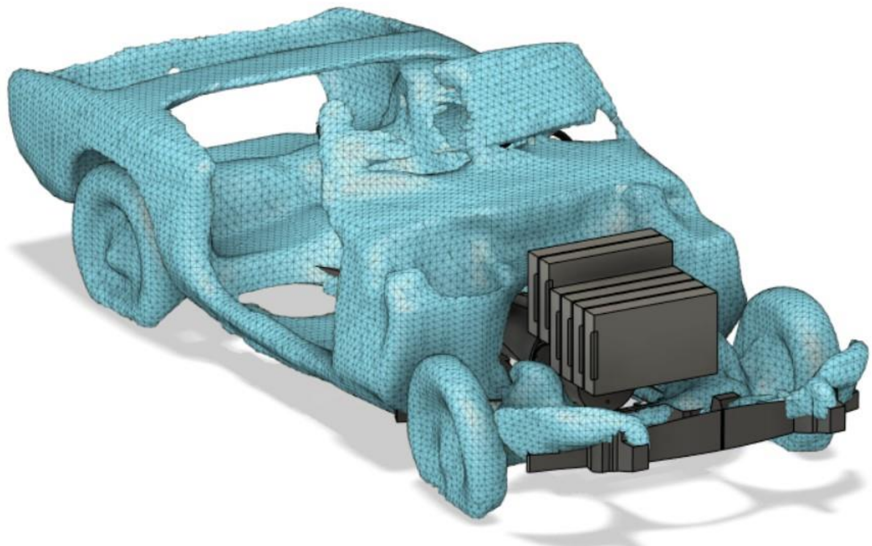


Figure 20. An initial configuration of batteries under the hood

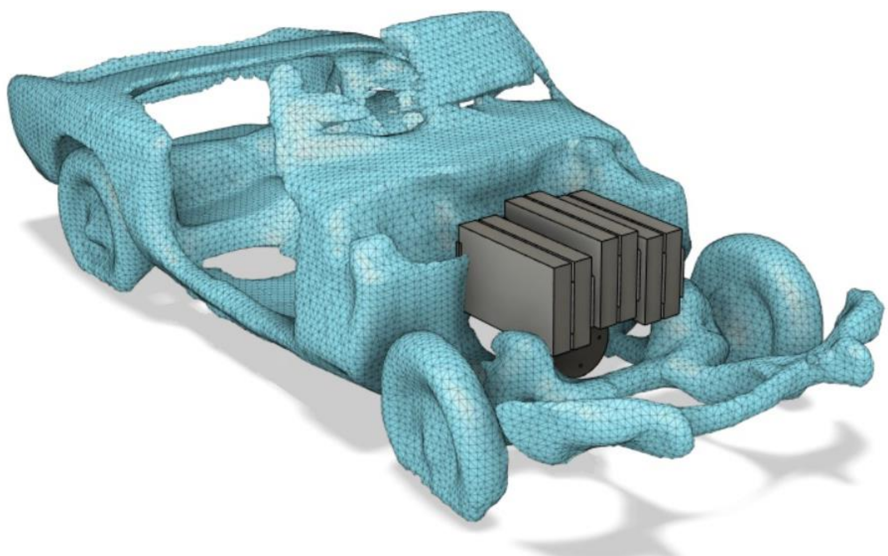


Figure 21. An initial configuration of batteries under the hood

Figure 22. A photo of the front end of the car with the engine removed

Figure 22 shows the front end of the car with the hood removed, note the close accuracy to Figure 19. After many rounds of testing different battery configurations, we arrived at the design which can be seen in Figure 23. This design maximized height in the Z axis and allowed us to fit the full stack of six batteries under the hood. This configuration only gave us about an eighth of an inch of space from the front top lip of the batteries to the underside of the hood. As a result, mounting and housing the batteries as well as integrating cooling systems and electrical equipment proved to be a significant challenge in the implementation of this design.

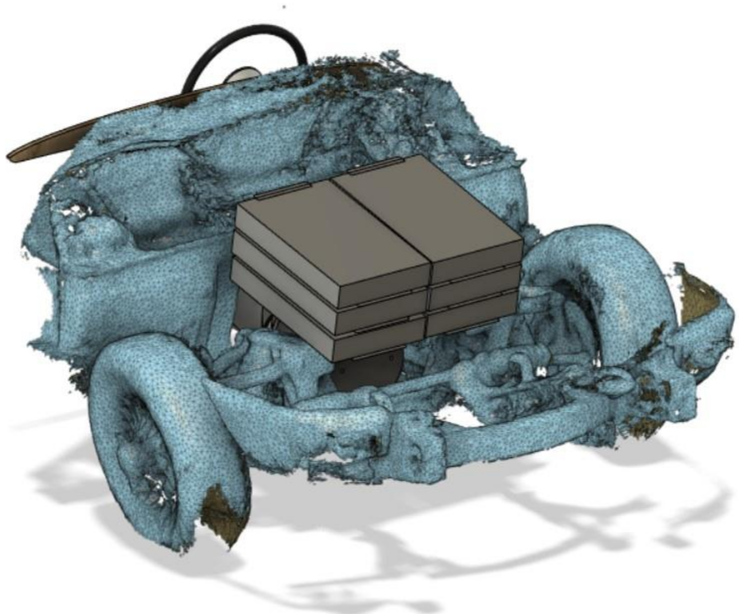


Figure 23. Final configuration of battery modules

Figure 24 shows the front end of the car with the engine removed. In order to mount the battery packs in the configuration we chose and Figure 23, the battery unit would have to fit above the engine mounts which can be seen in the center part of the photo but below the hood which can be seen at the top of the photo.

Figure 24. Photo of the space underneath the hood with engine removed

Figure 25. Initial testing of battery box sizing

To confirm our CAD models, we made a mockup accumulator out of cardboard and placed it in the car, which can be seen in Figure 25. This cardboard model fit as we expected it to, with roughly an eighth of an inch of clearance from the top of the box to the hood and roughly an eighth of an inch of clearance from the bottom of the box to the motor. Following this we felt we were in a good enough position to continue designing our accumulator interior modules and exterior housing.

Accumulator Module Design

We considered a number of potential designs which could be capable of housing our individual battery modules. Throughout the design process, we began by drawing up designs that were primarily concerned with space utilization and functionality. After this, and by running thermal analysis on these designs, we considered different approaches to the thermal challenges presented by our designs. Our team determined that a liquid cooling system for the battery unit would be more than capable of keeping the temperature of the battery modules well regulated.

In order to allow maintenance and future development, we decided the best housing method would be to build liquid cooling plates into the battery ‘modules’ (further design for these liquid cooling plates can be found in the pages 33 and 34). Using this module design, the whole unit (battery and cooling equipment) could be inserted into the accumulator housing. Our finalized design contains six of these ‘modules’ that would fit into the single accumulator housing.

Figures 26 and 27 depict one of the first designs we drew up. It demonstrates the cooling plate integrated into the battery housing such that both units combined create a single battery 'module'. This model was designed to slide on rails into and out of the accumulator housing. This model would have relied heavily on 3D Printing components such as the rails and flanges (shown in light gray). We ultimately shelved this model due to the slow nature of 3D printing and relatively poor strength and finish quality.

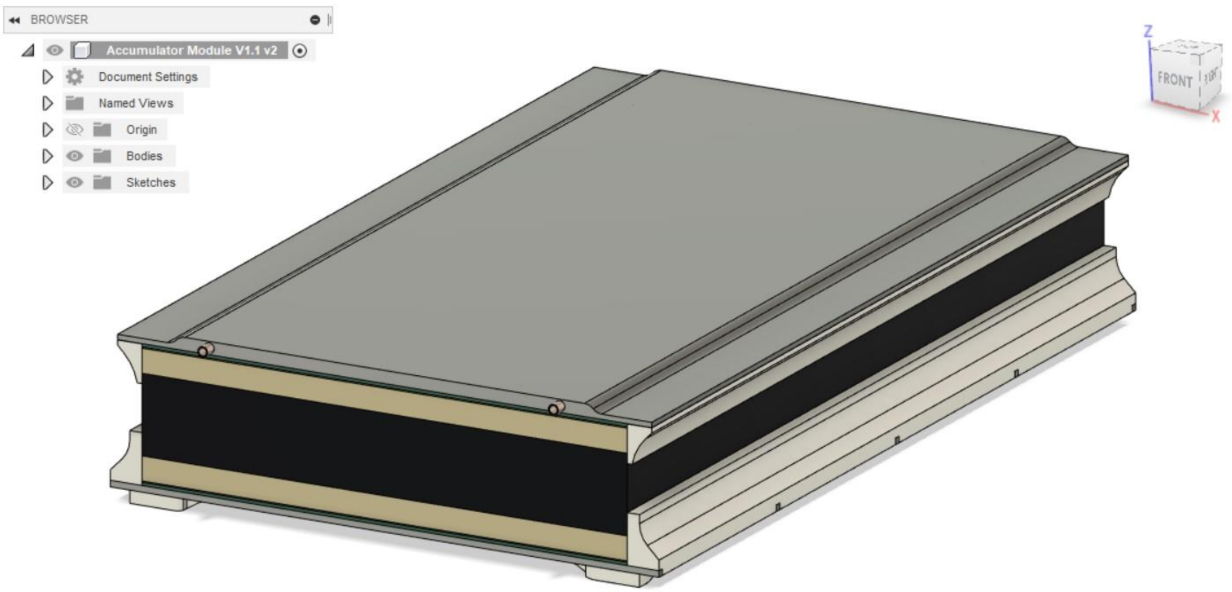


Figure 26. Battery Module v1 Top

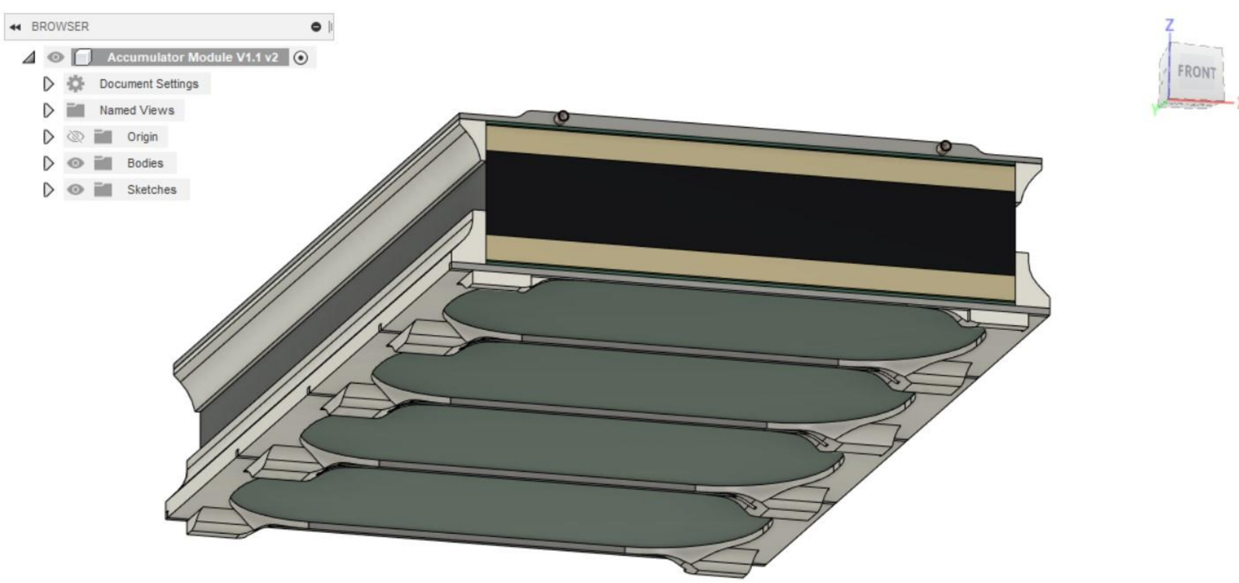


Figure 27. Battery Module v1 Bottom

In Figures 28 and 29 the tessellating nature of the battery modules can be seen. This tessellation was essential in all of our test and final designs. By designing the modules such that they can be tessellated, we were able to optimize the space the batteries took in the Z Direction. This optimization was considered essential ever since we measured the available space under the hood.

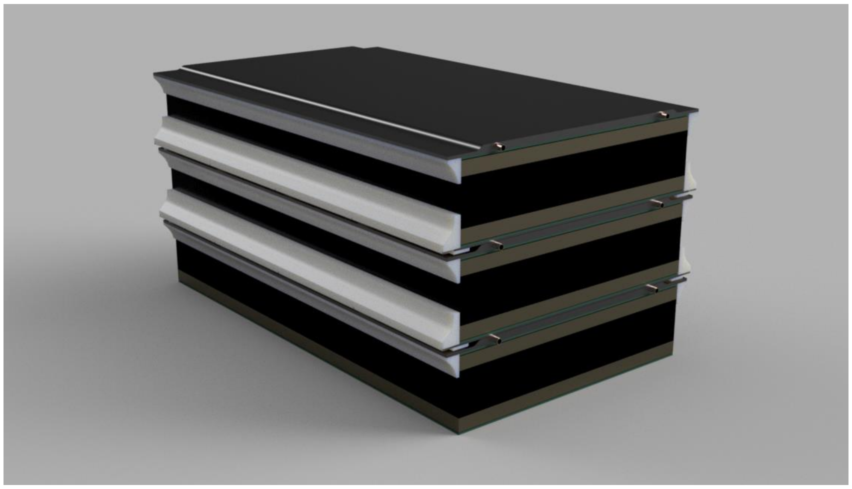


Figure 28. Battery Module V1 tessellated isometric view.

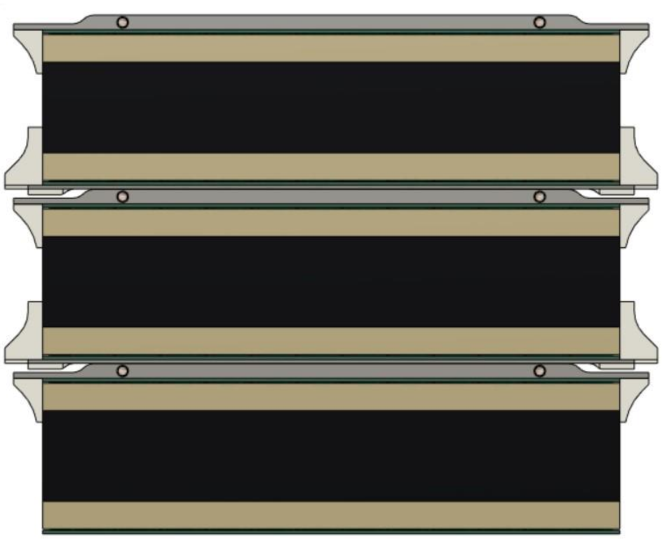


Figure 29. Battery Module V1 tessellated front view.

We decided the best course of action would be to switch to a design that was accommodating to manufacturing. As a result, we began early development on a design that relied almost purely on 2D cuts that could be accomplished on a laser cutter. Each of the red cells below demonstrate the positive (+) end of an 18650, while the blue cells demonstrate the negative (-) terminal. This configuration would allow our team to make the necessary modules on a laser cutter and then adhere the module together with COTS adhesives. This manufacturing and fabrication process would be significantly easier than having to rely on 3D printing or milling of plastic. The first of these designs can be seen in Figures 30 and 31.

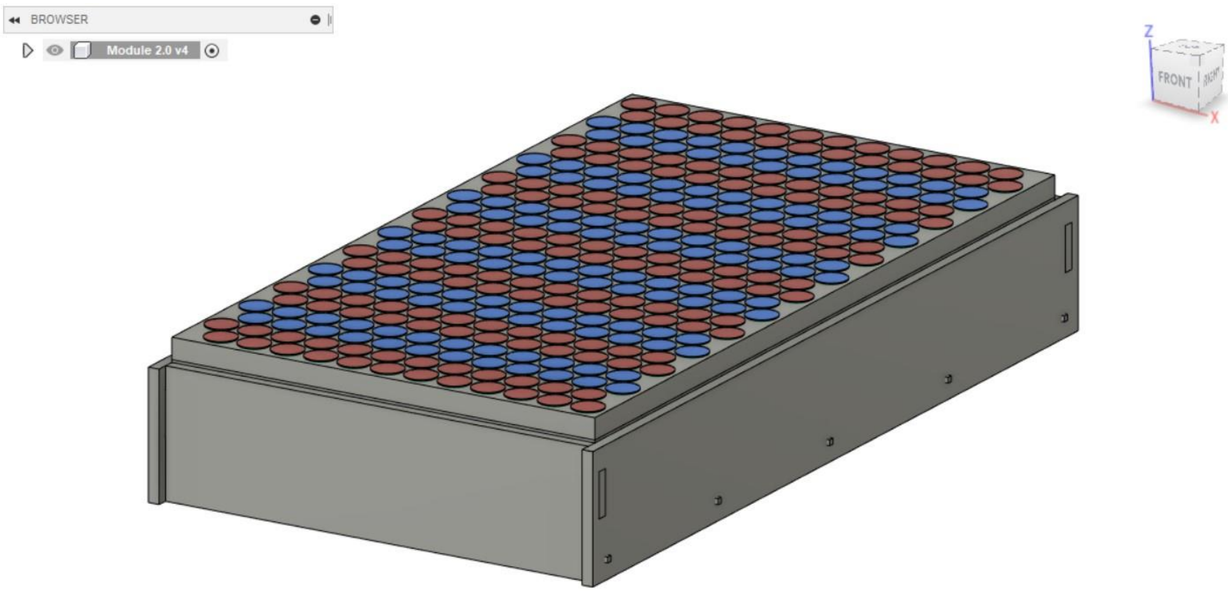


Figure 30. Battery Module v2 Top

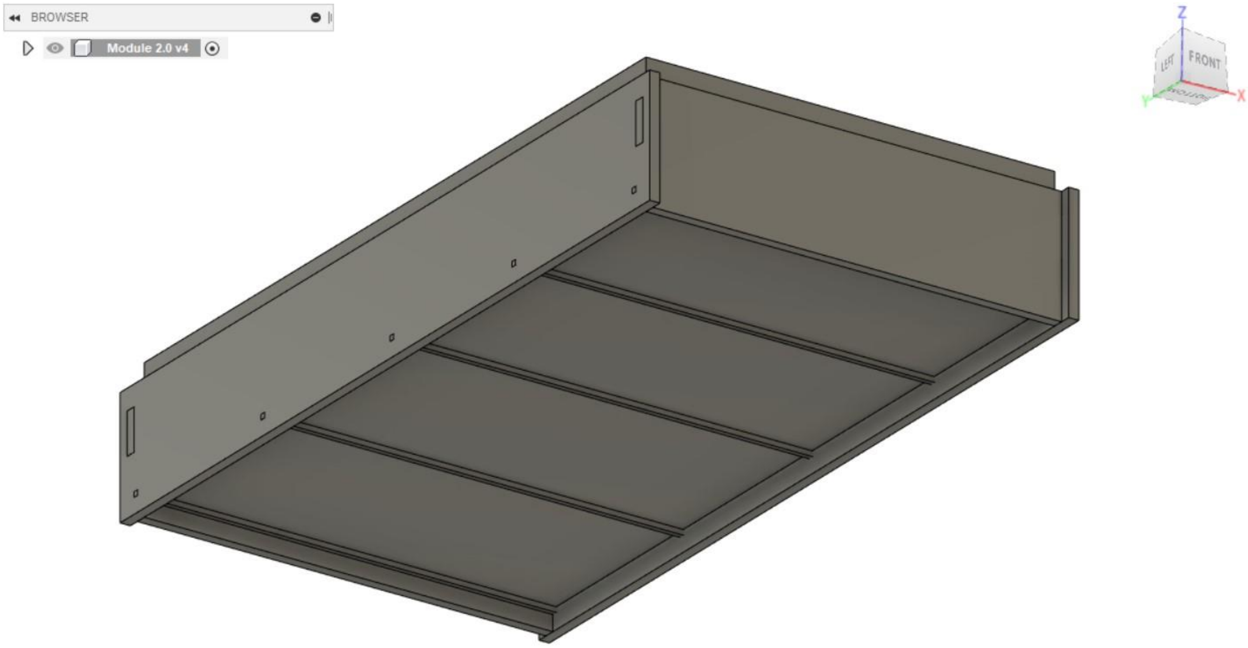


Figure 31. Battery Module v2 Bottom

Each of our designs use an electrically insulating material on the bottom and top faces of the battery. Commonly known in the industry as "thermal interface material", we've researched a number of options including FR4/G10, Nomex, and Formex. Underneath the designs in Figures 26 and 27, as well as Figures 30 and 31, run lengths of ⅛" steel key stock to provide support to the bottom sides of the battery module structures for a low cost of roughly $1 per length. With this design and some optimizations our team was close to being able to fit the entire accumulator within the required space of roughly 20" x 22" x 10".

In addition to the individual module designs we also considered designing the accumulator housing overall to integrate the batteries more holistically. Some of these designs can be seen below in Figures 32 and 33. Figure 32 was an early idea of using C-channels in a tiered design. These channels provide environmental housing as well as thermal isolation for the battery units. In this tier design there would be two packs of batteries and the top, middle, and bottom sections resulting in three pairs of two modules each.

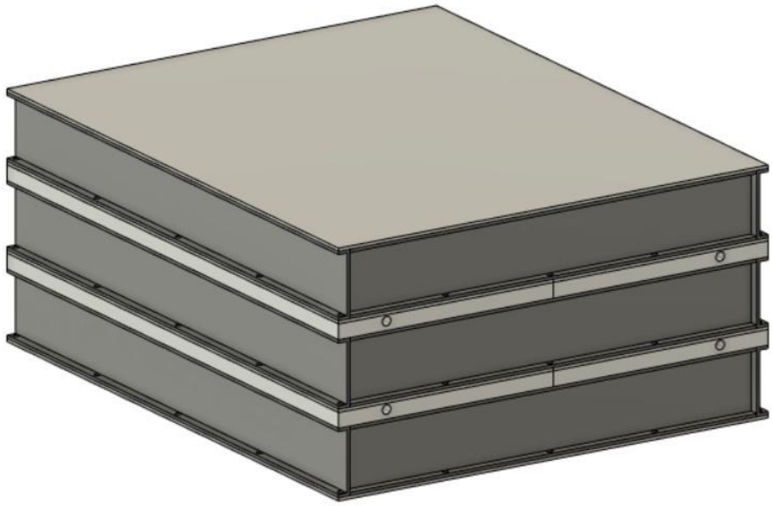


Figure 32. Battery Housings V1 Isometric View

Figure 33 was a potential design for housing the batteries in the trunk of the car. In this configuration, we considered an individual housing for each pair of batteries. This would potentially allow for hot-swappable batteries, as well as the ability to remove the modules while still in their housings for maintenance.

Figure 33. Battery Housings V2 Isometric View

Figures 34 through 37 show our final module design. This design used 2D sections of laser cuttable material adhered together to provide both structure, cable management, and easy fabrication. Figure 34 shows the bottom module of the battery pack while Figure 35 shows the stack of three modules integrated together. By removing the key stock suggested in Figures 26, 27, 30, and 31, it can be seen in Figure 35 that we were able to optimize the height such that each battery pack rests directly on top of and underneath one of the cooling plates.

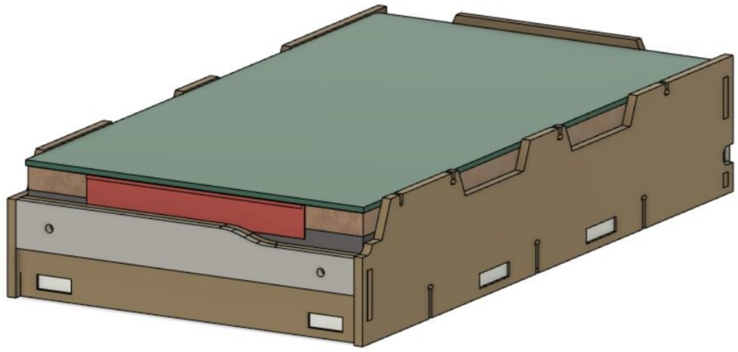


Figure 34. Bottom module of the final battery design

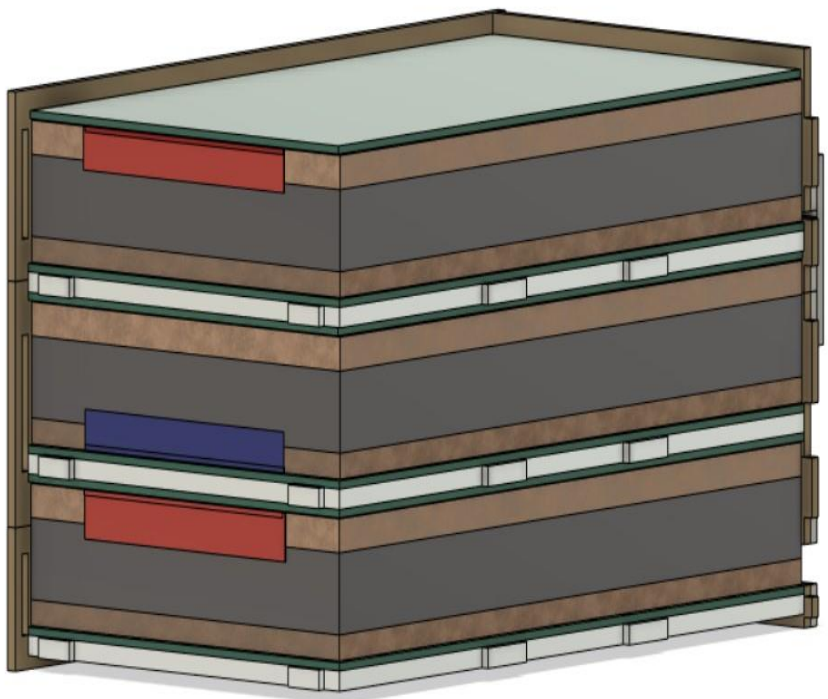


Figure 35. Final Module design tessellated into a 'Stack'

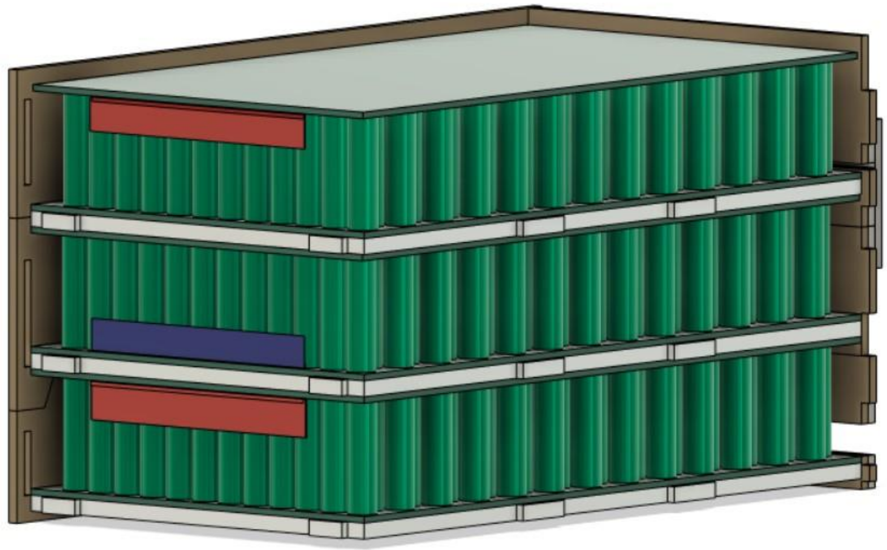


Figure 36. Photo showing the cell density in the final battery design

Figure 36 shows the cell density per volume and interior configuration of our final design. Figure 37 shows the overall design assembled.

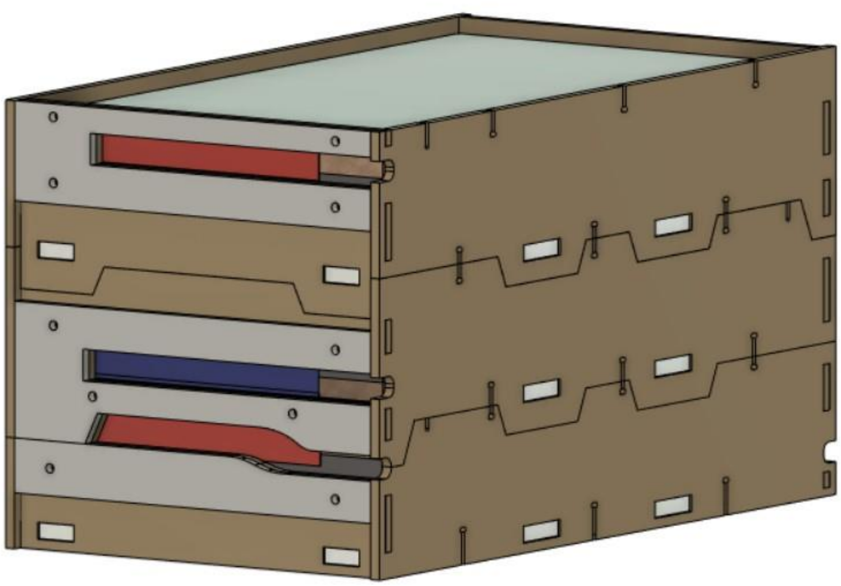


Figure 37. Isometric view of the final battery design

In order to cool the battery cells, we designed the cooling plates in Figure 38. The cooling plates we designed consisted of an aluminum plate 3/8 of an inch thick which we milled to size. We then used a ball end mill to cut a channel in the aluminum and inlay copper tubing. This allowed our team to create a liquid cooling plate without having to worry about manufacturing seals or resultant leaking. The result can be seen in Figures 38 and 39.

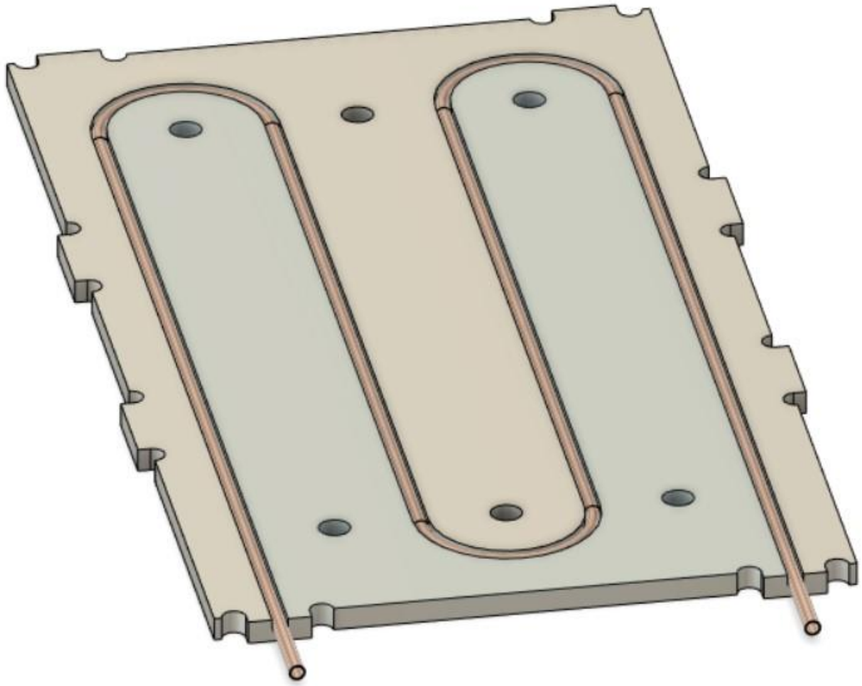


Figure 38. Isometric view of the final cooling plate design

Figure 39. Cooing plates after machining

After manufacturing the cooling plates and laser cutting the material, we began assembly of the battery pack shown in Figure 40. It can be seen that the lowermost and middle modules were fully integrated at this point while the top module housing was in place without the batteries. The cable management regarding the lowermost battery is mostly completed while the middle battery is in progress at the time of this photo. On the leftmost side of the figure some of the copper tubing for the liquid cooling plates can be seen.

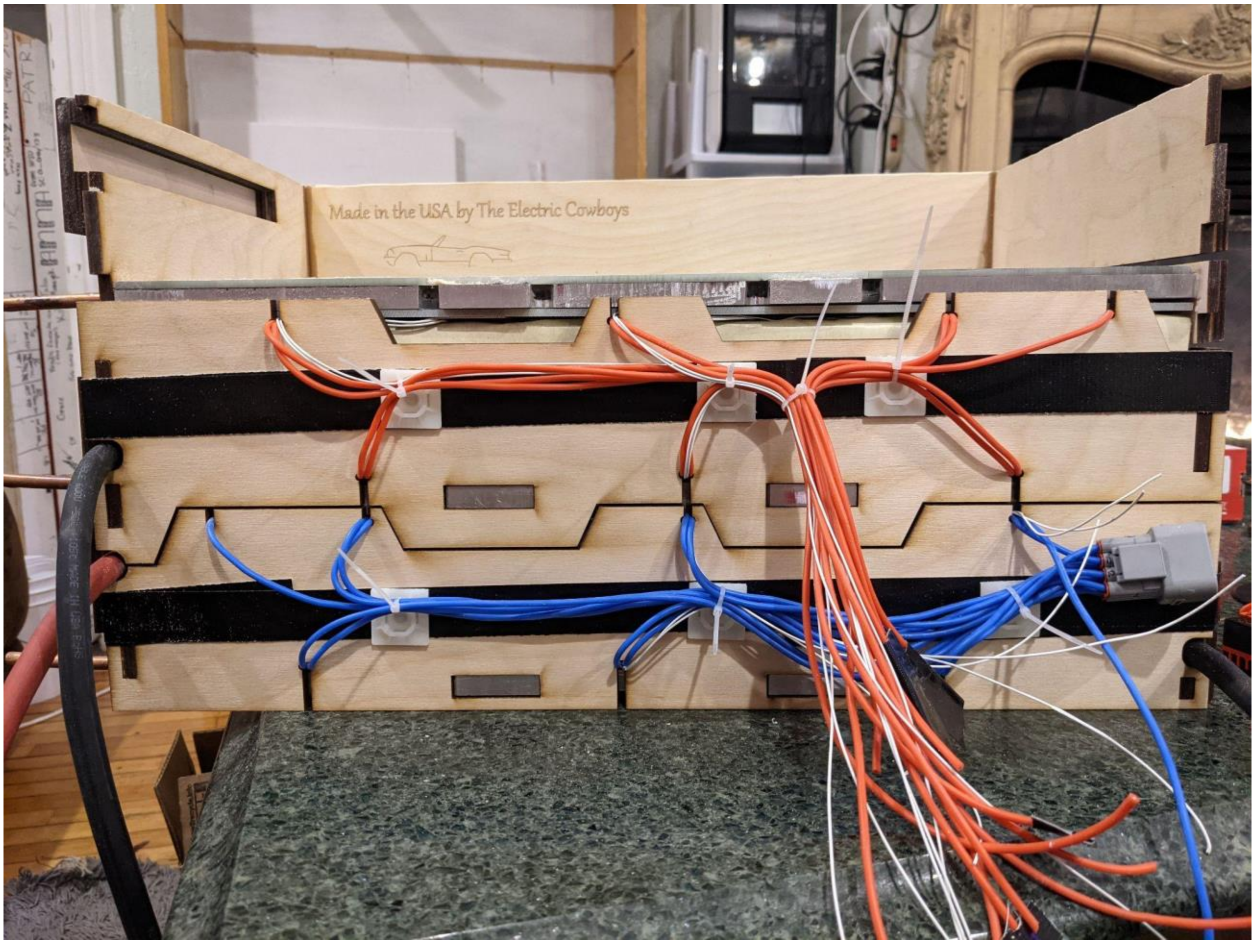


Figure 40. Mid way through final assembly of the battery modules

Accumulator Housing Design

We considered a number of designs for housing the batteries. The primary criteria for these designs were minimal additional material, while maintaining a safe buffer from the environment as well as protection in the event of a thermal runaway. Figures 41 through 43 show an early design of a potential battery housing using active cooling with heat pipes and Peltier modules. This was a configuration that was initially considered after the location proposed in Figure 20 however this design was scrapped once we finalized the location of the battery packs to the location proposed in Figure 22.

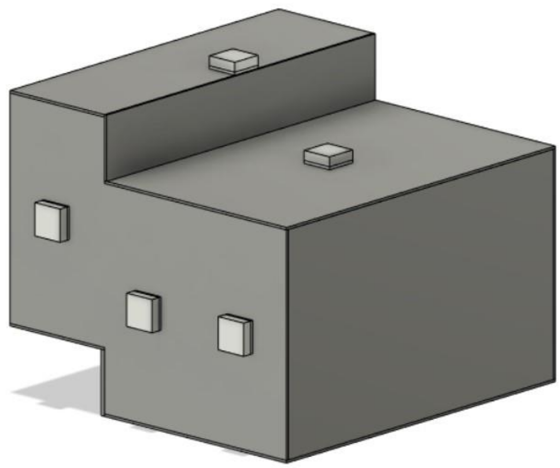


Figure 41. An early design of a potential battery housing

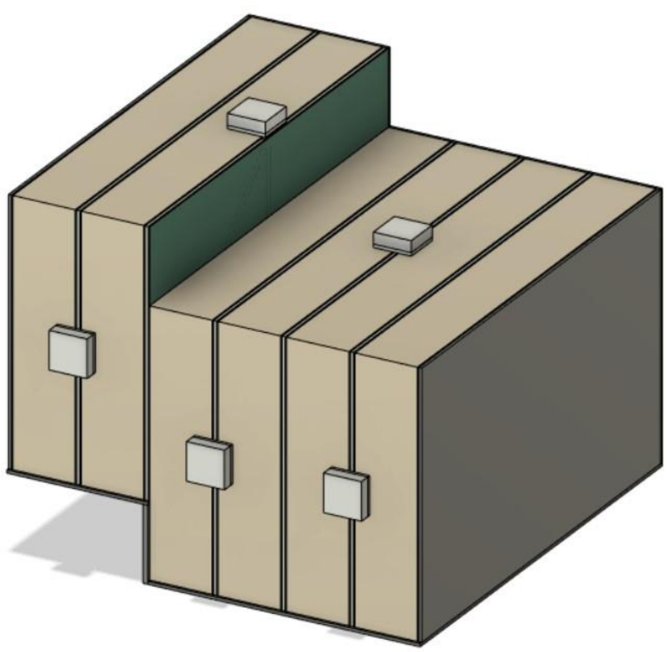


Figure 42. An early design of a potential battery housing

Figures 42 and 43 show cutaways of the proposed battery housing. This vertical module design would allow increased accessibility from maintenance and access to the cell modules. In Figure 43 it can be seen that the cooling plates would be significantly thinner with embedded heat pipes conducting heat to Peltier modules on the outside of the box. This was a relatively novel design using significant amounts of energy to actively cool or heat the battery to an exact requested temperature.

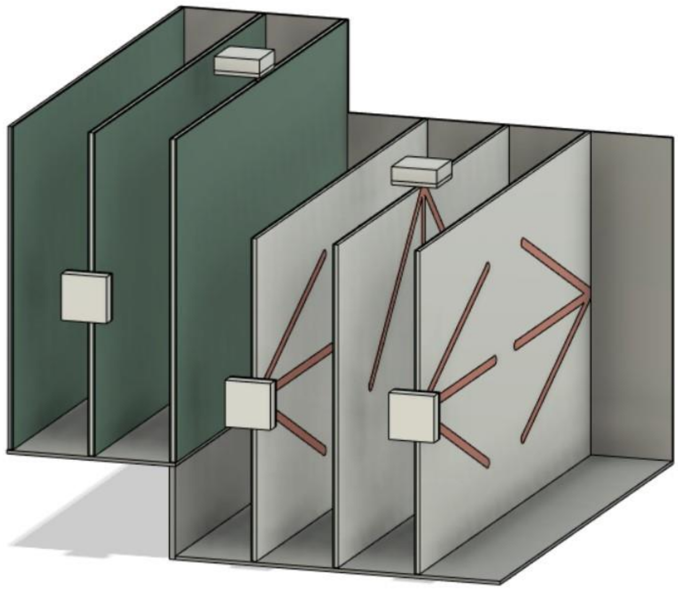


Figure 43. An early design of a potential battery housing

Ultimately, we decided not to go with this design both due to its untested nature as well as the difficulties in manufacturing and packaging. Our finalized design can be seen in Figure 44. This was a relatively simple 1/16” sheet steel housing. We designed this for simplified manufacturing and fabrication as well as integration. We submitted the designs in Figures 44 through Figure 60 to local fabrication shops.

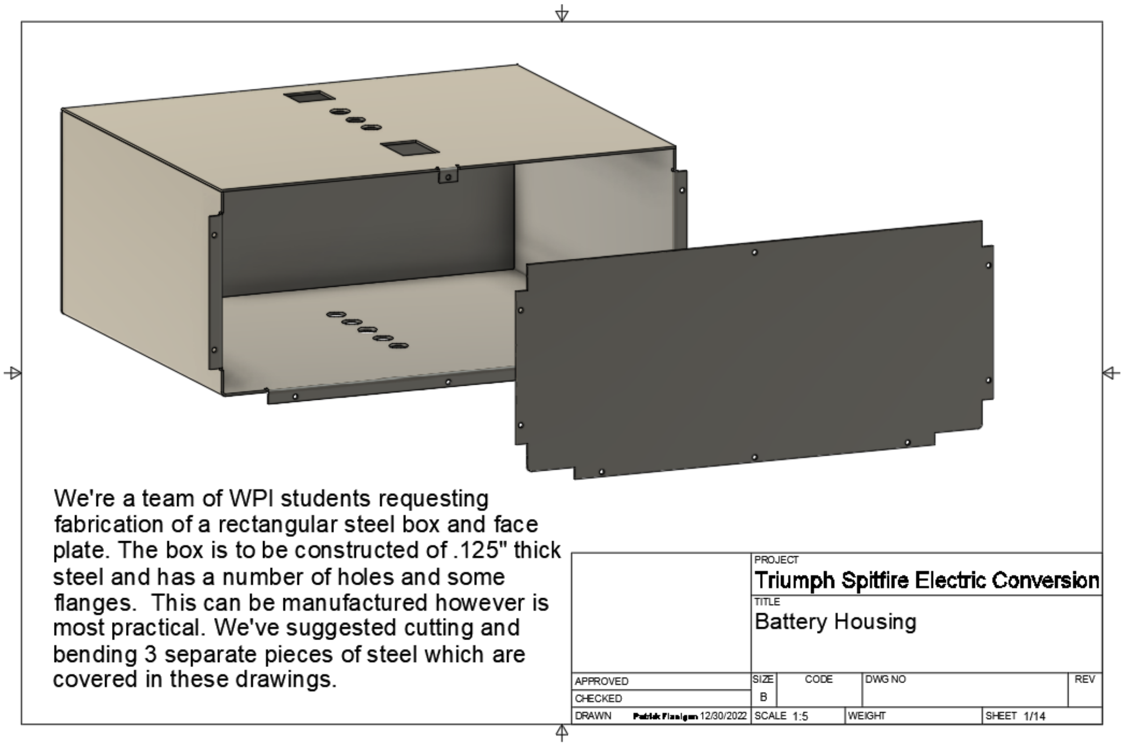


Figure 44. The Final Designs of the Battery Housing Submitted to Fabrication Shops

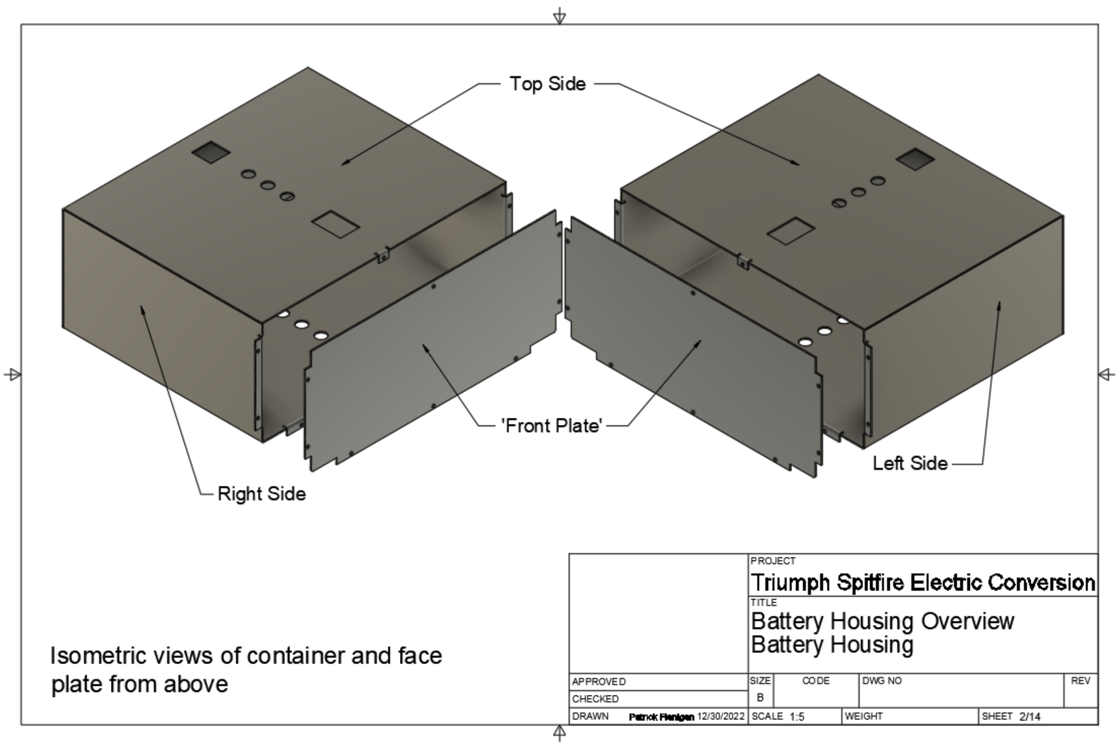


Figure 45. The Final Designs of the Battery Housing Submitted to Fabrication Shops

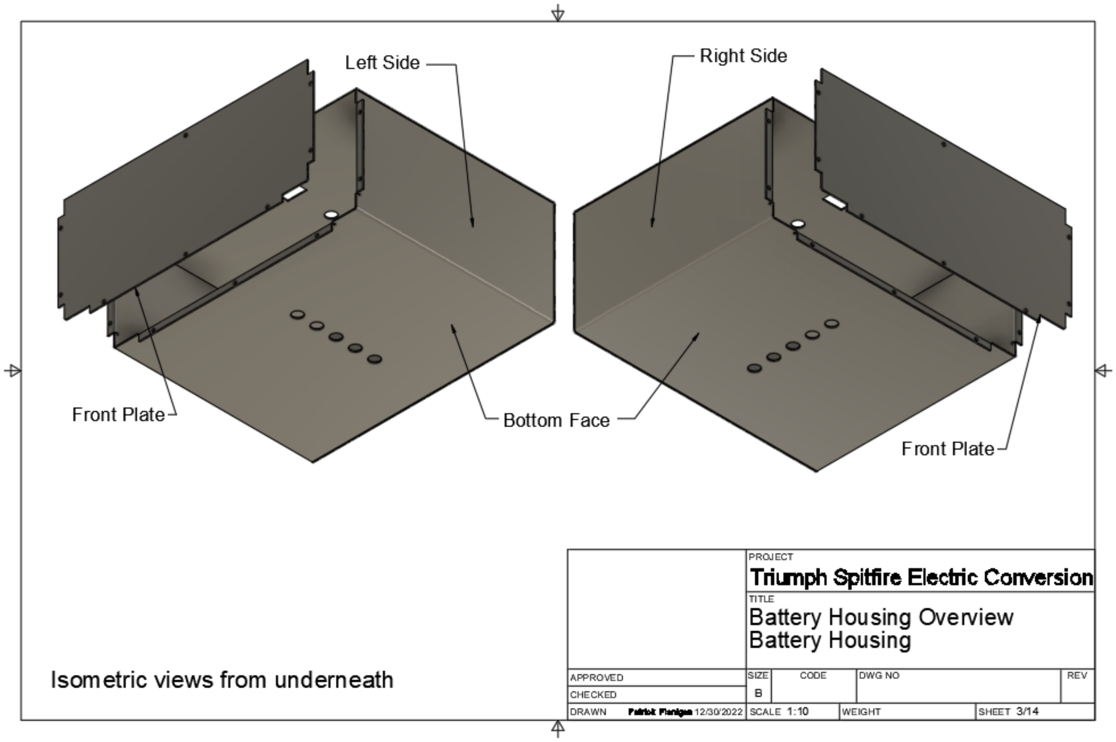


Figure 46. The Final Designs of the Battery Housing Submitted to Fabrication Shops

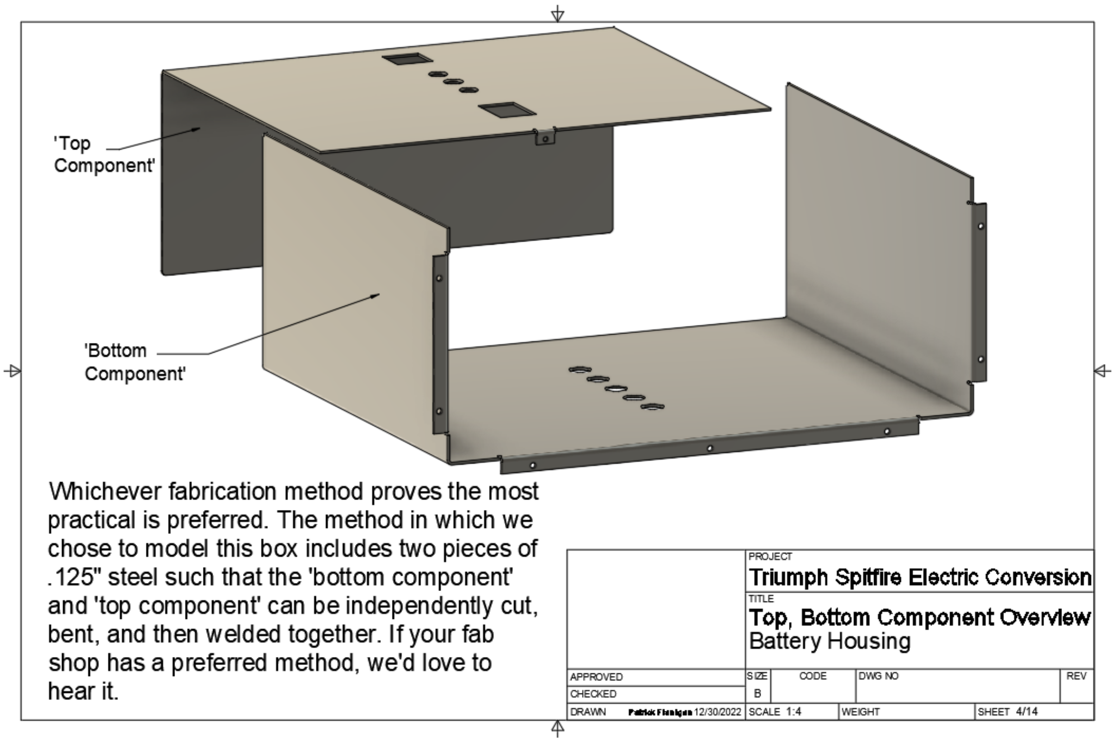
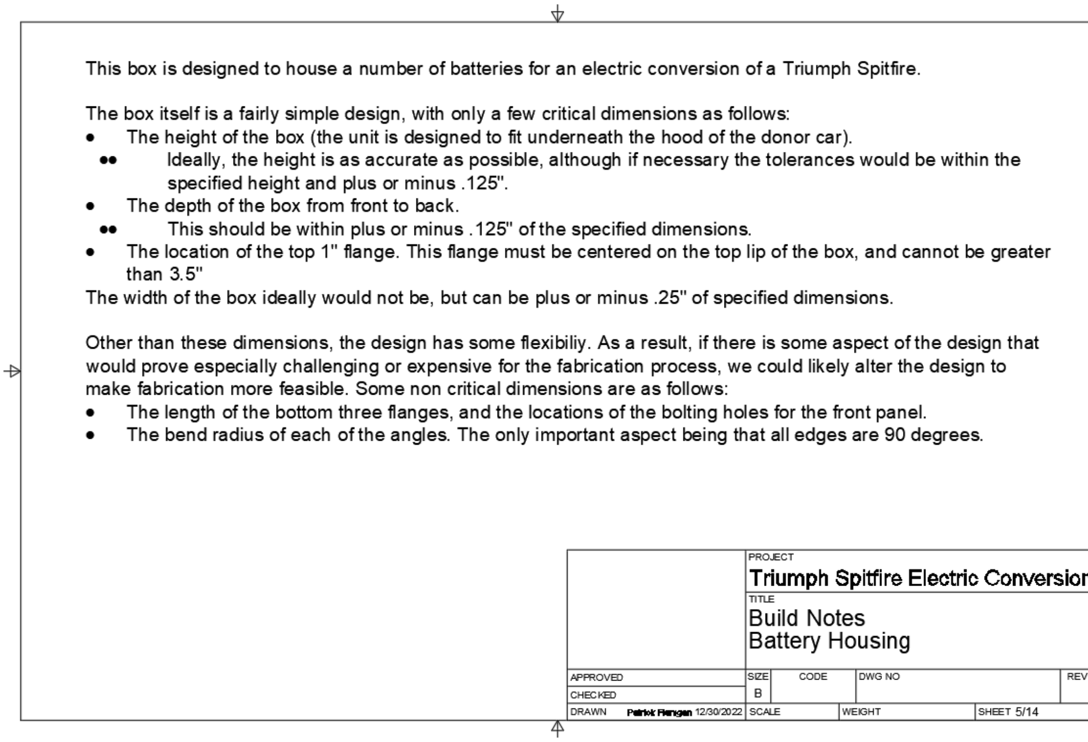


Figure 47. The Final Designs of the Battery Housing Submitted to Fabrication Shops


This box is designed to house a number of batteries for an electric conversion of a Triumph Spitfire.

The box itself is a fairly simple design, with only a few critical dimensions as follows:

- The height of the box (the unit is designed to fit underneath the hood of the donor car).
  - Ideally, the height is as accurate as possible, although if necessary the tolerances would be within the specified height and plus or minus .125".
- The depth of the box from front to back.
  - This should be within plus or minus .125" of the specified dimensions.
- The location of the top 1" flange. This flange must be centered on the top lip of the box, and cannot be greater than 3.5"

The width of the box ideally would not be, but can be plus or minus .25" of specified dimensions.

Other than these dimensions, the design has some flexibiliy. As a result, if there is some aspect of the design that would prove especially challenging or expensive for the fabrication process, we could likely alter the design to make fabrication more feasible. Some non critical dimensions are as follows:

- The length of the bottom three flanges, and the locations of the bolting holes for the front panel.
- The bend radius of each of the angles. The only important aspect being that all edges are 90 degrees.

	PROJECT Triumph Spitfire Electric Conversion				
	TITLE Build Notes Battery Housing				
APPROVED	SIZE	CODE	DWG NO		REV
CHECKED	B				
DRAWN Patrick Flanigan 12/30/2022	SCALE		WEIGHT	SHEET 5/14	

Figure 48. The Final Designs of the Battery Housing Submitted to Fabrication Shops

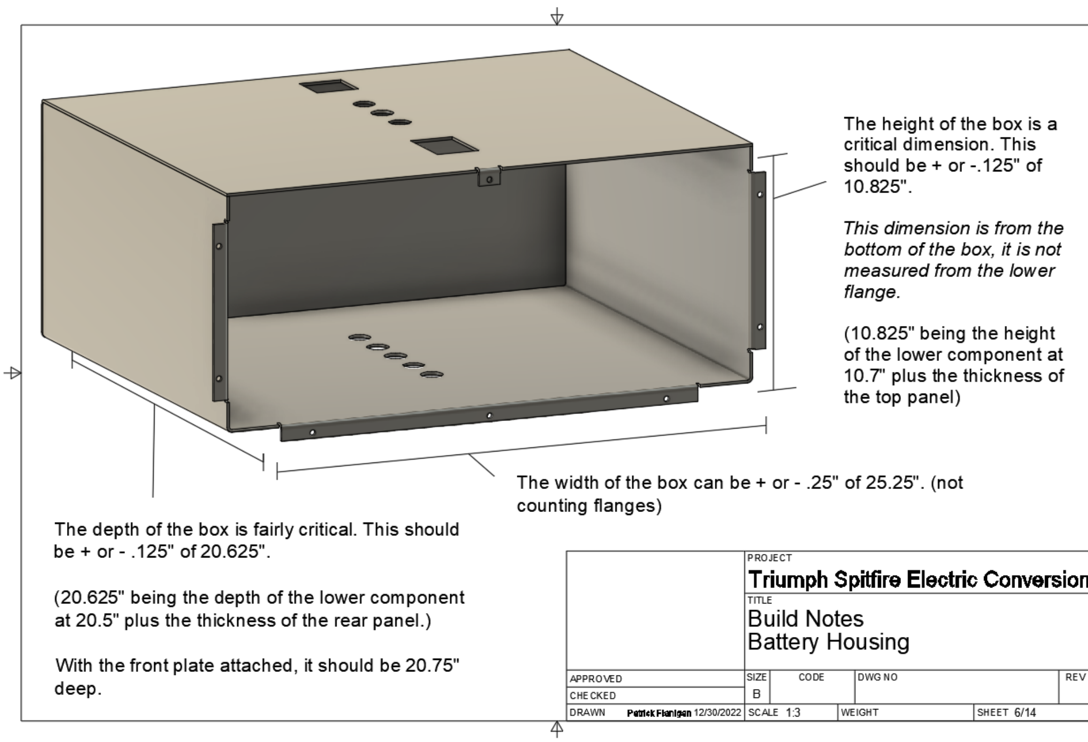


Figure 49. The Final Designs of the Battery Housing Submitted to Fabrication Shops

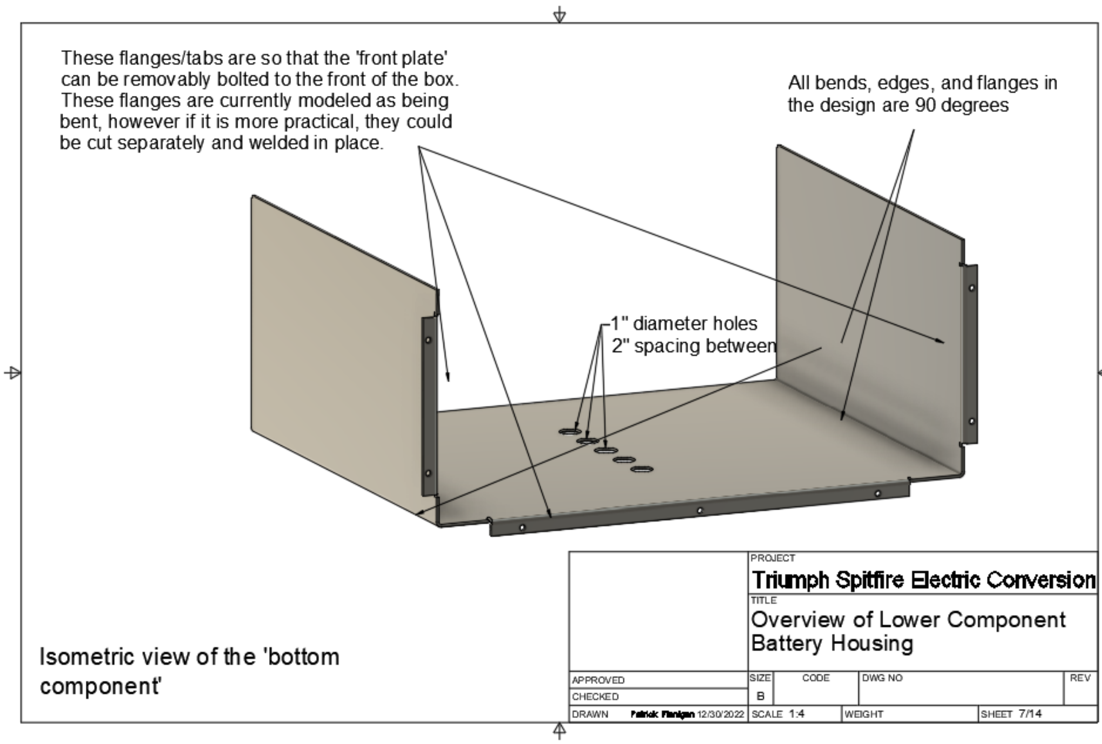


Figure 50. The Final Designs of the Battery Housing Submitted to Fabrication Shops

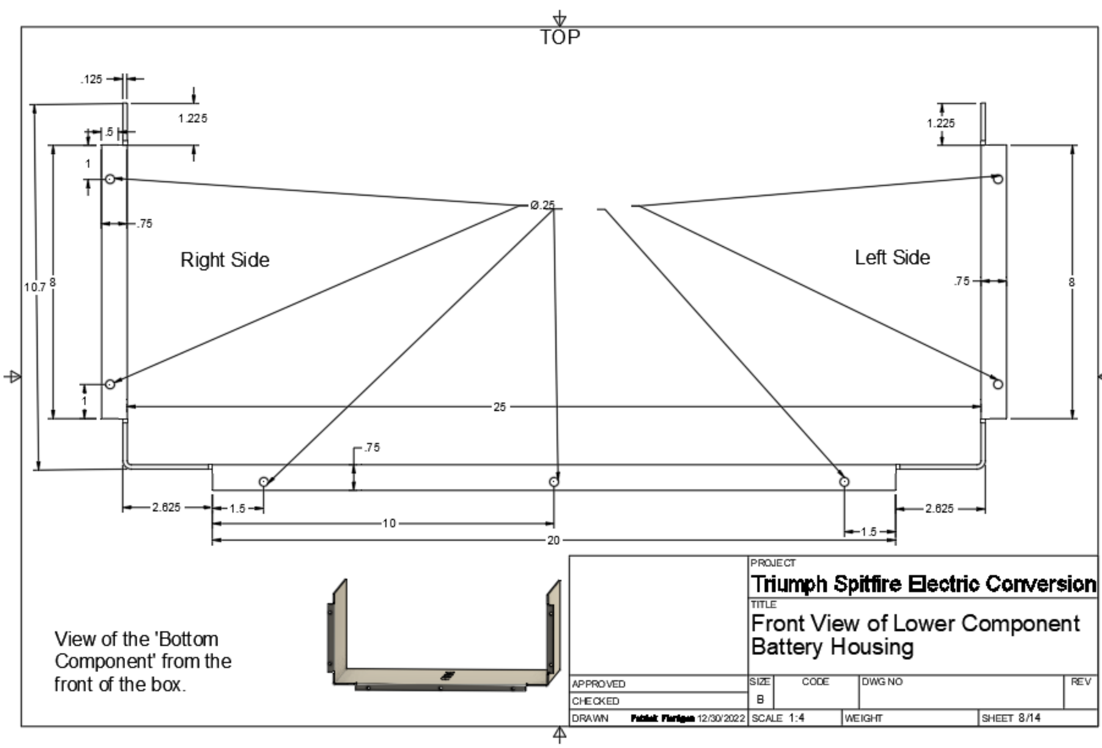


Figure 51. The Final Designs of the Battery Housing Submitted to Fabrication Shops

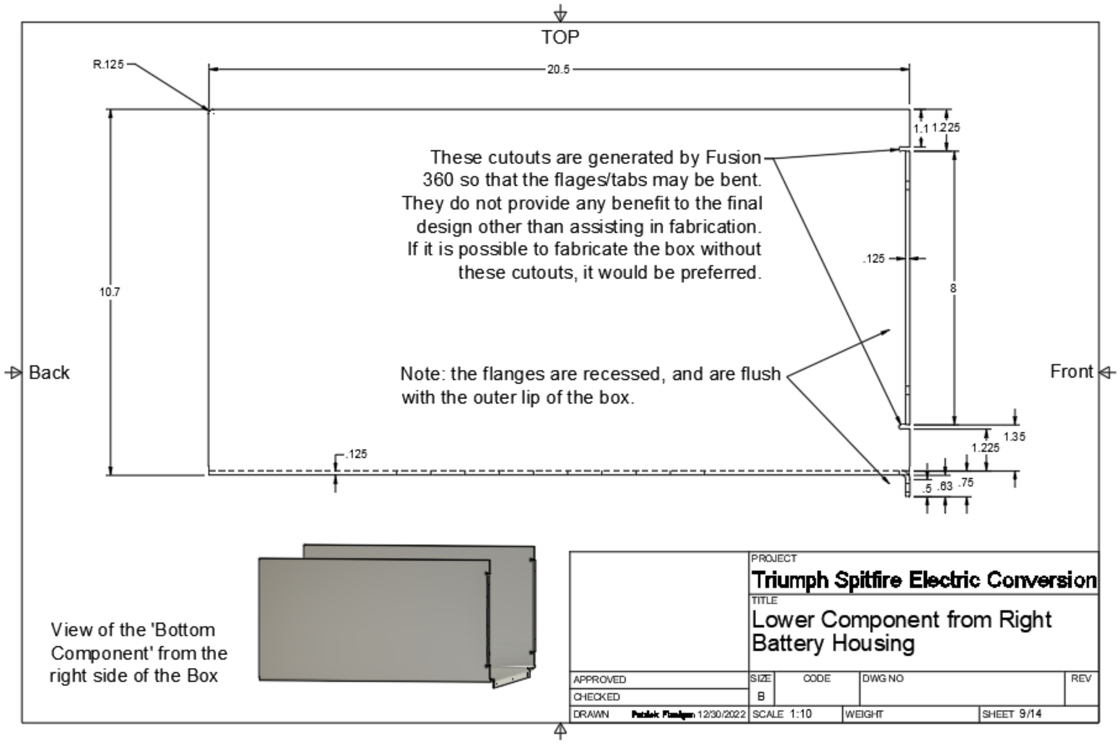


Figure 52. The Final Designs of the Battery Housing Submitted to Fabrication Shops

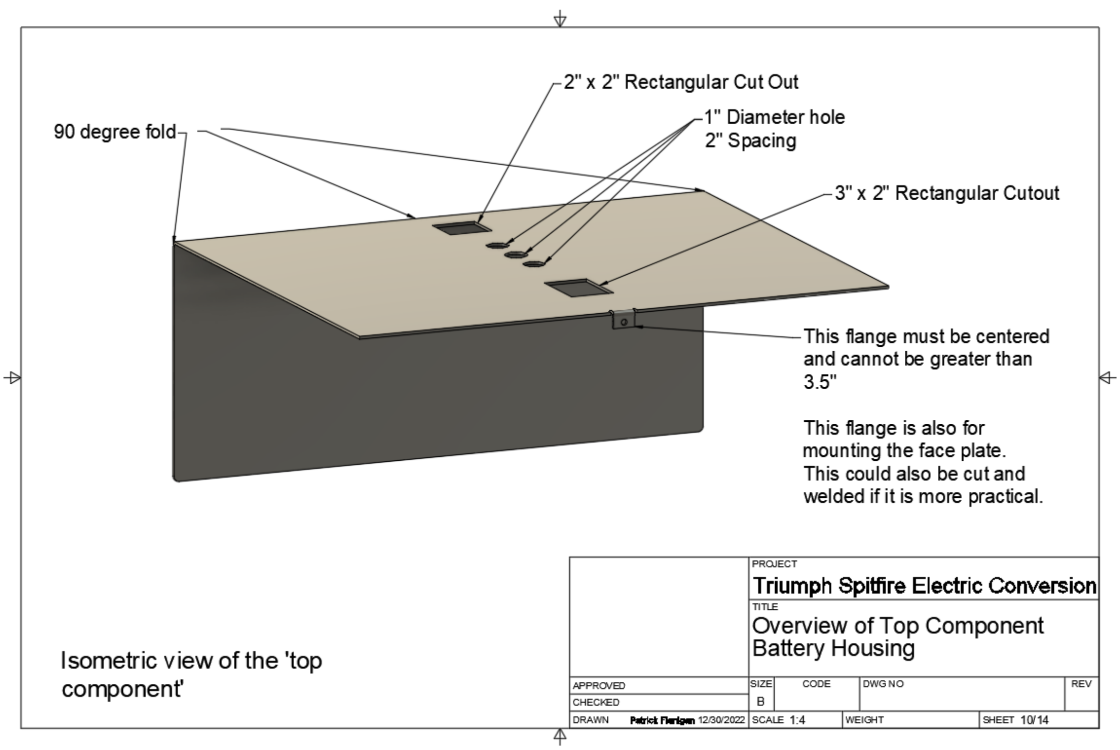


Figure 53. The Final Designs of the Battery Housing Submitted to Fabrication Shops

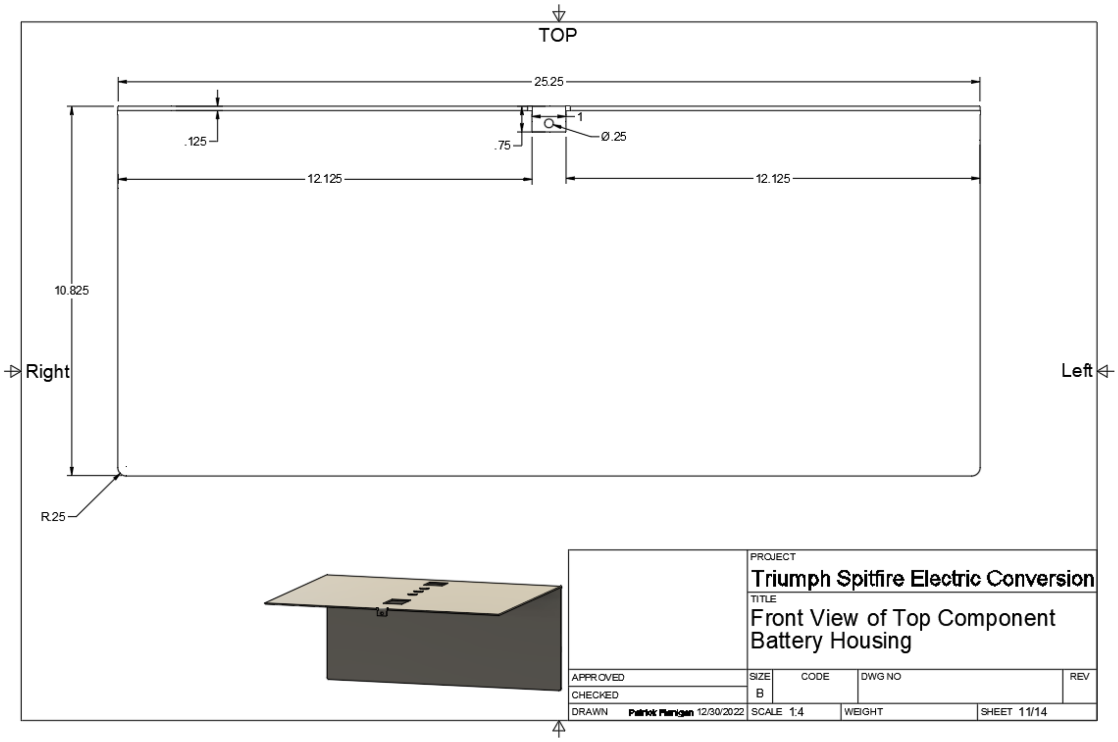


Figure 54. The Final Designs of the Battery Housing Submitted to Fabrication Shops

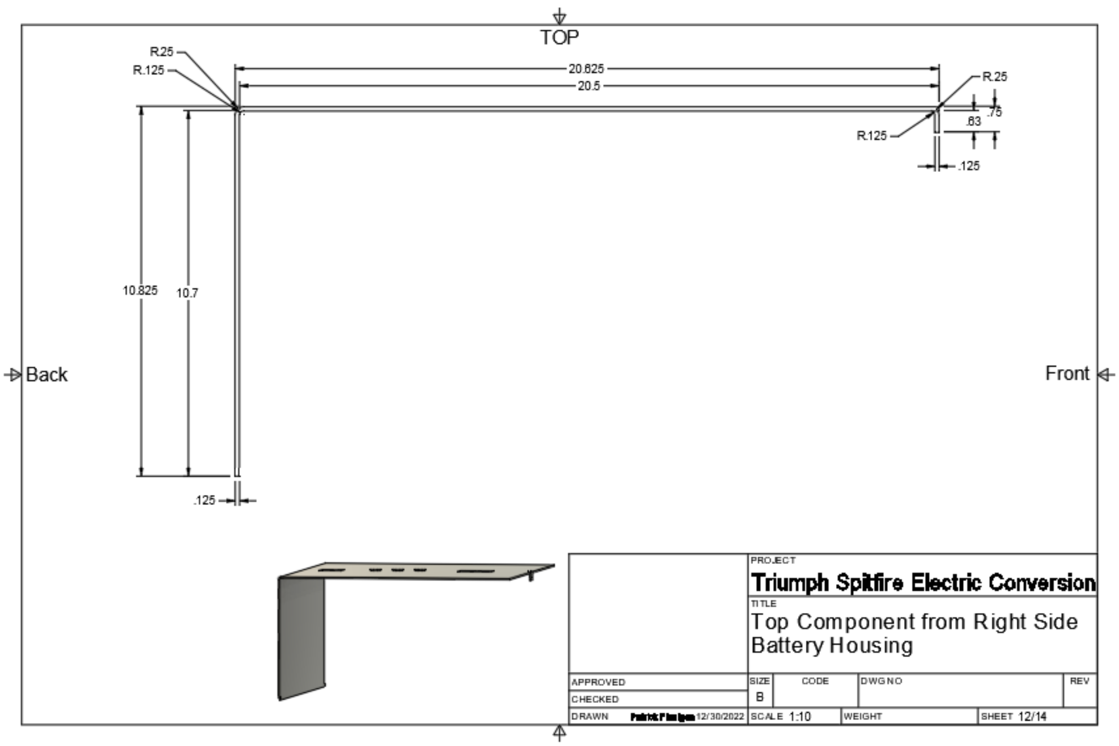


Figure 55. The Final Designs of the Battery Housing Submitted to Fabrication Shops

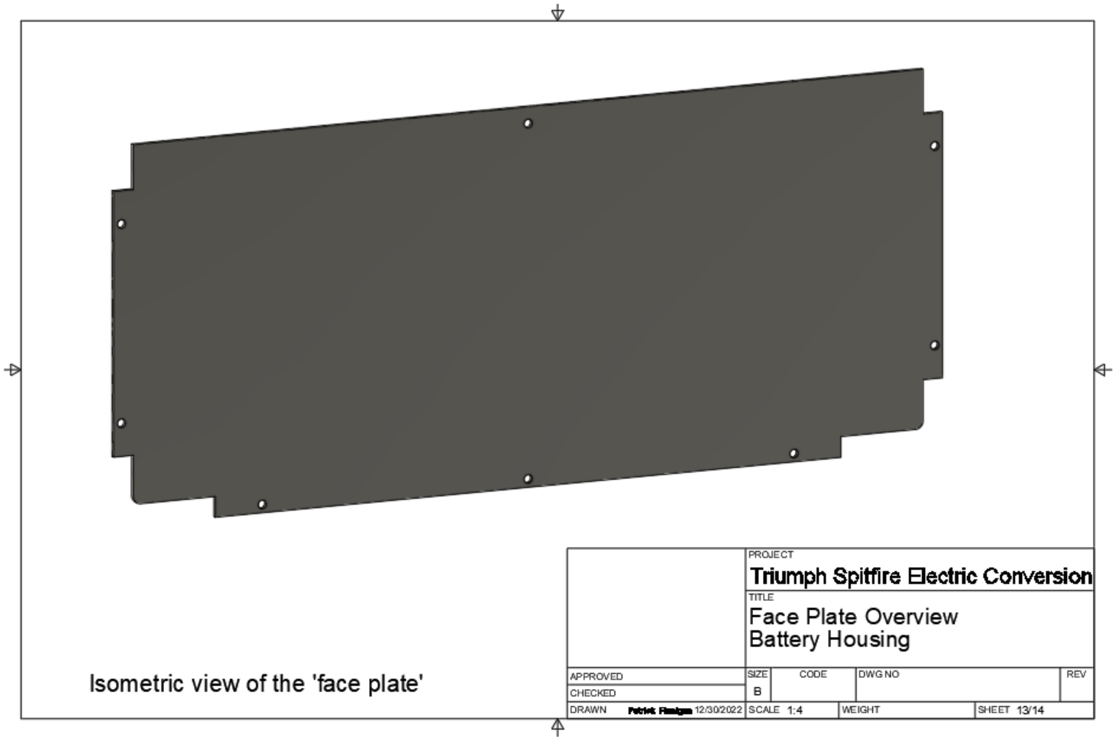


Figure 56. The Final Designs of the Battery Housing Submitted to Fabrication Shops

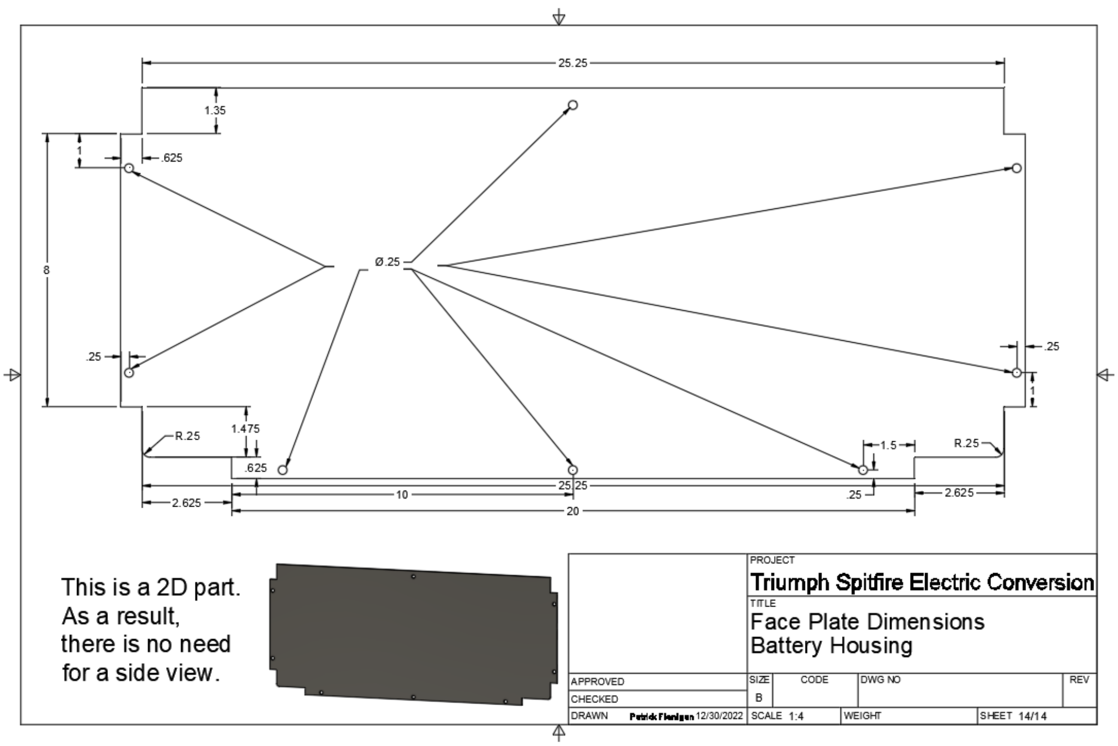


Figure 57. The Final Designs of the Battery Housing Submitted to Fabrication Shops

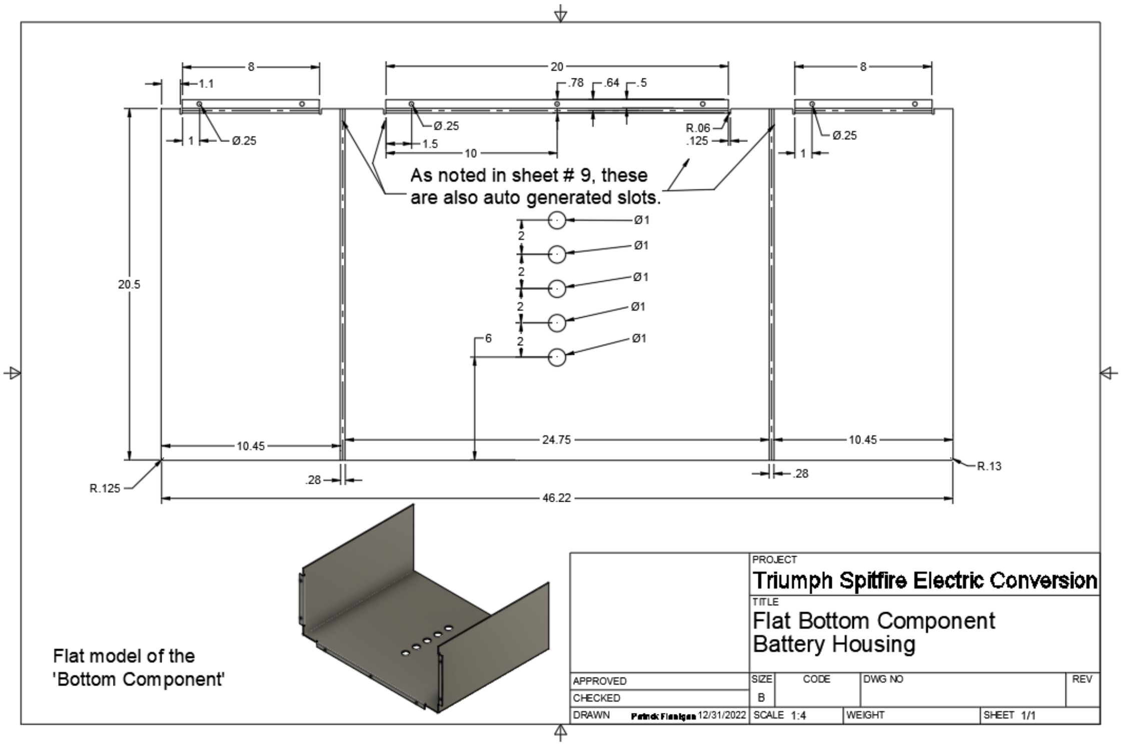


Figure 58. The Final Designs of the Battery Housing Submitted to Fabrication Shops

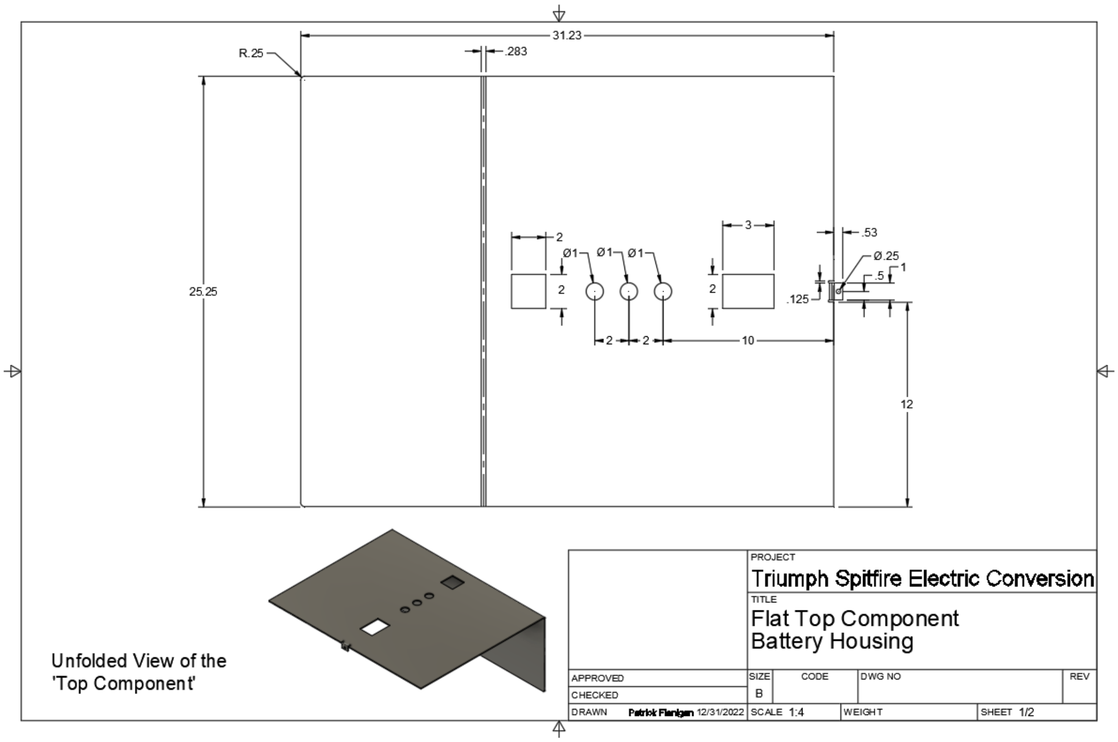
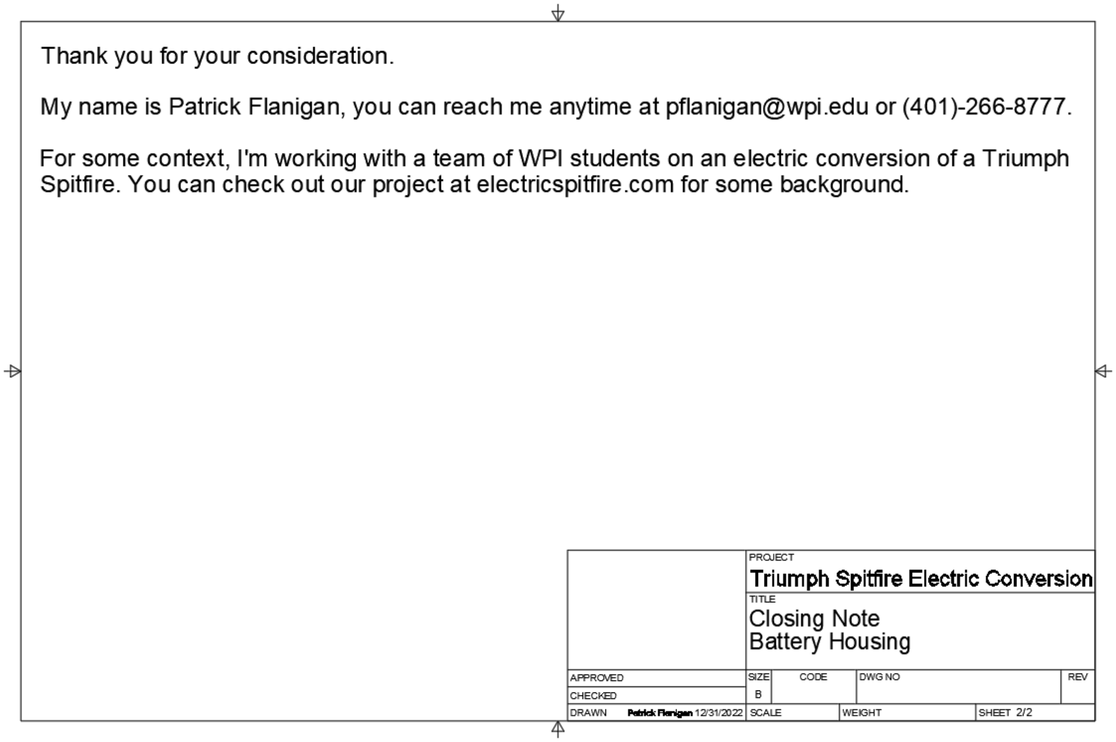


Figure 59. The Final Designs of the Battery Housing Submitted to Fabrication Shops


Thank you for your consideration.

My name is Patrick Flanigan, you can reach me anytime at pflanigan@wpi.edu or (401)-266-8777.

For some context, I'm working with a team of WPI students on an electric conversion of a Triumph Spitfire. You can check out our project at electricspitfire.com for some background.

PROJECT
Triumph Spitfire Electric Conversion
TITLE
Closing Note
Battery Housing

APPROVED	SIZE	CODE	DWG NO		REV
CHECKED	B				
DRAWN Patrick Flanigan 12/31/2022	SCALE		WEIGHT	SHEET 2/2	

Figure 60. The Final Designs of the Battery Housing Submitted to Fabrication Shops

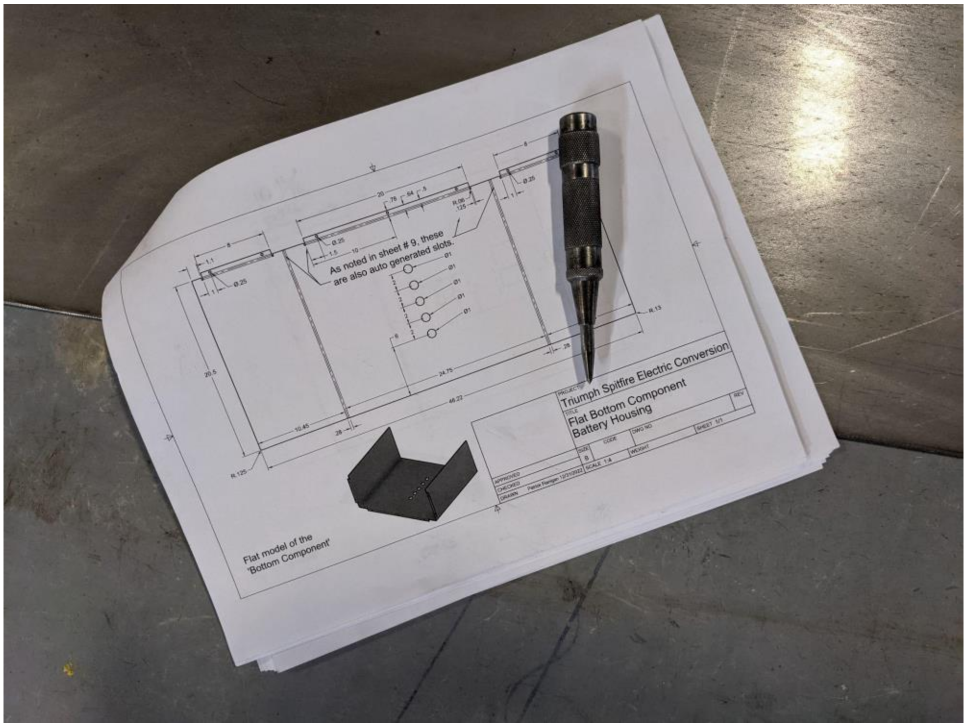


Figure 61. The Final Designs of the Battery Housing Submitted to Fabrication Shops

Figure 61 shows the on-paper designs of the battery housing taken at the ProShaper metal working shop. Figure 62 shows Charlie from ProShaper TIG welding the exterior of the accumulator housing. Finally, Figure 63 shows the finalized battery housing with the modules undergoing final integration before a test drive.

Figure 62. Charlie at ProShaper TIG welding the corners of the battery box.

Figure 63. The completed battery box undergoing integration.

Figure 64 shows initial fitment test of the two battery stacks in the newly fabricated accumulator housing. The precision between the top of the stacks and the housing itself can be seen due to the optimized design both in the modules and the accumulator housing.

Figure 64. Initial fitment tests of the battery stacks in the battery box.

Accumulator Electronics Integration

Finally, to integrate a number of electrical components, we decided to add locations for two dedicated junction boxes. The first of these junction boxes would house our battery management systems while the second of our junction boxes would house the supporting electronics including two contactors and a shunt. Figure 65 shows the initial fitment of junction boxes 1 and 2 on to the accumulator housing.

Figure 65. Initial Fitment of Junction Boxes 1 & 2 onto the battery box

Figure 66 shows the three battery management systems initially integrated into junction box number one. The larger 2-gauge cables can be seen on the outermost parts of the battery management system while the 26 smaller 22-gauge cables can be seen for balancing the different in-series banks of the battery.

Figure 66. BMS Cable Management Inside Junction Box #2

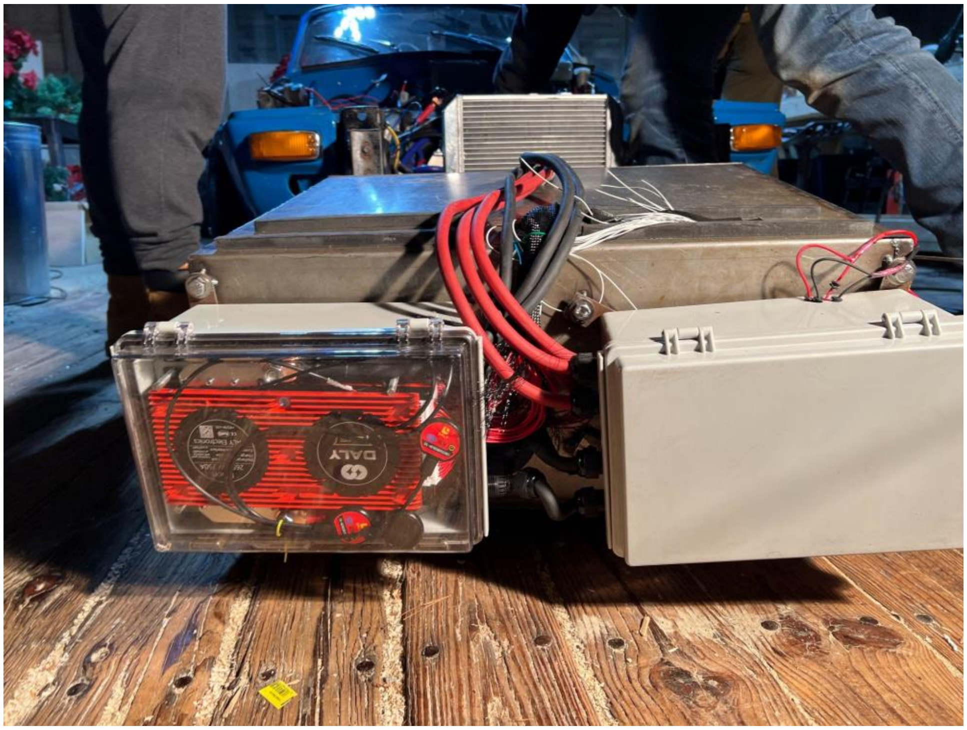


Figure 67. Finalized Integration of Junction Boxes 1 & 2 onto the Accumulator Housing

Figure 67 above shows the final integration of junction boxes 1 and 2 with the battery management systems contactors and supporting electrical equipment in place. These locations provide good functionality however there's more work to be done in order to fit all of this equipment underneath the hood as well as solve cable management issues created by the locations of this equipment.

Electrical Design:

Overview:

We designed and implemented a 96V / 12V ‘split’ system in our EV design. This system allows typical automotive subsystems such as external lighting, thermal control, Jetson, etc, to operate using the existing 12V auxiliary battery. In addition, the high voltage system allows for main systems such as the electric motor, motor control unit, and accumulator to move kilowatts of electricity. The systems are connected by a 96V/12V DC-DC converter which converts the high voltage into a low voltage and allows the 12V battery to be charged while the car is powered on. In order to provide our team the most freedom in design and implementation of the drivetrain and onboard computer systems, we decided to custom design the electrical grid from the ground up.

96 Volt System

Accumulator and Motor:
We configured our system to 96 volts. This decision was based on battery availability. Since we had access to affordable 48V/200A battery packs, we initially purchased four. These battery packs were wired in a series/parallel configuration to achieve a 96V/400A high voltage system. From here, we selected a 96V permanent magnet alternating current motor (PMAC). The motor and MCU system we selected was capable of demanding 660 Amps at 96 Volts, although at the time the theoretical battery unit mounted the car could only achieve 400A continuous and 440A at peak. Due to funding allowances, we decided to purchase another set of batteries which would be wired in series and hooked up in parallel to the other two sets of battery packs. Our system evolved into a 96V, 720A peak system.

Contactors:
We purchased two 96V contactors rated to a continuous amperage of 500A, which we chose to place on the positive and negative terminals between the battery and the MCU. We will place the other contactor on the negative rail to ensure no current draw from the battery and to provide our own safety while we work on the 96V system. The negative rail contactor is also advantageous because of our regenerative braking mechanism. Regenerative braking converts the mechanical energy created from decelerating into electrical energy. An approximate maximum of 30A is sent back to the battery via the negative high-voltage DC rail from the motor control unit. The signal wires on the main battery contactors are connected to a physical E-stop switch on the dashboard of the vehicle. Once the switch is toggled, it will disconnect the battery pack from all subsequent systems. These contactors are operated with a 12-volt, normally open circuit, meaning when 12V is not provided to these contactors, they will open and the car will shut down. Our third contactor came with the MCU unit we purchased. This contactor isolates the MCU branch and can act as an additional motor stop. This contactor is rated to 500A of continuous current, much like the E-stop contactors. However, our motor stop contactor comes with 24 V signal wires that attach to the key switch and the MCU. Finally, we added a physical emergency stop on the MCU branch. It is a high current in line ‘button’ that breaks the connection with no signal wires. This is our final ‘failsafe’ in the system which guarantees the opening of the circuit. On the datasheet for our contactors in Appendix B2, a current greater than 2000A at 320V will close the connection permanently and the connector runs the risk of arcing. For our 96V system the break current approaches closer to approximately 4000A according to the ‘Estimated Make & Break Power Switching Ratings’ graph on the datasheet. This sparks the need for fuses in this system.

Fuses:

It is standard procedure to place fuses on the main leads of the battery pack. In case the circuit is shorted, we want the fuse to pop first and cut power. In our configuration, we programmed the BMS units to trip their reprogrammable MOSFETs at 230A per battery module. This will halt current flow going to and from the battery if the current is greater than or equal to 230A. In addition to this, the BMS units are physically fused at 350A.

Charging:

Potential Solutions:

We had a couple of options to develop our charging solution: industry standard charging Levels 1, 2, and 3. With AC Level 1 charging, we are limited by the amperage and overall output power from a typical household outlet, (15A, 110V) (Bahrami, 2022). If we pull more than 15A we would expect to trip most standard circuit breakers (rated to 15 amps), although there are residential circuits that may be rated above this. Typical Level 2 AC charging solutions utilize charging equipment (typically a J1772) in a commercial or residential setting and an on-board charger. Furthermore, a Level 2 charger operates at 240VAC with a typical amperage rating of 40A, although it is possible to have a higher amperage than this. (Bahrami, 2022). To implement DC charging (Level 3), communication from the vehicle management system to the onboard charger is required, as well as specialized hardware (Bahrami, 2022). A large limitation we had was lack of CAN communication ability in our BMS. The BMS's we purchased were not programmed to accept and utilize data from a smart charger. These constraints allowed us to rule out the possibility of Level 3 charging.

Most common, a Level 2 on-board charger is primarily used at publicly accessible charging stations. In order to implement Level 2 charging, we were able to use our charger which was capable of handling an input voltage range of 100VAC to 240VAC, an output voltage of 96V, and an output current range of up to 10A. We were able to implement this setup with a standard SAE J1772 female connector. The J1772 connector needs a pilot signal "handshake" in order to open the contactors and feed power to the vehicle. This signal is provided by an Active Vehicle Control Module (AVC2 board).

Ultimately, we chose to go with an onboard charging setup that is capable of charging at both Level 1 and Level 2 chargers. This means our system is capable of accepting 110-220VAC at a standard 110 outlet or J1772 charging station.

Typically onboard level 2 chargers are safer and align with SAE charging standards. However, having an off-board charging solution is typically cheaper and easier to implement, in addition to this, the charger can then be disconnected and stored in the trunk. However, this method is consequentially less safe considering the user is directly plugging into a 96V system. Level 1 chargers allow for lower voltage circuitry, and are also simpler to implement, only needing to handle 110VAC and 15A from a residential wall outlet and output 96VDC at a specified amperage. See Table 4 and 5 below for simplified pros and cons:

Pro	Con
Location Versatile	More Expensive
Faster Charging Capability	Complex Wiring Strategy
Safe and User Friendly	More Weight

Pro	Con
Less Expensive	Residential Charging Only
Simple Wiring Strategy	Slower Charging Capability
Less Weight	Potential Safety Hazard

Our vehicle's individual battery packs are approximately 4kWh each. We have six, giving our system a 24kWh and 250Ah capacity total. Ampere hours are calculated by dividing the kWh by the total voltage (96V). This needs to be taken into consideration when selecting a charger. The output amperage of a charger is vital when it comes to total charge time. For our battery, a charger with an output amperage of 7A to 20A would correspond to a total charge time of 36 to 12.5 hours respectively from a completely dead to a fully charged battery pack. We can find these values by dividing the ampere-hours from the battery by the output amperage from the charger.

<u>Implementation:</u>

We selected an onboard charger that can take a voltage range of 110~240V so it may charge in residential (standard 100V outlet) and commercial settings (J1772 EVSE). However, the power of the charger was limited by the manufacturer at 1kW to accommodate our residential setting. The charger will not pull more than the maximum amperage a residential outlet can provide. Our 1kW of power will stay constant regardless of the input voltage. Output current can be found by dividing total power and output voltage which gives ~10.5A. This means that no matter which setting (110V or 240V) we will receive the same amount of amperes to charge our battery ~10.5A. It will take approximately 24 hours for our battery to fully charge from depletion. From this experience we learned that unless we have a charger capable of variable power supply, we cannot efficiently charge the battery in both 110VAC and 220VAC settings.

Wiring:

For the battery pack, the wires between the series connected batteries will be transmitting a maximum of 240A and 48V, therefore, we used 1 AWG gauge wire. To connect the series batteries in parallel we used 1 AWG gauge stranded copper wire. Transmitting up to 600 Amps at 96 Volts requires significantly uprated conduits and adapters. When handling the larger DC currents from the battery to MCU we used 4/0 gauge wire which is rated to approximately 380A of continuous current. Our continuous draw from our battery to the MCU will be approximately 220 Amps. If the motor pulls more current, our wire will need to be able to support a higher temperature for a short period of time. We will need a well-insulated wire for this connection. Furthermore, the fuse on our MCU trips at 500 Amps so we cannot exceed this rating. Our DC/DC converter is rated at 600W, and 96V will be going into the device. Therefore, we can calculate input amperage by dividing the power by the input voltage. As a result, we calculated the device pulls ~6.25A. In ideal conditions the converter would output 12V and 50A. However, if we factor in the ~90% efficiency rating, the output amperage falls closer to 45A. Corresponding wire gauges for the 96V components are found in Table 3 below. Not depicted in this chart are the effects of the autonomous steering mechanism on the 96V system.

Device	Input Amperage (A)	Output Amperage (A)	Input Voltage (V)	Output Voltage (V)	Input Wire Gauge (AWG)	Output Wire Gauge (AWG)
Combined Battery Pack	N/A	0-720 DC 240 DC (continuous)	N/A	96 DC	N/A	2/0

MCU	0-500 (DC)	0-480 AC 180 AC (continuous)	96 DC	96 AC	2/0	1
DC/DC converter	0-6.25 DC	0-50 DC	96 DC	12 DC	13	4
Charger	0-15 AC	0-10.5 DC	110-240 AC	96 DC	10	11

Table 3. Wiring Breakdown for 96V Components

Grounding:

Our 96V system has an isolated grounding system as it is not connected to the frame of the vehicle. Because of this we bought an isolated DC/DC converter to support this strategy. Our MCU does not require grounding.

Key Switch:

A 96V key switch is provided with our MCU. This key switch primarily acts to isolate and switch off the motor. The signal wires for the key switch connect to a main contactor.

Wiring Diagram:

All of these considerations are reflected in Figure 68. This wiring diagram shows our current 96V system status without the autonomous steering mechanism.

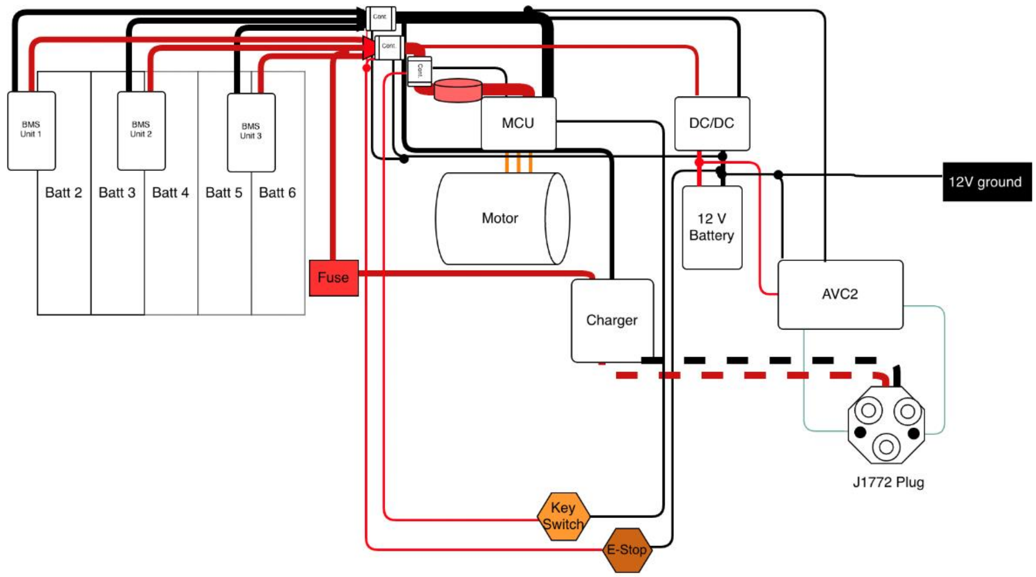


Figure 68. 96V System Wiring Diagram

12 Volt System

<u>Overall Function:</u>

Most lead acid batteries cannot handle a charging current of more than 30A. The battery in the vehicle is a Magna Power BCI 24 with a cold cranking amperage (CCA) of 600A. From the CCA we can approximate the ampere hours of the battery to be around 55 Ah. A maximum charging rate of lead acid batteries is recommended to be about third or a fourth of the charging capacity. This means using our current battery we should not charge the battery at a rate above ~18.5A to preserve the batteries life. In order to efficiently charge the 12V lead acid battery we will need to select a DC/DC converter with a lower power rating. The ideal converter will need to output 20A maximum and 12V minimum.

Downstream of the 12V battery we have our On/Sleep relay and our Sleep/Off relay. This controls the car’s states. The On/Sleep relay is controlled by the ignition switch already established in the vehicle. We designed it this way because when we park the car and turn the ignition off, we don’t necessarily want all the auxiliary systems to power off. We still want to be able to see our main battery's charge level through BMS communication with the on-board computer, the Jetson, as well as monitoring and control of the accumulator’s thermal control unit. Figure 69 shows which systems are powered on and off when the ignition key is turned off.

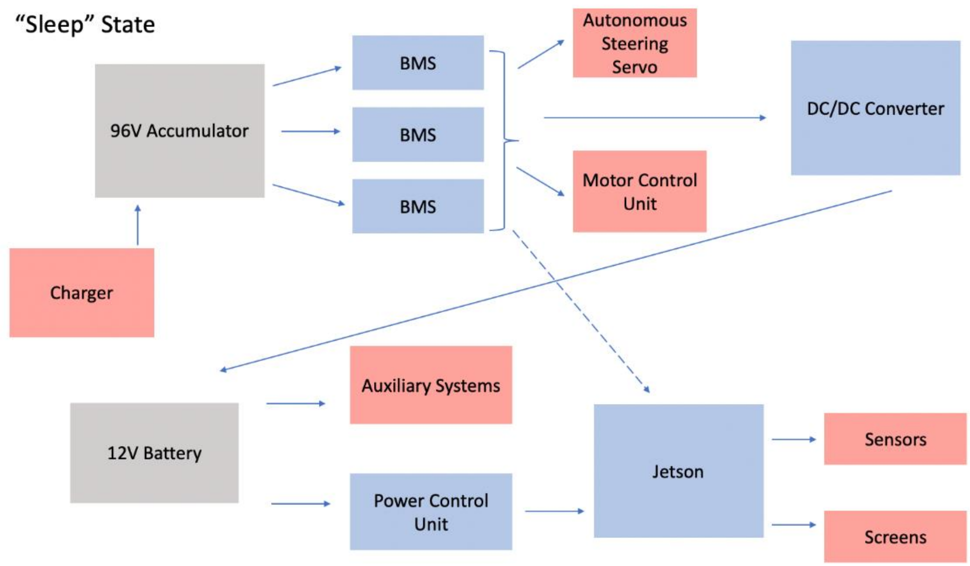


Figure 69. Car Sleep State

Note. Red highlight represents off while blue represents on. The solid lines represent power while the dotted lines show communication wires.

The Sleep/Off relay is controlled by a button which will be located under the car's hood. When the button is pressed, it will shut off all auxiliary systems downstream of the 12 V battery.

<u>Components and Wiring:</u>

The car's main auxiliary functions are controlled by a series of switches on the car's dashboard. These switches include windshield wipers, headlights, high beams, running lights, and the right and left blinkers. These components are wired through a 12V 100A fuse box. The headlight/high beam switches are also connected to relays. Due to the high current draw of the headlights and high beams it is safer to use relays to limit the current going through the driver operated switches. The relays are given the full current while the switches are fed to signal wires. The high beams are wired so that they are only activated when the headlights are. The blinker switches give their signal to a blinker relay next to the running light which will control the blinking of the light. All components will be grounded to a bus bar which will then be connected to the chassis. The Jetson is powered by a power supply unit that takes the 12V provided and boosts it to 19V to satisfy the Jetson's operating voltage. Figures 70 and 71 depict our current 12V wiring diagram and component wiring chart with input and output currents and voltages.

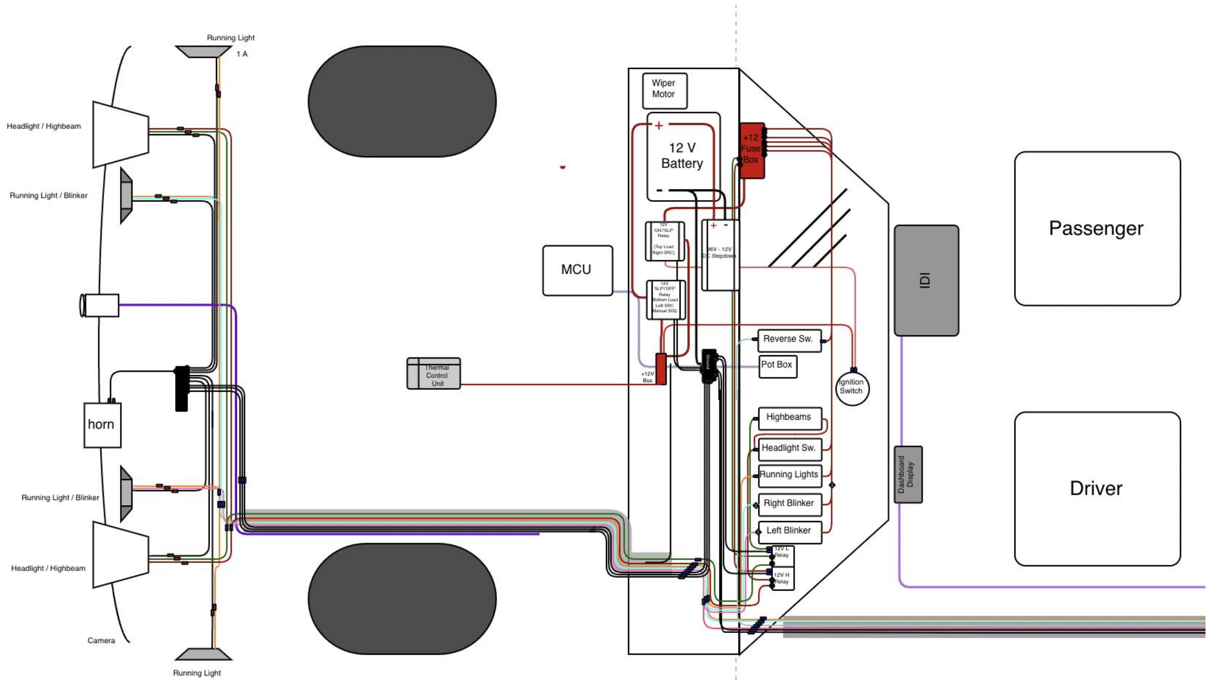


Figure 70. Front End 12V System

Note. This diagram is not yet complete without the thermal control unit circuit architecture.

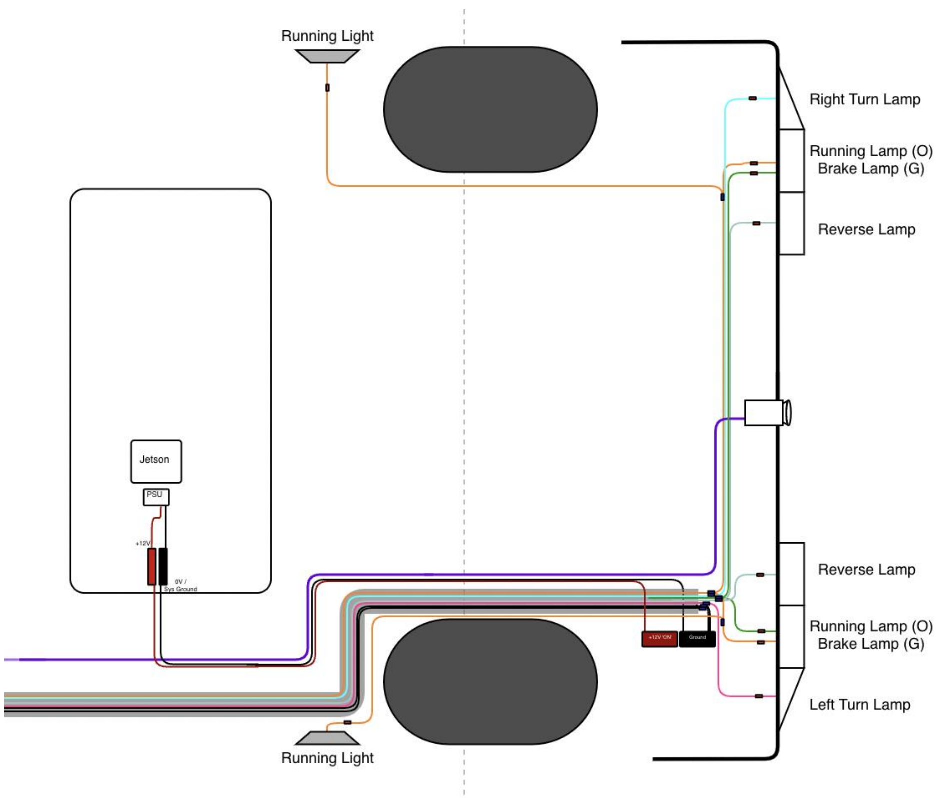


Figure 71. Back End 12V System

Powertrain:

Overview:

Triumph Spitfire Mk4 OEM Specifications:

Engine Hp: 58 HP
Engine Torque: 72 FT-Lbs
0 - 60 Time:15.8s
Curb Weight: 1625 (Using 1700 for all calculations)
Differential Gearing: 4.11
Transmission Gearing: Manual

First Gear Gear Ratio	Second Gear Ratio	Third Gear Ratio	Fourth Gear Ratio	OD (J-Type) Gear Ratio	Reverse Gear Ratio
1 : 3.86	1 : 2.16	1 : 1.39	1 : 1	1 : 0.85	1 : 3.86

Table 6. OEM Transmission Gear Ratios

Differential Selection:

A differential takes the power from a vehicle's transmission and splits it amongst rear wheels in rear wheel drive (RWD) or all wheel drive (AWD) cars. When a car turns, a differential is needed to enable the outermost rear wheel to rotate faster than the interior rear wheel to counteract inertia and reduce wheel spin at high speeds. (Pearlman, 1998).

In our design, we originally wanted to make a rear wheel drive (RWD) system with a differential rated for the stresses that will be induced. The current spitfire differential is old, slightly damaged, and has been previously rebuilt. Torque is also what determines the stress to a differential and not horse power, and electric motors put more stress on the drive train due to the instantaneous build up of torque, when compared to an internal combustion engine which takes longer to reach peak torque levels (Threewitt, 2019). Due to both of these factors, it would be wise to replace it so that failure points are reduced. After extensive research considering a replacement standard for the Triumph differential, a Datsun 510, and Subaru R-160 differential, it was found that while the Subaru R-160 rear differential is not a perfect fit into the Spitfire, it is the chosen upgrade for this car which does not require significant alteration to the frame . This differential has a 4.44:1 gear ratio and is from a Subaru WRX STI with a Type RA 310 HP Engine, and thus should be more than capable of handling the torque from our chosen electric motor. There are a few additions which need to occur to make the R-160 fit into the frame of the

Spitfire. The differential is attached to the frame in five key points: The front and rear brackets, the spring perch, prop shaft and half axles (Morrison, 2020). These all require modifications to make sure the differential will fit in the frame.

There is one thing we did not account for when researching for the differential: the budget of this project. Since our budget has been severely limited, a decision needed to be made to prioritize funds. Since the motor and accumulator set up is almost 80% of our budget, we decided to postpone buying a differential in the likely event we do not have enough funds to buy and install one. It is still an incredibly important aspect of our project, and in the future our hope is to have enough budget leftover so that we may purchase a differential, specifically the Subaru R-160, but now it will not be a part of our final design.

Table 7 displays alternative differentials of varying gear ratios, as well as their 0-60 times and top speeds with a PMAC 38kW motor and an AE86 transmission in the Spitfire (more analysis completed in the motor section). The red boxes show between what times you would hit 60 MPH. For example, with a 7.33 gear ratio, one would achieve 0 MPH to 60 MPH in between 8.68 and 10.18 seconds (which is between 4th gear and overdrive) and a top speed of 63.95 MPH. We considered these 0-60 times to be reasonable, and as a result considered any differential gear ratio less than 1:5.8 to be acceptable.

Gear Ratio	1st Gear	2nd Gear	3rd Gear	4th Gear	OD	Top Speed (MPH)
7.33				8.68	10.18	63.95
6.33			7.23	10.05		74.05
5.8			7.89	10.97		80.82
5.3			8.64	12.01		88.44
5.14			8.91	12.38		91.2

Table 7. Rear Differential Options (0-60 and Top Speed)

Note: Blank boxes are not applicable for a 0-60 time

U-Joint Analysis:

A Universal Joint (U-Joint) is the vehicle component which enables power to be transmitted at varying degrees of freedom. This angle of contact changes because the wheels follow the terrain surface while the frame stays at relatively stable altitude due to shock absorber springs (Sabhadiya, 2022).

The current spitfire u-joints should work in theory, and with spare time and money, replacing the current u-joints with performance Fiat 1800 / Alfa Giulietta u-joints would increase reliability

and are interchangeable with the current joints. This was set as a low priority aspect of the project; however it is important to research each aspect of this car, and if time and money allowed, this would be a further addition to upgrade this car.
After extensive research, and analysis of the full car working model at the time of our comprehensive design review, the team decided not to replace the original U-Joint. This replacement would have required modification or replacement of the Spitfire's original driveshaft. Driveshafts matching our requirements ranged from $400-$700 and after inspection of the driveshaft’s current state we decided this was not necessary. Modification of the driveshaft is also a complex process requiring specialized tools not easily accessible to our team. This also influenced our choice to keep the Triumph Spitfire’s original driveshaft.

Transmission Selection:

A transmission in a car is used to convert a motor’s torque and rpm to what is ideal for the situation. If more torque is needed for a hill or acceleration, the transmission would have a high gear ratio and a lower rpm. If more rpm is needed, a lower gear ratio is required which produces less torque but greater speeds. This relationship is due to the power equation in which RPM and torque are directly proportional to power output (Hawley, 2020).

In the automotive industry there are 4 main transmission types, manual, automatic, continuously variable transmission (CVT), and single speed reducer transmission. Manual transmissions are found in many DIY project electric cars as they are able to increase the torque and speed range of an inexpensive electric motor at a reasonable cost despite being unconventional commercially. Automatic transmissions do not function well with electric motors as they are built to automatically shift at certain RPMs. Due to an electric motor’s ability to produce its max torque instantly, and as a result bring the motor up to max RPM quickly, it is not practical to use an automatic transmission for this application. CVTs function with a gradual gear shift which responds directly to a car’s resistance through pneumatic pressure (Choksey, 2021). This would provide the optimal gear ratio in any situation and would be ideal for this design, however during research it was difficult to find any calculations or specifications on these transmissions and using one would introduce a cumbersome engineering problem in terms of mounting / packaging. Finally, most electric vehicles use a single speed gear reducer which a constant gear ratio meant to adjust a motors rpm to provide a desired torque. Most car manufacturers who make EVs use this transmission as electric motors have a broader range of torque and rpm than an internal combustion engine (ICE).

Below are attached various performance graphs comparing CVTs and Reducers (Figure 72, Table 8, and Figure 73).

A. Continuously Variable Transmissions – This graph shows the power and torque verses rpm of a typical CVT in a petrol vehicle. The data shows an almost linear power output with increasing rpm and a clear optimal power peak at around 280 hp. The selected electric motor would not need this necessarily as its power output is variable given its amperage and torque demand.

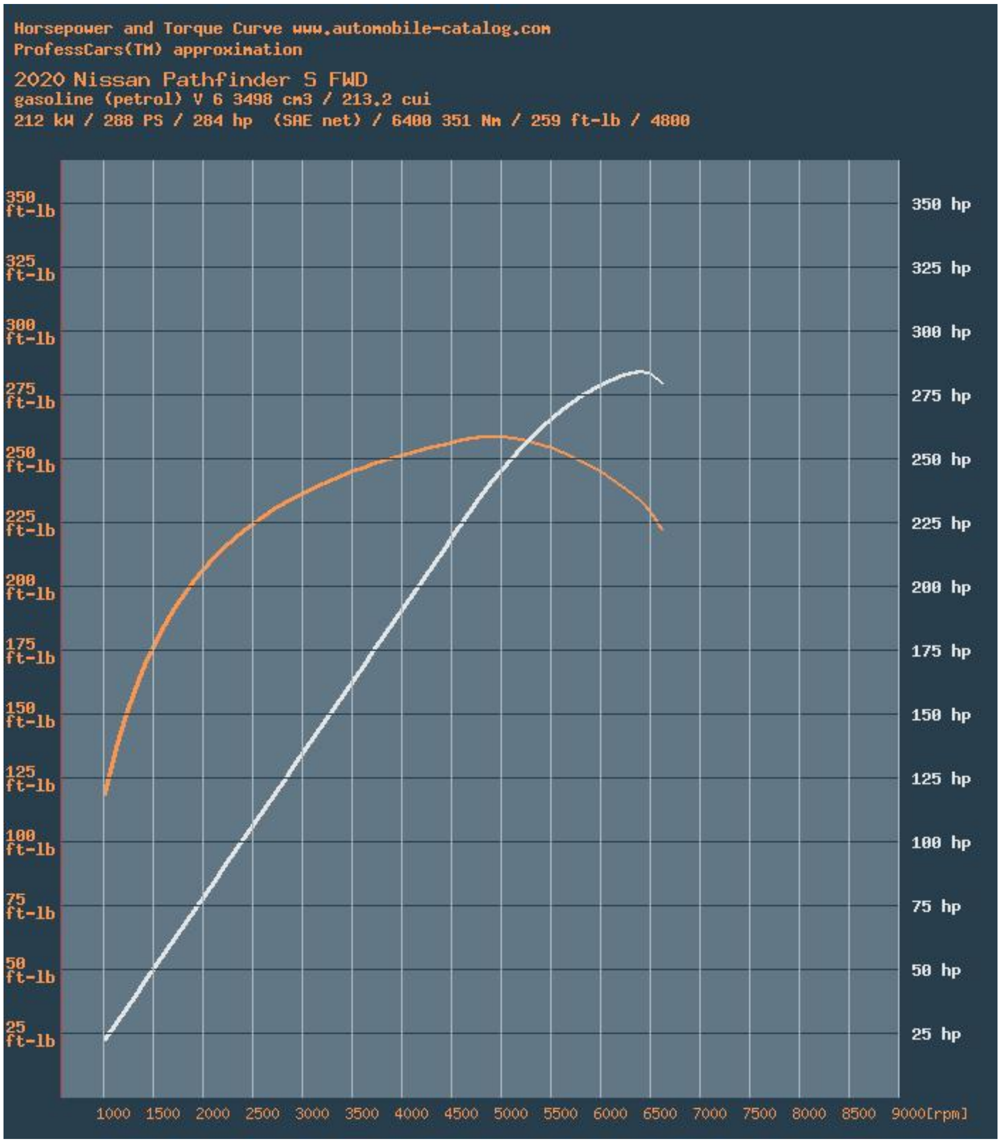


Figure 72. Horsepower vs Torque Curve of a Nissan CVT

B. Reducers – Single gear reducers are utilized in most commercial electric vehicles. With the selected motor for this project, single speed reducers were researched with respect to acceleration and top speed. As you can see below, a reducer simply does not provide a reasonable acceleration and top speed. To obtain one you must sacrifice the other with this approach.

Reducer Performance Chart						
Spitfire Wheels:	OD (in)	Circumference (in)	Rev/Mile	RPM		
	22.4	70.37	900.36	6000		
Motor Power:	Voltage (V)	Amperage (Amp)	Inductance (Nm/Amp)	Torque (Nm)		
	96	400	0.15	60		
Reducer	1st Reducer	2nd Reducer	3rd Reducer	4th Reducer	5th Reducer	6th Reducer
Total Gear Ratio:	1	2	4.44	5	6	8
Torque Output (Nm):	60	120	266.4	300	360	480
Force (N):	196.72	393.44	873.44	983.61	1180.33	1573.77
Acceleration (m/s^2):	0.26	0.51	1.13	1.28	1.53	2.04
Max Output RPM:	6000.00	3000.00	1351.35	1200.00	1000.00	750.00
Max MPH:	399.84	199.92	90.05	79.97	66.64	49.98
0 To 60:	105.01	52.50	23.65	21.00	17.50	13.13

Table 8. Reducer Performance Chart

Note: The chart above does not include air resistance or other external factors which would bring top speeds and accelerations down non-linearly.

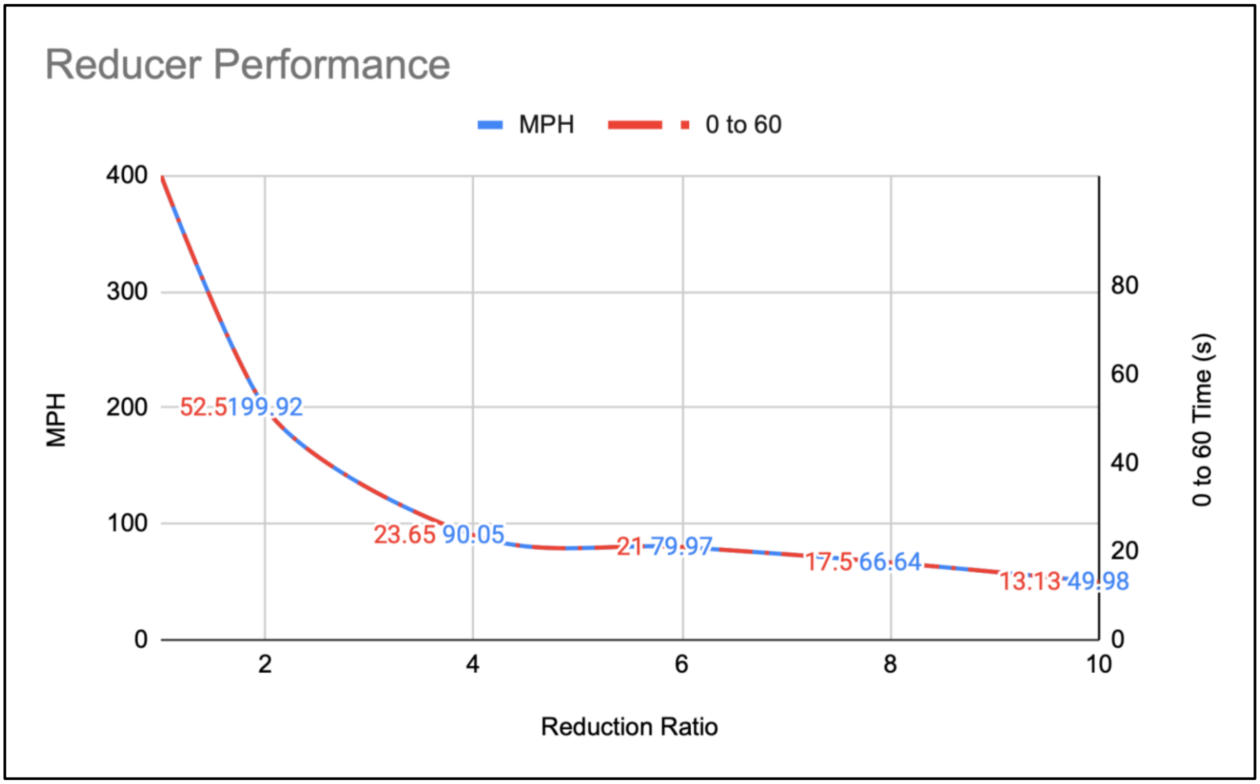


Figure 73. Reducer Performance Graph

C. Manual Transmission – See tables 12 and 13 for the manual transmission performance with the selected motor. In these graphs, one can see the benefit of a manual above the listed transmission alternatives. It provides the best benefits with minimal sacrifice to performance. However major inefficiencies are introduced through the suggested gear box which is to be considered.

Transmission Implementation Analysis

For integration into this project, we chose a manual Toyota Corolla AE86 (T-50) transmission. While it is true that a single speed reducer is ideal for most EVs, we selected a manual transmission due to the fact that our budget limited the power capabilities of our motor and battery pack compared to that of standard EV companies such as Tesla.

During the design process of renovating the car, we wanted to consider converting the entire drivetrain, not just the motor. We considered keeping the current Spitfire transmission however we ultimately decided it would not be the best fit. The Spitfire transmission tends to be a known failure point (even without modification) and we expect the instantaneous torque to increase after conversion which would put an additional load on the known failure point. There is also no reverse gear in the Spitfire transmission. Furthermore, while we can certainly run the electric motor in reverse, it will not work in practice because the transmission in first gear is not designed to be run in reverse. Once the current transmission was no longer a viable option, we continued researching other transmissions.

When picking the transmission, we mainly considered three different ones because we had documentation that they all fit into a Spitfire Mark IV conversion and/or a similar Spitfire conversion without too much modification (*"Best" 5 Speed Conversion for Spitfire?: Spitfire & GT6 Forum : The Triumph Experience*, n.d.). We considered a Toyota T-50 AE 86, Toyota W-50, and a Ford T-9 transmission. The T-9 transmission regardless of price and fit is reliable and a strong option however it is known for not having that smooth of a shift. The W-50, like the T-9, is a reliable transmission and has tighter and more common shift patterns. The W-50 typically comes from 1960s cars so that means it is usually older/has been through more wear and tear and made from heavier material. However, the top choice for the transmission is the T-50. Others have said it is an "easy fit" for integration and it is a well known and loved gearbox in the car community (*Toyota T 50 Trans Swap to Spitfire 1500: Spitfire & GT6 Forum: The Triumph Experience*, n.d.). The T-50 is also a newer transmission in comparison to the W-50 and it is made from a lighter material. We ended up choosing a T-50 because we were able to easily source one for $270, which fit within our budget, and it was our ideal option for a transmission.

With this transmission, many challenges came to our integration team. Since the transmission was cataloged incorrectly, it can be a 1985 or 86 transmission and all serial numbers were nearly impossible to read, so buying components for this transmission was difficult. We were able to find a shifter, clutch assembly, throw-out bearing and carrier, and slave cylinder. A few parts were mis ordered, but we eventually found the correct necessary components. Below are brief descriptions about the original W50 transmission (Table 9) and the new proposed T50 (Table 10).

Part	Description	1st Gear	2nd Gear	3rd Gear	4th Gear	OD
W50	Manual	3.29 : 1	2.04 : 1	1.39 : 1	1 : 1	0.853 : 1

Table 9. W50 Transmission Gear Ratios

Part	Description	1st Gear	2nd Gear	3rd Gear	4th Gear	OD
T50	Manual	3.59 : 1	2.02 : 1	1.38 : 1	1 : 1	0.861 : 1

Table 10. Transmission Gear Ratio Comparisons

Transmission to Driveshaft Connection:

A. Introduction

The Spitfire's original transmission transmitted power to the driveshaft using two flat flanges with a 4-bolt pattern. The OEM transmission had one mounting flange, and the driveshaft had a matching flange connected to the Spitfire's OEM U-Joint and driveshaft (see below in Figure 74 and 75).

Figure 74. OEM Transmission-side Flange

Figure 75. OEM Driveshaft-side Flange

The next step to successfully transfer the rotational output from the electric motor to the rear wheels was connecting the selected transmission (Toyota AE86 T-50) to the Spitfire's existing driveshaft. The T-50 transmission output is a 0.985 x 22 splined shaft and needed to be connected to the Spitfire's driveshaft in a robust manner. This connection is required to rotate ranging from ~ 3,000 to 5,000 RPM and handle the output torque of the transmission without deformation. Because this is a rotating part, keeping its weight balanced is also important as the driveshaft's balance has a significant impact on the car's vibrations at higher RPMs.

Typically, a purchasable slip yoke can accomplish the task of connecting a transmission output to a driveshaft. The slip yoke acts as one half of a U-Joint, while the driveshaft has a matching yoke welded to it. If the two yokes have matching specifications, they can be connected with a U-Joint. However, due to the car's age, limited demand, and the obscurity of the two parts we were attempting to connect, there were no purchasable options for a slip yoke that would match both the T-50 transmission’s spline pattern, and the Triumph Spitfire's U-Joint dimensions.

However, we were able to source a slip yoke from Powertrain Industries (Part number PTI-2302-22) at a reasonable price of $55 with the matching 0.985 x 22 spline (depicted in Figure 75). It is important to note that this slip yoke did not have dimensions that allowed for integration with the Spitfire’s U-Joint or driveshaft. We were unable to source any other components that matched the T-50’s 0.985x 22 splined shaft and matched the yoke dimensions of the spitfire.

Based on this information, the mechanical engineering team developed two possible solutions to transfer the rotational output of the transmission to the driveshaft and ultimately rear wheels:

1. Modify the 2303-22 Slip Yoke to adapt to the OEM Spitfire driveshaft's 4 bolt mounting flange. (see Figure 76)

2. Modify the OEM driveshaft by replacing its U-joint with the 2303-22 yoke. In this configuration two 2303-22 slip yokes would be purchased. (See Figure 77)

To assess the viability of the two options available to us, CAD models of each solution were designed using Fusion 360. To choose the most viable solution; effectiveness, cost, difficulty of modifications, availability of tools, and required time to produce were analyzed.

Figure 76. 2303-22 Slip Yoke compatible with T-50 transmission output spline

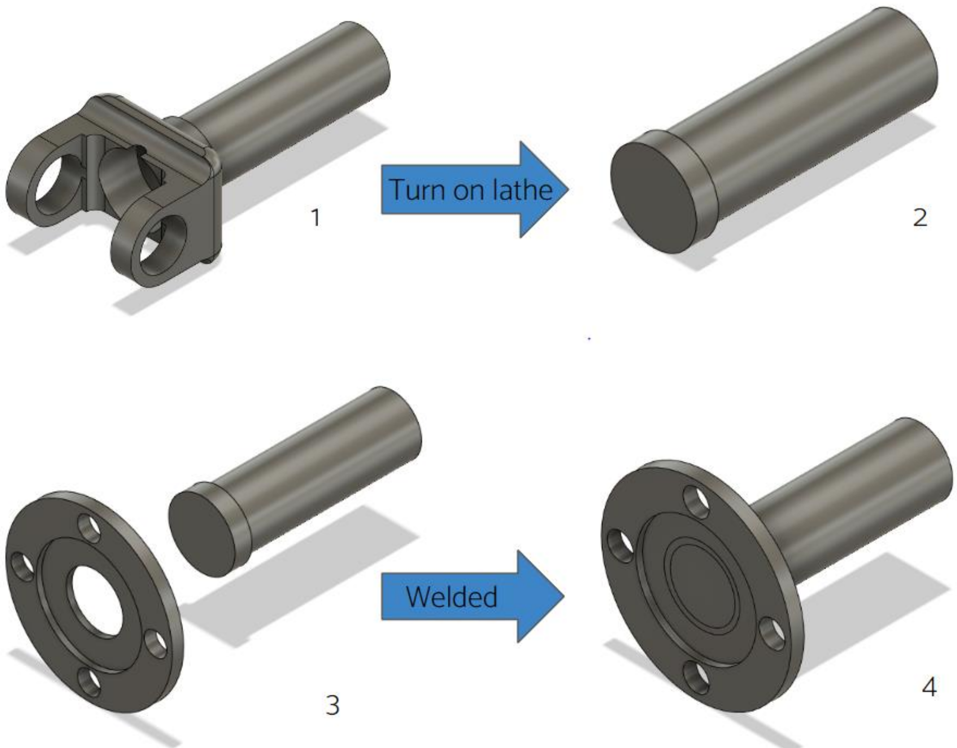


Figure 77. Transmission to Driveshaft Connection Option 1

If the first option was chosen, the transmission would be connected to the driveshaft in a similar manner as the OEM transmission and would retain concentricity of the driveshaft. This solution only cost $55, with the purchase of 1x PTI-2302-22 slip yoke. This is due to our acquisition of a suitable 3/8in steel plate received through donation from Coastal Equipment Corporation. This plate could be used for the circular flange noted in part 3 of the figure above. This modification could also be completed using tools and machines readily available to our team in Washburn labs. Finally, because the OEM driveshaft had not been removed from the car during disassembly, option 1 did not require us to further disassemble the car, which would also add reassembly time in the future.

This solution was cheap and effective while also being efficient. The parts were easily manufacturable, and it was a sound solution. The drawback to this solution was it relied on the Spitfire's OEM U-Joint. Although this U-Joint is robust enough for this application we are unsure of the remaining lifetime on the OEM U-Joint. A benefit of this integration is it allows for an OEM Triumph driveshaft to be retrofitted in the future to keep the car on the road. This would require no bespoke work.

The second option to connect the transmission to driveshaft utilizes 2x PTI-2302-22 slip yokes ($55 each), and 1x PTI-2351-20 U-Joint ($25.00). A machined collar would be milled from blank steel stock graciously donated to our team from Coastal Equipment Corporation. The total cost of parts would be ~ $135.00 In this configuration the original driveshaft would be cut just behind the OEM U-Joint, and a custom sleeve would be used to make up the difference between the outer diameter of the slip yoke spline and inner diameter of the driveshaft. The slip yoke spline, sleeve and driveshaft would then be welded together (Figure 78).

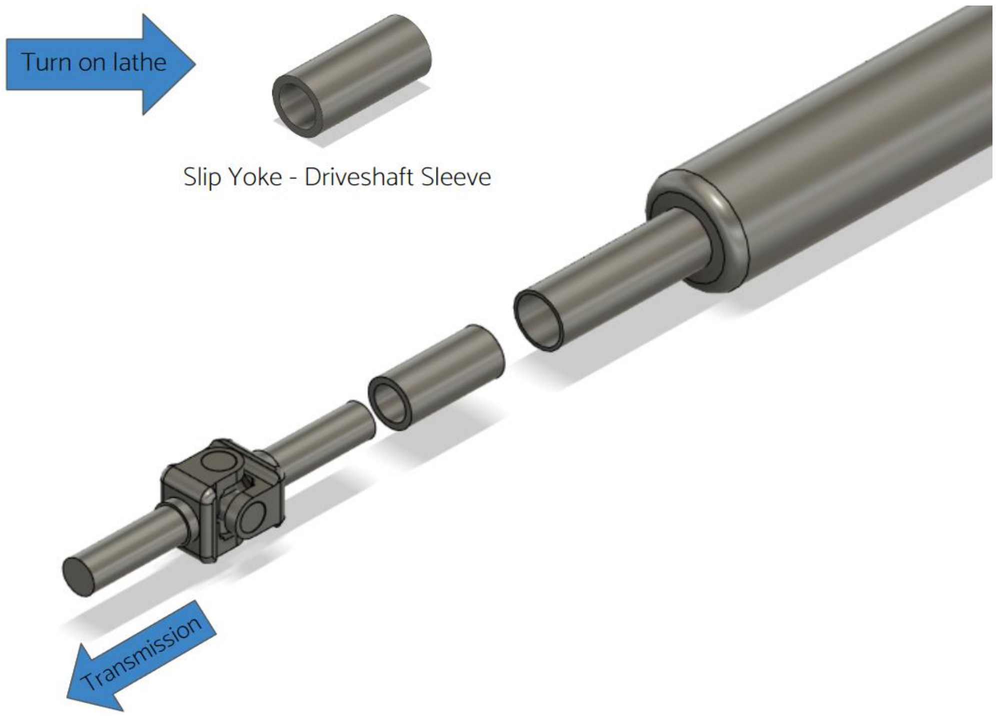


Figure 78. Transmission to Driveshaft Connection Option 2

This second integration option done correctly should be just as effective as the first solution. However, its part cost is more than double. The modification to the drive shaft would also be challenging, as modifying driveshafts can introduce vibrations if concentricity is not maintained. The tools required to do this job are also only used by specialized mechanic shops that regularly do driveshaft modifications. Because of this, we would have difficulty completing this modification to our own standards. The price to have this outsourced to a mechanic shop ranged anywhere from $300-$1000, with even the lowest price stretching our budget. We also estimated that option 2 required a longer timeframe for machining and fabrication.

Based on the analysis of effectiveness, cost, difficulty of modification, availability of tools, and required time to produce, the first option was selected. This coincided with the recommendations of our advisor team when these two options were presented during our Comprehensive Design Review (CDR) presentation.

B. Prototyping Slip Yoke Modification

After analysis and selection of our transmission-driveshaft integration process, rapid prototyping was used to conceptualize the integration of the T-50 transmission outside of CAD. The team 3D printed the required mounting flange to better visualize the concept, as well as dry fit the components to ensure correct mounting (see Figure 79). 3D printing was done on an upgraded Ender 3 V2 FDM printer, using PLA filament. Because this part was only used for visualization and sizing, strength was not a concern.

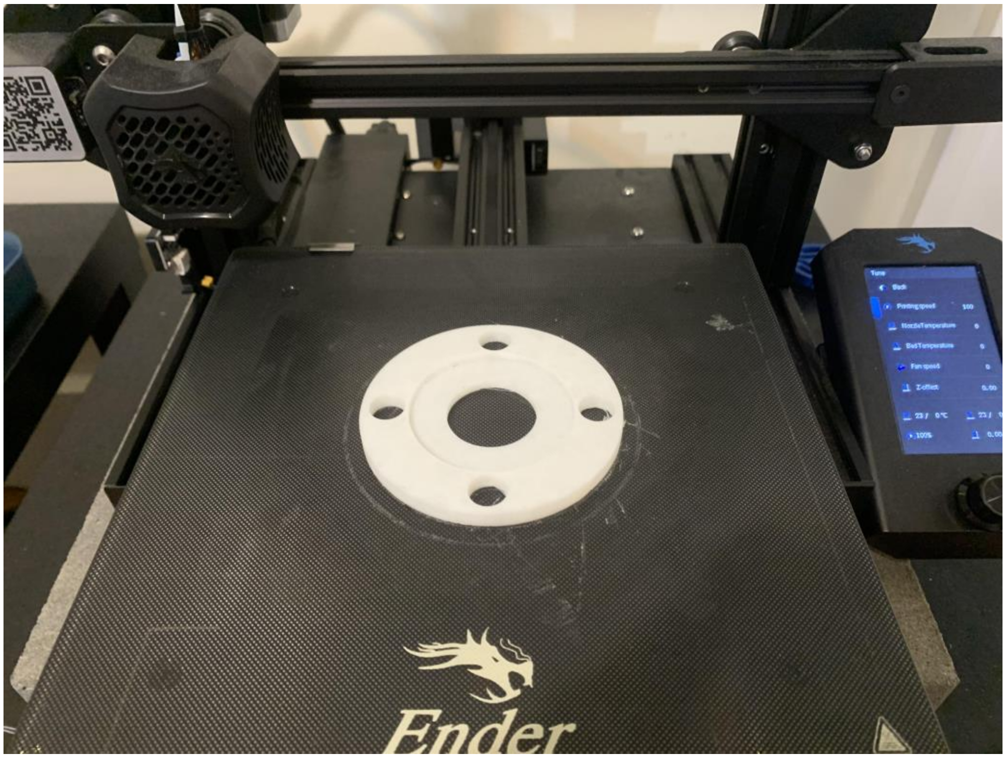


Figure 79. 3d Printed Prototype Slip Yoke Flange

After printing this flange and testing its fit on the slip yoke shaft, the team confirmed that this integration solution was promising, and required minimal effort in comparison to our second transmission-drive shaft connection solution.

C. Manufacturing of Transmission - Driveshaft Integration

To manufacture this integration solution two parts were required:

- Re-profiled 2302-22 slip yoke
- Circular mounting flange.

To reprofile the 2302-22 slip yoke, a first cut was made using a Do-all C-4 metal cutting bandsaw to remove a large section of the yoke protruding past the splined shaft (see Figures 80 and 81). This reduced the complexity and setup when preparing for turning on a lathe.

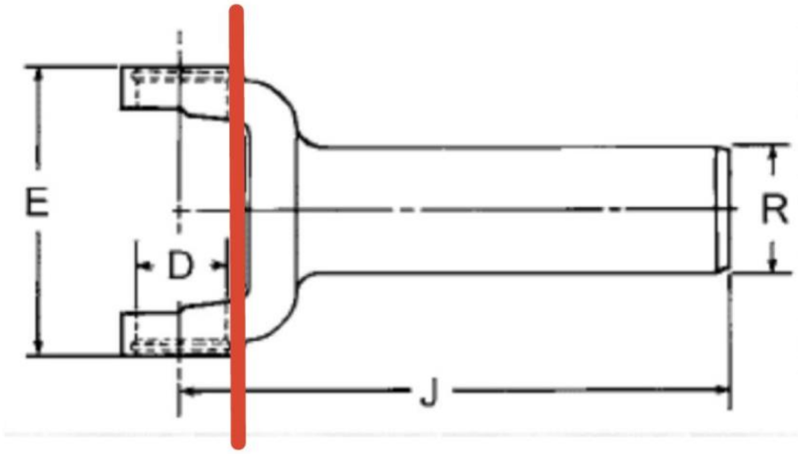


Figure 80. 2302-22 Slip Yoke Top Down.
Note: Red line denotes location of rough cut made by metal bandsaw

Figure 81. Rough Cut Material Removed from Yoke end of Slip Yoke

The rough-cut slip yoke was then reprofiled using a HAAS ST-30SSY CNC lathe. This lathe was required as the geometry of the slip yoke reprofiling operation was an interrupted cut, requiring the lathe to have significant power and clamping force. To complete this operation the spline of the slip yoke was fixtured within a 3-jaw chuck (see below Figure 82). The yoke end of the slip yoke was then turned down to a diameter of 1.260in, matching the outside diameter of the splined shaft.

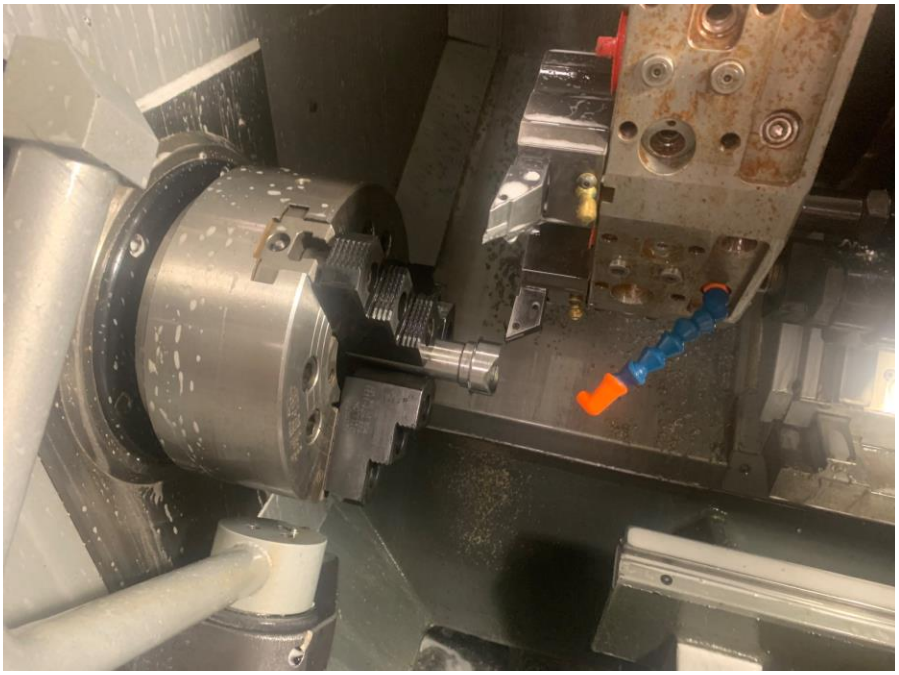


Figure 82. Reprofiling the slip yoke to a consistent OD of 1.260in" using a HAAS ST-30SSY Lathe

After this operation, we had a splined shaft with a consistent OD of 1.260in. (see Figure 83).

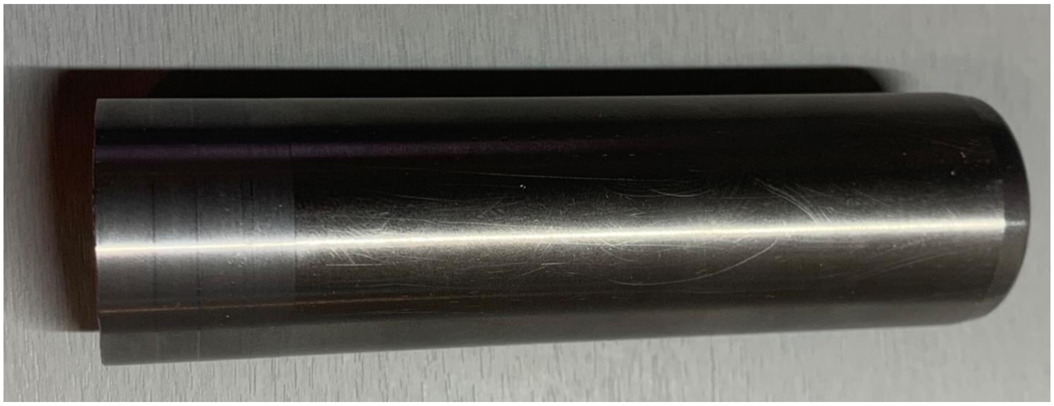


Figure 83. Re-profiled 2302-22 slip yoke spline shaft

The circular mounting flange was then milled from a donated sheet of 3/8in steel Although we are not 100% certain of its specific alloy, we believe it is a generic hot rolled steel. Starting with a ~ 10ft x 2ft plate of 3/8in, we cut the plate into a manageable size that could fit into HAAS VM2 using the Do-all C-4 metal bandsaw.

An aluminum fixturing block was prepared for our final cutting operation through a series of operations including rough cutting, facing, drilling, and tapping (see below Figure 83). The workpiece also received the 4-bolt pattern during this operation. This let us bolt the plate to the fixture block securing the inner part when completing the outer contour toolpath. Our tool path designed in Fusion 360 would separate the outer stock of the workpiece, so we also utilized the

VM-2's fixture plate T-slots along with step setup blocks and setup clamps to secure the outside portion of the workpiece (see Figures 84 and 85).

Figure 84. Setup of workpiece fully fixtured and ready for final milling operations.

Figure 85. Workpiece after milling 1.270in inner diameter center hole

Figure 86. Circular Mounting flange after final operations on HAAS VM-2 Mill

With both the reprofiled 2302-22 slip yoke and circular mounting flange machined, they were inspected and tested to verify their fit (see Figures 87, and 88). The final step in manufacturing this adaptor was to weld them together. As none of our team had experience welding, this job was outsourced.

Figure 87. Fully machined Slip yoke mounting flange

Figure 88. Reprofiled 2302-22 slip yoke spline shaft fit into circular mounting flange for transmission to driveshaft integration.

When installing the slip yoke into the car after final assembly, a problem arose. When designing the part to match the OEM Spitfire slip yoke, it was presumed that the bolt pattern would be in a symmetrical "X" pattern. However, when it came to install the slip yoke, it became clear the Spitfire slip yoke bolt pattern was slightly different from what was originally thought. While two bolts fit at the top and the bottom of the slip yoke, the angle at which the other two bolts were positioned on the Spitfire slip yoke did not fit the custom slip yoke by 0.2". While it would have been easy to increase the diameter of the holes which did not fit to allow the bolts to be installed, the team decided that this would reduce the structural integrity of the part, and thus it was decided to re-drill all four holes to fit the Spitfire slip yoke.

Transmission Adapter Plate

Overview:

In order for this electric motor to properly interface with the transmission, an adapting plate was manufactured. This plate matches the bell housing of the T-50 and had mounting points along the perimeter (where the AE86 Corolla engine would originally bolt up) and four main points concentric with the input shaft for the motor to mount up. Once the plate is bolted to the transmission, the motor is then bolted to the center of the plate and the armature of the motor should mesh with the flywheel through means of the motor coupling which is described in further detail later in this report.

Challenges:

In order to make a finished product capable of handling the induced stresses while providing integral support to the motor, many challenges had to be overcome. There were no blueprints on the T-50 design so a very tedious process of sketching the transmission face on a paper and scanning document into CAD and tracing the face was undergone. Around 6-7 iterations were done since this process was very difficult due to various distortions. Once a proficient CAD was created for the bellhousing face, mounting points were designed into the face. Our team was fortunate enough to gather material from previous MQPs including a ¾" thick aluminum plate which has various holes in it already.

Design and Reasoning:

This plate was designed as shown below and machined out of ¾" Aluminum (see Figures 89 and 90). This material and design allow for a safety factor of 15. This means our team potentially could have used a thinner steel substitute; however we chose to use the aluminum due to its highly machinable properties.

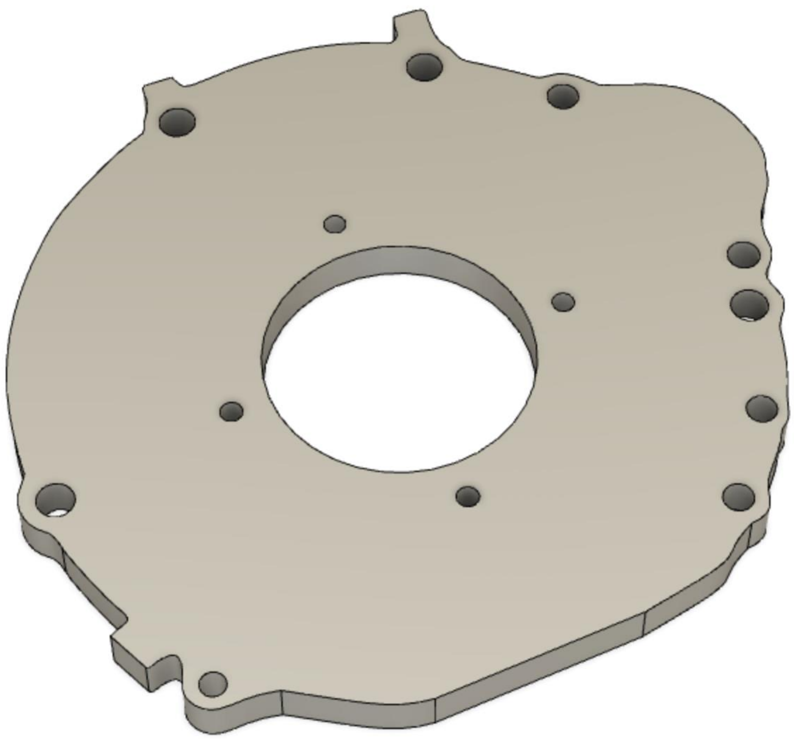


Figure 89. Motor Transmission Mounting Plate

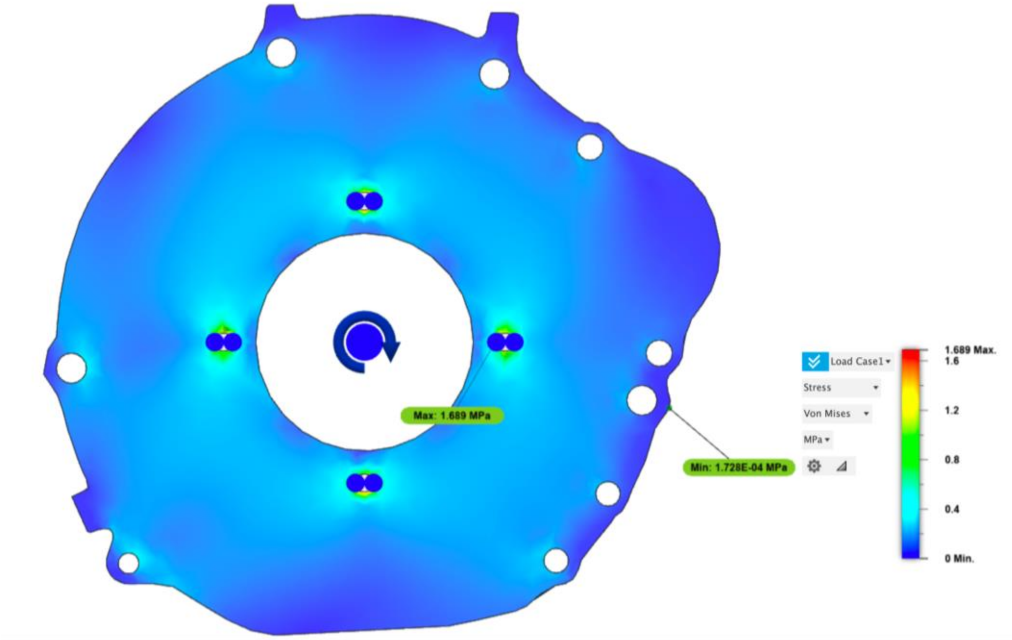


Figure 90. Mounting Plate Stress Analysis

Machining Process:

This plate took a significant amount of time to machine while our team was still new to the specific machines and their operation. We used a Haas VM2 which has the work area necessary for this size component. The plate was made by spot drilling the holes with a ⅜" spot drill, followed with a ⅜" end mill and a simple end mill operation around the perimeter and center of the plate. The plate was fixtured with four toe clamps which provided sufficient clamping forces for our operations.

Prototype Review:

The design is perfect for the car's adapting plate; however it may need to be replaced with fresh material that does not already have holes in it. ¼" steel should provide a proper replacement as this is what most other adapting plates are made from. Figure 91 shows the final adapting plate after the machining process.

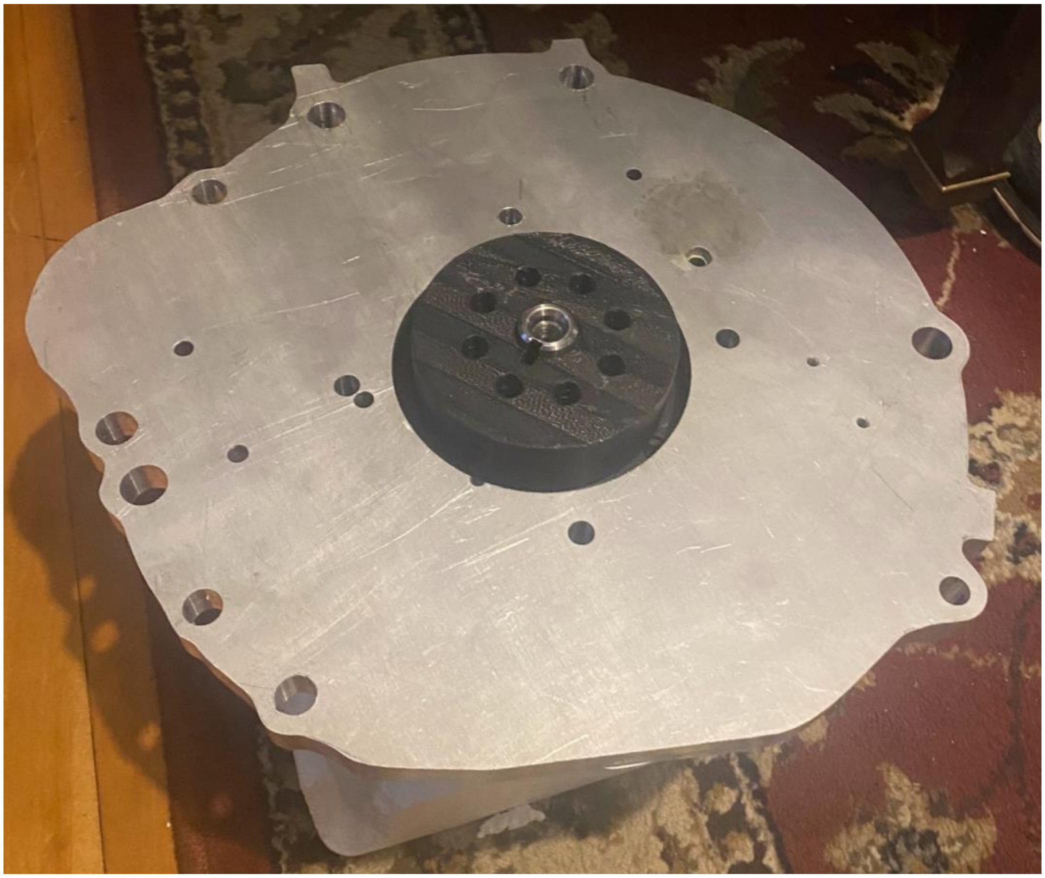


Figure 91. Mounting Plate Prototype

Cooling System:

Another aspect of this project - the cooling system, while seemingly less important than other critical parts such as the electric motor and batteries, is as important to this project as them. While still much more efficient than an internal combustion engine, at the Amperage that these components are operating at, it is no surprise that these parts quickly become overheated due to power dissipation. In many cases, if left unchecked, these components will fail when overheating, a disaster not only for the project but also the driver of the vehicle. Therefore, a cooling system must be designed to address the inevitable overheating, which is capable of handling the cooling of multiple components for long periods of time.

When first researching electric motors, it became clear that a liquid cooled motor would be the best option for this project. Liquid cooling is much more effective than air cooling, due to water and ethylene glycol's (the two ingredients which make up common vehicle cooling liquid) exceptional specific heat capacity. With a mix of 50:50 water to ethylene glycol at 70 degrees Fahrenheit, its specific heat capacity, or rather the quantity of heat absorbed per unit mass of the material (Wang, L., Nicola, D. D., Chen, S., & Zerouli, Y.,2022), is 0.82942 BTU/lb °F (Engineering Toolbox, 2003). This far exceeds that of air, which is a measly 0.24 BTU/lb °F Chan, T., 2021). Once this was known, there were multiple options in terms of liquid cooled motors. The motor and inverter that were selected had the option for a premade cooling system which came with a radiator, tubing and coolant pump, however it was incredibly high priced. It made more sense to work around the original Triumph Spitfire radiator, which not only came with the car and thus much cheaper, but also contains more than twice the coolant capacity of the motor's radiator. This would also allow routing coolant to the batteries, which would be a much harder task with the premade cooling system.

It then became clear that a cooling system would have to be designed. The first step in this process was to find the input and output diameters for each respective component's cooling hose, and find a way to alter the hosing diameters to fit the components within the cooling system. The Triumph Spitfire's original radiator has a hose diameter of 1.25", and the motor and inverter hosing has a diameter of 0.5". The four cooling plates designed to cool the batteries will have a diameter of 0.2". It is quite easy to find hose adapters to reduce the hosing diameter to fit each component, however by reducing diameter you increase not only flow rate, but also pressure. Therefore, a decision was made to have 0.5" tubing be the standard tubing for the cooling system, which would allow an increase in velocity without pressure reaching too high of a value. Calculations were required to confirm our system would have the power to cool each component, but would also keep below a certain pressure.

Based on research, it was found that an average internal combustion engine cooling system has a flow rate of 0.0003 to 0.00037 m^3/s at an engine RPM of around 2250 to 2750, which results in an average flow rate of five gallons per minute (Perang, M., n.d.). Due to the fact that an average car uses a belt driven pump from the engine to pump coolant throughout the engine bay, flow rate changes depending on the RPM of the engine. Due to the fact that the Spitfire engine has been removed, it means that an electric pump powered by the car's 12 volt system will be required. °C, and the cooling system of a car is meant to remove 30% of that heat (Bancoadmin, B., 2017). The maximum temperatures the batteries and electric motor will reach is much less, thus requiring less cooling to begin with. It was initially decided that two 12 volt pumps, one working at 3 gallons per minute, and one working at 1.2 gallons per minute, would be more than enough to cool each component. This is due to the fact that an average combustion engine produces 2-9 GPM of flow at a given time, depending on the RPM of the vehicle. As the electric motor and inverter system are much more efficient than a combustion engine, we concurred that 3-4.2 GPM would be more than acceptable to cool these components. The secondary pump was considered to create a secondary system to independently control the flow of coolant to the batteries (in situations where cooling the accumulator would reduce its efficiency), however it is unknown how a pump with reduced flow rate would affect the flow rate and pressure of the main pump. Therefore, the current iteration of the cooling system has a primary system where the main pump sends coolant to the inverter and motor, and to the four liquid plates cooling the batteries (see Figure 92). This was achieved through a plethora of tees and reducing couplings to achieve the desired hose diameter for each respective component (see Figure 93).

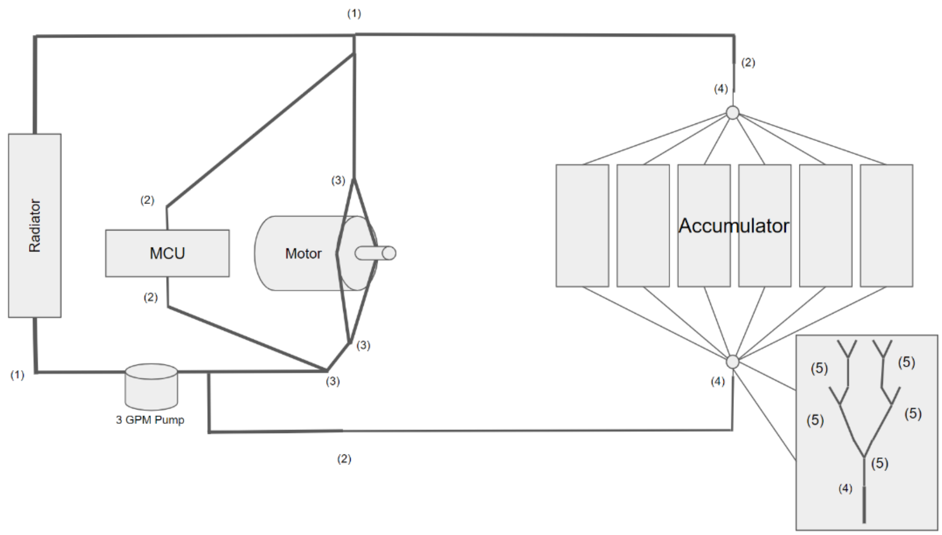


Figure 92. Cooling System Diagram

Number on Diagram	Number Used in Project	Description
(1)	X2	3/4”x1/2”x1/2” Tee
(2)	X4	1/2”x3/8” Reducer
(3)	X2	1/2”x1/2”x1/2” Tee
(4)	X2	3/8”x1/4” Reducer
(5)	X10	1/4”x1/4”x1/4” Tee

Figure 93. Tees and Splitters used for Cooling System

The next step was to conduct calculations on the system to confirm that it would work properly. The calculations were conducted using Google sheets to make calculations on different sections of the cooling loop easier (see Figure 94). The largest concern in this system is pressure, as the Spitfire's radiator is rated to seven psi. If the pressure within the system reached above this, it would cause the radiator to rupture, destroying the cooling system and potentially allowing the components to overheat. By using diameter of tubing to calculate each tubes respective area, along with the flow rate of each pump, velocities were able to be calculated at three places: as coolant passes into/out of the radiator, the general tubing of the system, and where coolant passes into/out of the battery cooling plates.

Velocities (v=Q/A)	m/s	
V1 (at radiator)	0.6641554748	
V2 (through system)	1.494349818	
V3 (through battery housing)	9.339686365	
Pressures (P=v^2*(rho/2))	Pa	psi
P1 (at radiator)	231.5788097	0.0336
P2 (through system)	1172.367724	0.17
P3 (through battery housing)	45795.61423	6.642

Figure 94. Cooling System Pressures

From there, Pressures were calculated using Bernoulli's equation for each respective place based on the change in hose diameter. This involved multiplying the square of the velocity by half of the density of a 50:50 ethylene glycol water mixture (commonly used in coolant systems).It is clear to see that the pressure within the system does not reach over seven psi at any point. It should be noted that a temperature of 70 degrees Fahrenheit is used for these calculations, and inevitably as the temperature of the cooling system increases, so will the pressure. Despite this, the calculated pressure at the radiator is very minimal, therefore it is highly unlikely that the pressure caused by an increase in temperature would reach seven psi at the radiator. This likely will not be the case for the other components, however proper rated hosing will be used to make sure pressure will not be a limiting factor of this system. While head loss, or rather energy/pressure loss throughout a system should be recognized, it is unlikely to cause too many issues due to the relatively small length of tubing planned to be used in this cooling system (around 15 feet). All of these values were incredibly promising and therefore we created the cooling loop to the motor and inverter.

Once the loop was complete, we wanted to see how the system dissipated heat between the motor and inverter. Prior to the test drive from Uxbridge to Worcester, we measured the temperature of the system. The starting temperature of the system (including motor and inverter) was 52 degrees Fahrenheit. The car was then driven 20 miles on the highway to Worcester with the cooling pump on circulating coolant at 3 GPM. Once the car reached Worcester, the temperature was measured again. Firstly, every component had the identical temperature, meaning the motor and inverter were properly receiving coolant. On top of that, the temperature of the system reached 67 degrees Fahrenheit, which is well under the maximum temperature of the motor and inverter. This means the flow rate of the system is more than capable of transferring the heat from the motor and inverter. While we were unable to calculate pressures of the system, at no point was there any signs of high pressure, even as the temperature increased.

Using the temperatures taken from the system, we were able to calulate the heat transferred throughout the system. This involved multiplying the mass of the coolant (kg), the specific heat capacity of the coolant (kJ/kg°C), and the change in temperature of the system (°C). Thus, we achieved a value of -122.93 Joules, which is an acceptable value of heat transferred through the system. In the future, we hope to conduct longer test drives which will determine how well the system stays cool over longer and more intense periods of driving.

One other issue that was a concern to this system was how adding two pumps in the current orientation would affect the overall system. It is feared that placing these pumps in this orientation could potentially cause back pressure/flow issues within the entire system. Thus, the secondary pump was removed from the design, and the accumulator would be cooled through the main cooling system.

Another important aspect of this cooling system is the price. The cooling system designed to come with the liquid cooling motor had a price of $450. This is very expensive, and due to the fact that the current budget is always incredibly tight on this project, as well as the cooling system being specifically meant for the motor and inverter, it made much more sense to design one with the components already in the car. With the Spitfire radiator being free, two 3 GPM pumps at $50 each, along with tubing and fittings coming in at a maximum of $100, the price of this current iteration of the cooling system falls to $200; $250 cheaper than the pre-built cooling system we had the option of purchasing. This extra cash will come in handy for other aspects of the project as we near the completion of this project. Unfortunately, time and budget were a restraining factor for this aspect of the project, and therefore the cooling loop connected to the battery was never completed. The cooling system to the electric motor and inverter, however, was a resounding success.

Overall, the cooling loop has found incredible success in cooling the motor and inverter. We hope in the future we will be able to connect the custom-made cooling plates to the main cooling system, so that we may provide liquid cooling to our accumulator.

Weight Distribution:

Weight Distribution is a key aspect of this project. By understanding how much the car will weigh, as well as how said weight is distributed, will greatly improve the chances of the project being a success. The curb weight of a Triumph Spitfire MKIV, including fuel, coolant, etc. is 760 kg (1850 lbs.). The engine weighs approximately 220 lbs., placing the center of gravity toward the front of the vehicle. When replacing components such as the engine, with an electric motor and batteries, it is vital to understand each component's weight as well as where they will be in relation to the car.

The first step was to subtract the weight being removed from the car, such as the engine, and then calculate the weight of everything that was getting put into the car, such as the electric motor and batteries. With the electric motor being 30 lbs., and the batteries and their housing being around 300 lbs., these components add to the final weight of the vehicle. While these components already reach greater than the combustion engine, it is worth noting that the gas tank (and fuel), which weighs around 50 lbs. when the tank is full, were also removed from the vehicle. The goal of the project is to have as much performance as possible, and by continually adding more weight, the risk of losing not only performance, but also efficiency becomes greater. While adding more weight usually means adding more batteries, thus improving performance, it also adds to the total weight of the car, which can be detrimental in the long run, especially if the suspension is not rated for said weight. In total, when removing what is no longer needed from the car, and adding what is needed, the total weight is expected to reach slightly over the original curb weight at around 1950 lbs.

The next step was to figure out how the weight would be distributed within the car. In the first design of the car, the batteries were placed in the rear of the car, due to greater space (from the removal of the gas tank), as well as protection from collisions and the elements. However, when looking into the weight distribution throughout the car, it was noted that having the majority of the weight in the rear would make the car have a center of gravity towards the rear of the car. While better for traction, this would make steering much more difficult, and would also result in a person being able to lift the wheels when pushing down on the rear. It was then decided to place the batteries in the front with the electric motor, as to move the center of gravity more towards the middle of the car. This resulted in a center of gravity towards the middle of the vehicle.

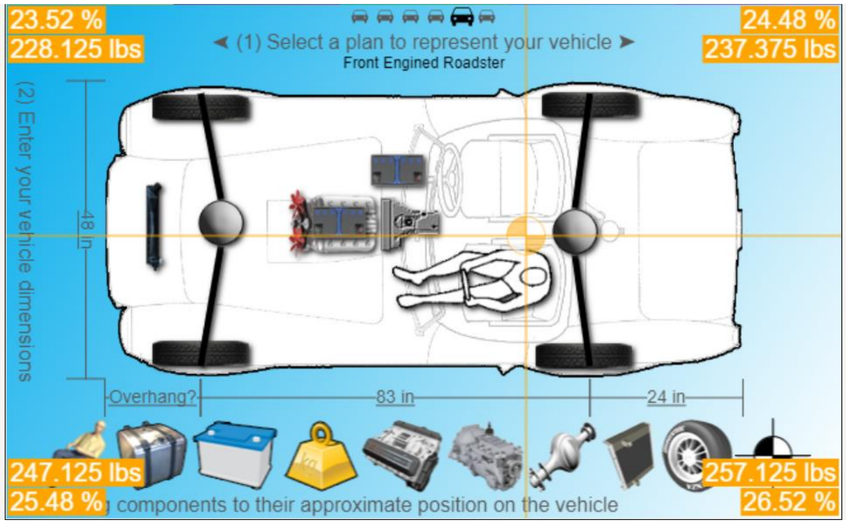


Figure 95. Above shows the weight distribution with the current iteration of the car. Note that the chassis is not included within this illustration, thus our team expects the center of gravity to be farther forward in the car than is shown.

Results:

Corner Weights		Front to Back		Side to Side		Total
Front Right	228.125 lbs	Front	475.25 lbs	Right	465.5 lbs	969.8 lbs
Front Left	247.125 lbs					
Rear Right	237.375 lbs	Rear	494.5 lbs	Left	504.25 lbs	
Rear Left	257.125 lbs					

Figure 96. Above shows the calculations for total weight of the car. Again, it should be noted that the chassis was not included in these calculations. The team's calculations put the total weight of the car at roughly 1950 lbs.

Figures 95 and 96 show an app used to calculate weights and weight distribution throughout the car. At the moment, it shows the center of gravity still leaning towards the rear of the car, however it should be noted that the chassis of the car, which makes up the majority of the weight, was unable to be added to this app. Due to the fact that the chassis' weight is distributed throughout the car evenly, this would move the center of gravity more towards the center of the car. It would also make the total weight make more sense, as currently the total weight is 969.8 lbs., however the team's calculations (along with the knowledge of the weight of the stock car) puts the final weight at around 1950 lbs. This would mean that the chassis is 1000 lbs., which makes rough sense. The team did not have access to a heavy enough scale to verify the weight of the car, however using known weights of components we implemented and took away, the total weight came to around 1950 lbs. In the future if we have access to a scale, we plan to validate our calculation by checking the weight on each tire.

Motor Analysis:

Through the preliminary process of researching electric motor candidates, it was determined that an AC Asynchronous 3-Phase motor was ideal for our application. “In a three-phase system, three wires are used to provide the same sinusoidal voltage” (Wattenphul, 2022). This means the motor can receive more power at greater efficiency when compared to a single-phase motor. Current high performance electric vehicle (EV) manufacturers such as Tesla, Nissan, and Subaru all use these motors. Early Calculations were completed on a variety of potential AC motors of all price ranges (see Table 11).

Motor	Description	HP Power Cont.	HP Power Peak	0 to 60 Time	Cost
PMAC-G12030	Fan Cooled AC	38.62	46.34	12.25	3500
PMAC-15/38kW	Liquid Cooled	28.32	84.97	7.7	3600
HPEVS-AC50	Fan/Air Cooled	41.20	65.00	9.45	4350
PMAC-G8055	Fan/Air Cooled	28.32	84.97	7.7	3325
PMAC-G8018	Fan/Air Cooled	7.72	27.68	17.8	1850
AC-34 1238E-6521	Fan/Air Cooled	24.14	53.10	11	3885
Nissan Leaf Drive System	Front Drive	107	107	6.82	3500
Ford Focus Motor / Transmission		143	143	5.88	1600
Tesla Model X	Rear Drive	362	362	2.92	1950

Table 11. Motor Comparison

The PMAC motors were found to be very popular with EV conversions due to their high-power output at reasonable costs. Some commercial EV car motors are shown for comparison’s sake.

As one can see, they are cheap and are superior to the other motors in terms of power output. Their drawback is the electrical systems required for these high-end motors which are 3-5 times larger than our current one and would be immensely expensive to implement. The project team decided to select the ME1302 15-38kW Liquid-Cooled PMAC Motor 48-120V. This motor is able to provide outstanding horsepower with our current electrical battery system (96V, 400A peak) at a low relative cost. Below are theoretical performance charts which convert electrical power to mechanical power and predict vehicle performance using the PMAC 15/38kW motor, a T50 transmission and the original rear differential (Tables 12 and 13 and Figures 97, 98, 99, 100, 101, and 102).

Nominal Operation (220 Amps Continuous)						
Spitfire Wheels:	OD (in)	Circumference (in)	Rev/Mile			
	22.4	70.37	900.36			
Motor Power:	Voltage (V)	Amperage (Amp)	Inductance (Nm/Amp)	Torque (Nm)	Differential	RPM
	96	220	0.15	33	4.11	6000
Mechanical Advantage:	**1st Gear**	**2nd Gear**	**3rd Gear**	**4th Gear**	**OD**	**R**
	3.59	2.02	1.38	1.00	0.86	4.04
Total Gear Ratio:	14.74	8.31	5.69	4.11	3.54	16.60
Torque Output (Nm):	486.50	274.24	187.71	135.63	116.78	547.95
Force (N):	1595.10	899.16	615.45	444.69	382.88	1796.54
Acceleration (m/s^2):	2.07	1.17	0.80	0.58	0.50	2.33
Max Output RPM:	406.98	721.99	1054.81	1459.85	1695.53	361.35
Max MPH:	27.12	48.11	70.29	97.28	112.99	
0 To 60:	12.96	22.99	33.59	46.49	53.99	

Table 12. Continuous Operation

Peak Operation (440 Amps Peak)						
Spitfire Wheels:	**OD (in)**	**Circumference (in)**	**Rev/Mile**			
	22.4	70.37	900.36			
Motor Power:	**Voltage**	**Amperage (Amp)**	**Inductance**	**Torque**	**Differential**	**RPM**

	(V)		(Nm/Amp)	(Nm)		
	96	440	0.15	66	4.11	6000
Mechanical Advantage:	**1st Gear**	**2nd Gear**	**3rd Gear**	**4th Gear**	**OD**	**R**
	3.587	2.022	1.384	1	0.861	4.04
Total Gear Ratio:	14.74	8.31	5.68	4.11	3.53	16.6
Torque Output (Nm):	973.0	548.48	375.42	271.26	233.55	1095.89
Force (N):	3190.20	1798.32	1230.90	889.38	765.75	3593.08
Acceleration (m/s^2):	4.14	2.33	1.60	1.15	0.99	4.66
Max Output RPM:	406.98	721.99	1054.81	1459.85	1695.53	361.35
Max MPH:	27.12	48.11	70.29	97.28	112.99	
0 To 60:	6.48	11.50	16.79	23.24	27.00	

Table 13. Peak Operation

The charts above are a general physics based calculation to demonstrate the effect of different gear ratios. They do not include air resistance or other external factors.

Once we understood the predicted performance, we needed to map out how the manual transmission would operate with the suggested design. Below, you can see each optimal gear shift and its corresponding speed and RPMs which it happens along with the speed mapping of the motor in peak and continuous operation.

RPM vs MPH and Gear Shifts
(ME1302 Motor with T-50 at peak power)

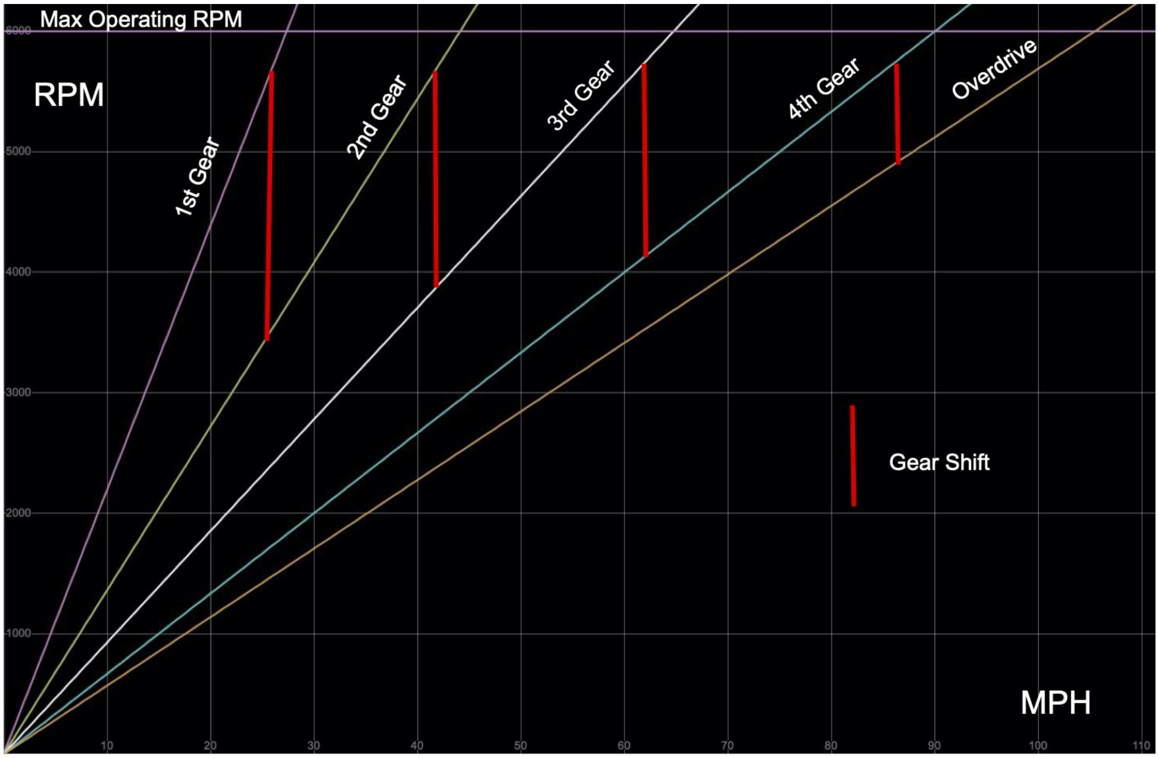


Figure 97. RPM vs MPH

Time vs. MPH
(ME1302 Motor with W-50 and R-160 at peak / continuous power)

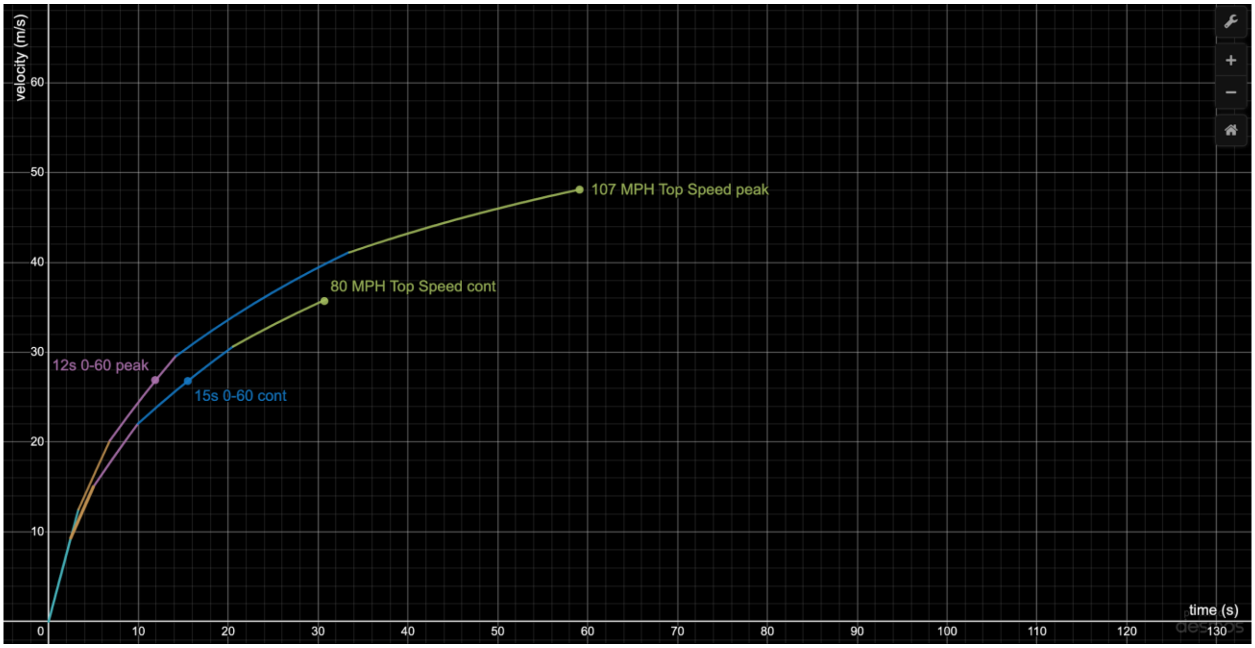


Figure 98. MPH vs Time on W50 Gear Ratios w/ drag

In order to understand how PMAC motor's function, the graphs below will act as an appendix for the ME1302 PMAC motor. Displayed first is the torque and current relation, followed by a graphic of the motor in vehicle operation, and the motor testing read outs provided by the seller.

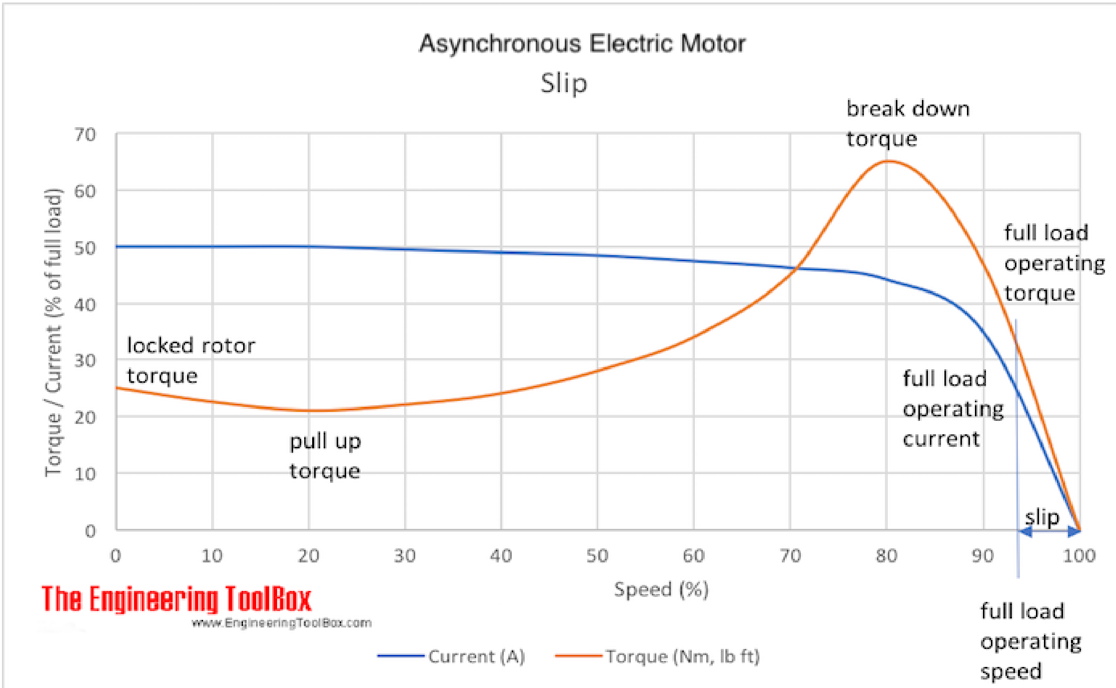


Figure 99. Torque vs RPM for AC Asynchronous Motor

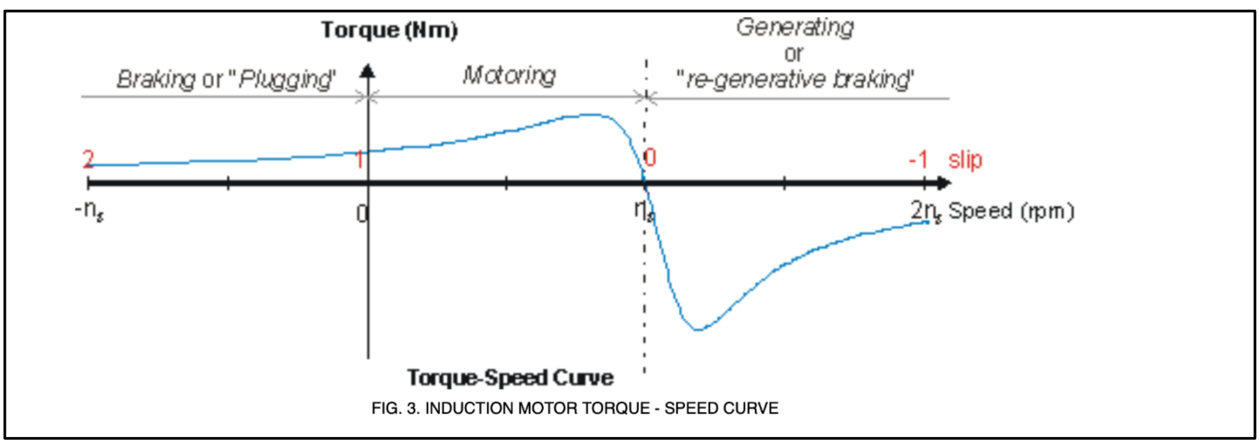


Figure 100. Torque vs RPM for AC Asynchronous Motor with Regenerative Braking

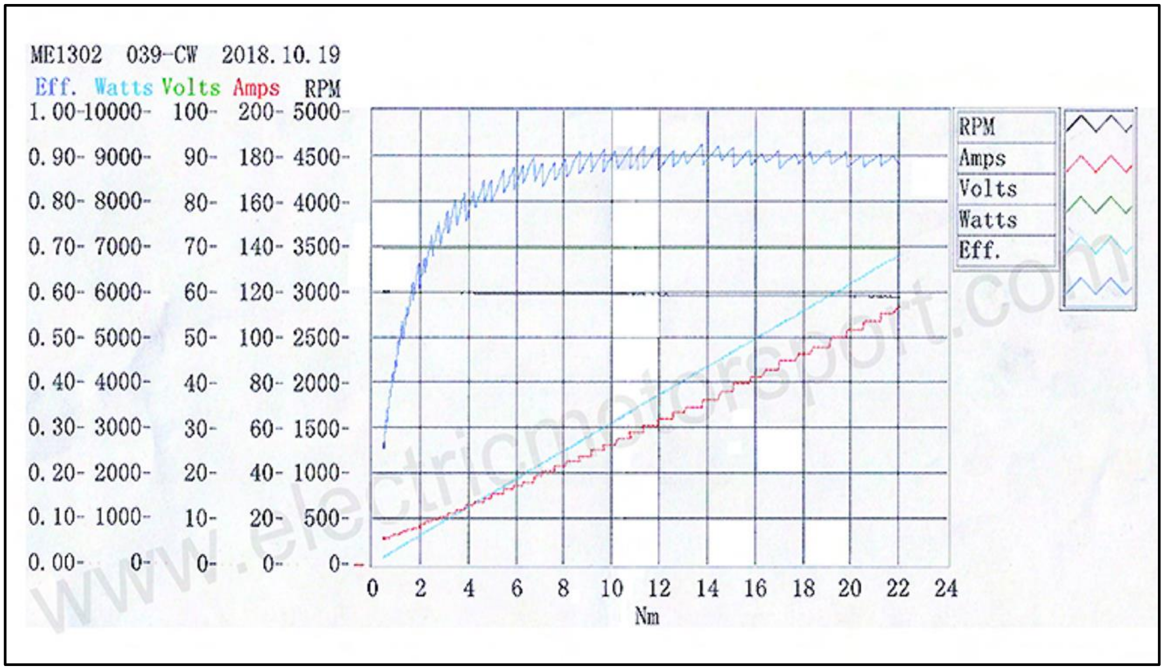


Figure 101. RPM vs Torque for ME1302
Note: Provided by manufacturer

Manual Transmission Operation with an Electric Motor:

Although it is unorthodox, an electric motor with a manual transmission is expected to function well. In many of the documented Spitfire EV conversions, a manual transmission is used to control the varying speeds of the motor (Martin, 2021). We expect the motor should be able to operate through the multiple transmission gears without a clutch, due to the low inertia of electric motors along with the use of RPM matching, which involves matching the RPMs of the motor with the RPMs of the transmission so that a clutch is not required to mesh the gearbox into the next set of gears (Santos, 2020). Our current design is to attach the motor directly to the transmission through means of an adapting plate and spline coupler which will attach the motor to the transmission. We plan on implementing the clutch to provide smoother shifting operation and a disconnect from the motor in case of haywire operation.

Motor Integration Components:

Motor Coupling:

Once the motor - transmission adaptor plate was manufactured, we needed to design a component to transmit the power from the motor armature to the input shaft of the transmission. This component, being inspired by existing electric adaptors, is a motor coupling. This motor coupling mounts on the keyed shaft of the motor and armature with a set screw to fixture it securely to the motor. The coupling has eight 10mm holes around the perimeter which serve as mounting points for the Corolla flywheel we implemented. The coupling was manufactured such that it could be bolted into the motor armature and mount on the key shaft but also be long enough to mesh with the base of the armature. This allows more power transfer to occur as the coupling is able to use the friction of the base of the armature and the bolt in its core to transmit power as opposed to just the keyed shaft. The coupling was also designed to mimic the AE86 engine in the sense that it has eight flywheel holes for the flywheel mounting, but additionally it houses the pilot bearing which seats on the tip of the input shaft. This was a very complicated component but is arguably the most critical part of the drivetrain. The coupling was manufactured out of hardened tool steel with the processes of turning primarily and milling the flywheel mounting holes and broached to house the 3/16” key of the motor. The component was originally turned and had the inner holes milled out; however, the process was found to be not accurate enough for the RPM requirements of this part and its need for absolute concentricity. We machined the component again using turning for all features besides the flywheel mounting holes. This provided perfect concentricity and quiet operation. Finite element analysis was completed on the design to ensure it would hold up to the induced stresses from the motor. This analysis was completed by constraining the coupling’s 8 through holes which will be rigidly attached to the clutch assembly and applying the stall torque of the motor (100Nm) as a radial load. As one can see, the expected load is about 102.6 MPa which is nearly 1/7 of the ultimate yield strength of this hardened steel. Below are images of the coupling from the design, analysis, manufacturing, and assembly phases (Figures 103, 104, 105, 106, and 107).

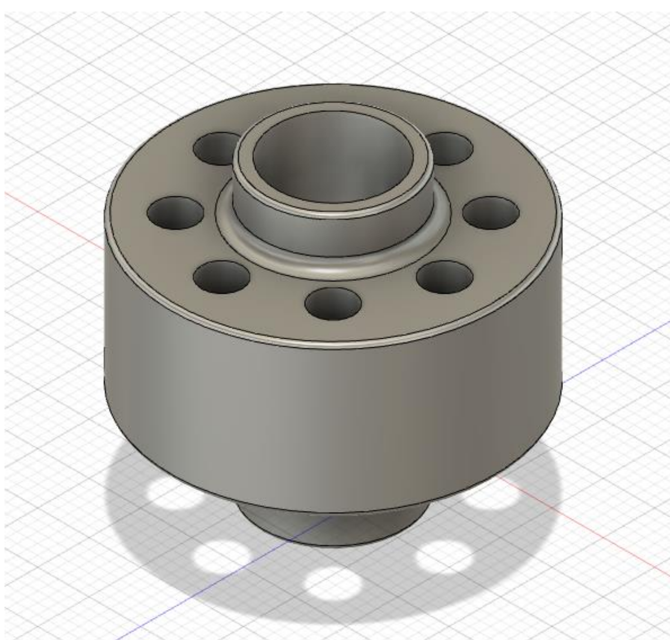


Figure 103. Motor Coupling Final CAD

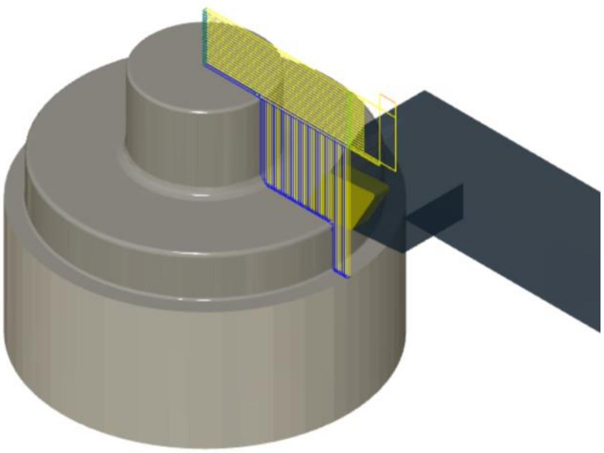


Figure 104. Coupling Turning Operation

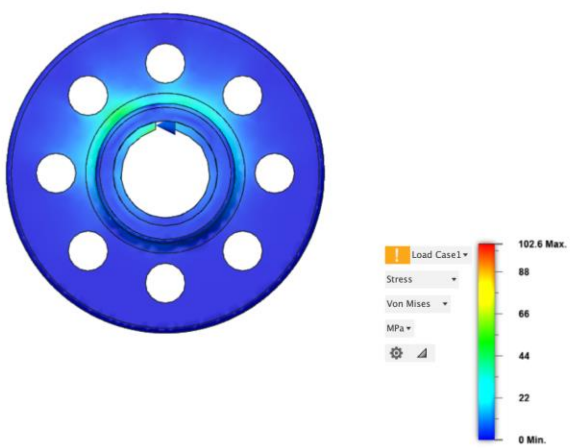


Figure 105. Coupling Finite Element Analysis

Figure 106. Coupling Turning Process

Figure 107. Coupling Final Model

Motor Spacer:

Once the motor coupling was manufactured, a spacer needed to be designed and manufactured. This component, though simple, is an integral component to the power transfer of the entire powertrain. This spacer's purpose is to offset the motor and coupling assembly enough to mesh with the input shaft of the transmission without being too far away from or too far into the bellhousing. This spacer, in addition to providing the required offset, also ensures no debris enters the bellhousing or clutch assembly and creates a fully closed system. The spacer was machined out of machinable polycarbonate. This material was selected to allow for some vibration dampening. It was machined using manual machines so as to not damage the automated machines and their cooling systems built to only handle machinable metals. Below are images of the spacer through the design and manufacturing process (Figures 108 and 109). As one can see, milling plastic leaves quite the mess and thus manual operations were preferred for this component.

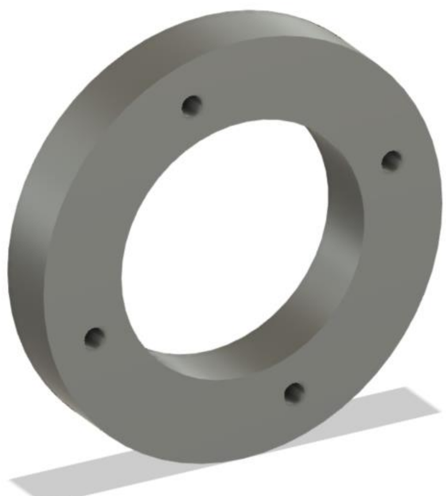


Figure 108. Motor Spacer CAD

Figure 109. Motor Spacer Machining on a Manual Mill with a Rotary Plate Fixture

Full Drivetrain Assembly:

Figure 110 shows an exploded view of our Spitfire's electric conversion drivetrain. Starting on the left, we have our ME1302 PMAC motor. This motor was a purchased part, and functions as the replacement for the combustion engine. Next is the motor coupler, which translates the rotation of the motor to the AE86 flywheel. This coupler was custom machined by our team. The Motor Spacer shown next was also machined by our team, and perfectly spaces the motor in relation to the sensitive internals of the transmission's clutch assembly. The transmission adapter plate was the largest CNC machined part created by our team, and acts as a faceplate and mounting point for our transmission and motor. The next three items within this view were all purchased. The AE86 Flywheel, Clutch Assembly, and Toyota Corolla AE86 (T-50) Transmission are all stock car components selected to match our engineered components. Finally, shown furthest to the right, is the Modified Flange Slip Yoke. This was another component manufactured by our team and couples the output spline of the T-50 transmission to the Spitfire’s driveshaft. See Appendix A for technical drawings of any components manufactured by our team.

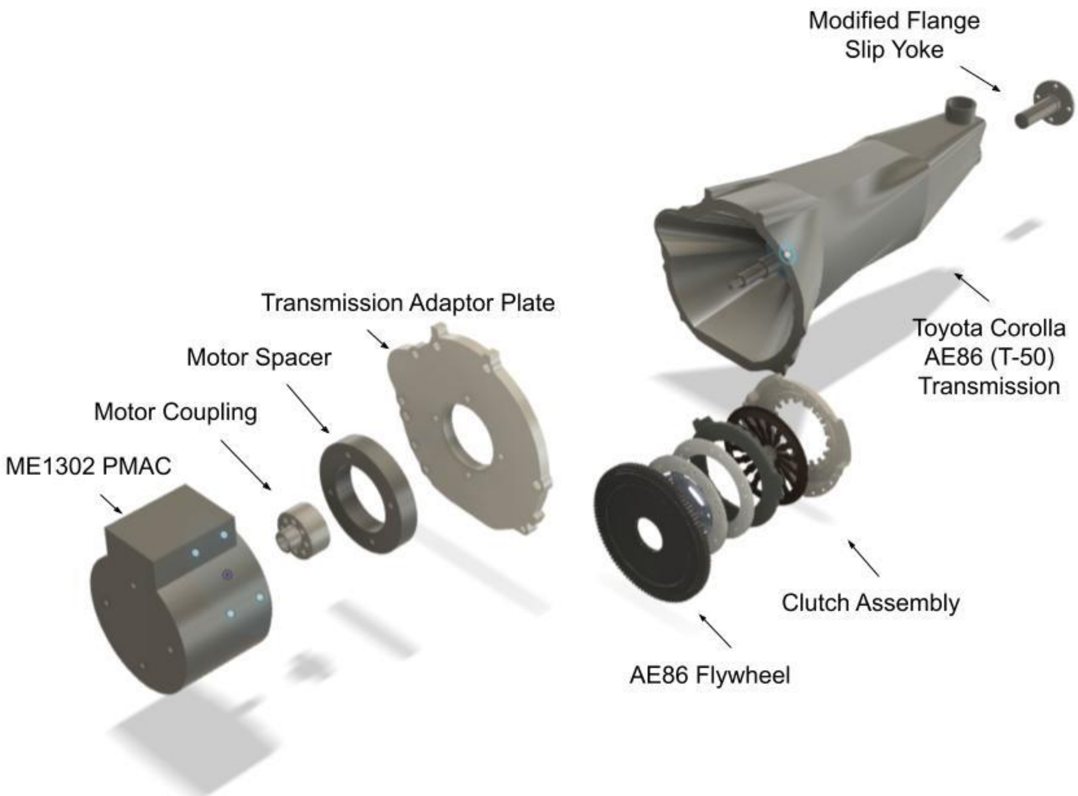


Figure 110. Exploded View of Engineered Drive Train

User Interface:

Overview:

For our system, we have some baseline requirements that we want to implement. One of these is for our UI to display data from the motor, battery, and temperature in real time. This allows the driver to know the basic data they need including their speed and state of charge. Another requirement of our system is that it produces warnings and errors if the system exceeds set parameters. This is seen if part of the system overheats, the battery charge is low, or if a fuse is tripped. This also includes any errors the battery management systems or the motor control unit produce. Beyond the requirements above, we also hope to have some extra parts we hope to include in our final design. This includes a remote database where we can store the car’s data and display it on a webpage, lane departure warnings, and possibly a navigation and music system.

While we hope to have the ability to go beyond the requirements, the requirements stated above are a necessity to make the Spitfire safe and easy to drive.

Hardware Selection:

When selecting the hardware that will run the UI, we first had to consider what other hardware this computer or controller will need to interface with.

Battery Considerations

The Battery Team has selected the Daly BMS as our choice of Battery Management System. It is a rather smart device and can be connected via UART, Bluetooth, or Controller Area Network (CAN) connection. However, these devices use a proprietary CAN protocol so it may be complex to communicate through that interface. These devices come with a UART-to-USB converter so we are first going to try communication through USB. We've found a python library specifically for these devices which makes communication to them over UART or USB quite simple. We are installing three of these devices, so our UI hardware must have at least this many USB 3 ports, or we can add a USB hub.

Motor Considerations

The Motor Team has selected the Sevcon Gen 4 as our Inverter and Motor Controller. This too is quite the smart device and is a common choice for FSAE teams. The controller's only means of communication is via CAN, however unlike the Daly's, the Gen 4 uses CAN open, one of the most common protocols for CAN communication (see Figures 111 and 112).

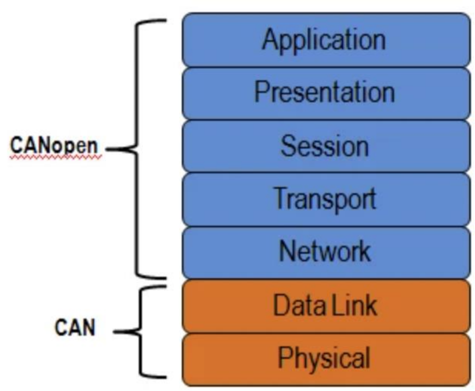


Figure 111. CANopen OSI Model

Figure 112. Sevcon Gen4 CAN Bus Port

This means our UI hardware must be able to connect to this network. To do this the hardware needs a CAN controller and CAN transceiver, although it is also possible to get expansion boards dedicated to this purpose if our UI hardware doesn't come with these built-in.

Dashboard Considerations

We need to display the information collected from the battery and motor onto a dashboard screen. We'd like this to be a touch screen so that the driver may interact with the information. From the dashboard or steering column the driver must be able to manipulate headlights, high beams, directionals, windshield wipers, ignition, and safety switches (contactors, Gen4 e-brake switch). All of this functionality could be converted to digital and handled by the UI hardware, but much of the existing functionality could remain analog to keep the digital interface simple and to avoid a central point of failure by relying too heavily on our UI hardware. In our dashboard design we've opted to keep as much analog as possible, largely for reliability but also to keep in line with the car's vintage aesthetic. Our UI hardware must be able to ship video to the screen and take touch events back as input. The simplest and most reliable way to do this is with an HDMI connection for video and a USB connection for touch events, and indeed this is how our selected screen operates. There is a connection on our transmission for our mechanical speedometer but there is no connection on our new motor for the mechanical tachometer so our UI hardware will have to drive a small motor based on the RPM data it receives from the Gen4.

Other Considerations

In addition to all of these requirements for our UI hardware, we must be able to connect to at least 2 cameras and process the incoming video from both of them as quickly as possible. This means we'd like some good graphics processing capabilities on our UI hardware. Finally, we want to have a good development platform that will allow us to build the required functionality in the time remaining in the project, as well as set the system up for future development so more advanced functionality could be added throughout the lifetime of the car.

Final Hardware Decision

We decided to use a single-board computer (SBC) rather than a microcontroller due to the large amount of I/O the UI hardware needs to do. We would like to be able to do these various communications in parallel, so the system is never blocked waiting for a response from another device. The computer we have selected is the NVIDIA Jetson Xavier NX Developer kit, a single-board computer from NVIDIA (see Figures 113 and 114).

Figure 113. Jetson Xavier NX Developer Kit

Figure 114. Jetson Xavier Processor Module and Carrier Board

This computer is geared towards professional edge AI applications, and as such has a shocking amount of horsepower for its small form factor. It includes a 384-core NVIDIA Volta GPU with 48 Tensor Cores and a 6-core NVIDIA Carmel ARM64 CPU. It can perform 21 tera-operations per second (TOPS). It runs a version of Ubuntu called Jetson Linux, which has support for a real-time kernel if we find our system is not meeting our real-time execution requirements. For our system, the real-time execution requirements are that the user interface can update without any time lag. This time lag could include animations being choppy and rough, or if the information is unable to be processed quickly. But since this system is primarily a human interface, the real-time requirements are relatively relaxed and the Jetson has enough horsepower so that there is no latency noticeable to the driver and therefore a real-time kernel isn't necessary. To add to this, we also plan to keep the lane assist software separate from the Jetson as well. This way, there is less worry with the real-time execution requirements since only the user interface will be running on it. Developing on a Linux system will hopefully speed up developing time as there is vast support available and our team is already quite familiar with Ubuntu. Additionally, the developer kit has all the I/O we need to interface with the other systems in the car such as the BMS, Gen4, and screen: 4x USB3 ports, I2C, SPI, UART, 2x MIPI CSI, HDMI, and DisplayPort. Additionally, it has an onboard CAN controller so by soldering on a small CAN transceiver we can communicate with the Motor Controller (see below Figure 115 and 116).

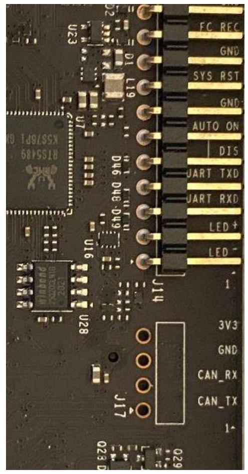


Figure 115. Pinout for mounting CAN hardware on the NVIDIA Jetson

Figure 116. Jetson CAN Hardware

With some configuration the CAN controller can be activated as an interface similar to Wi-Fi or ethernet. This should allow simple and fast communication to our Motor Controller (see Figure 117).

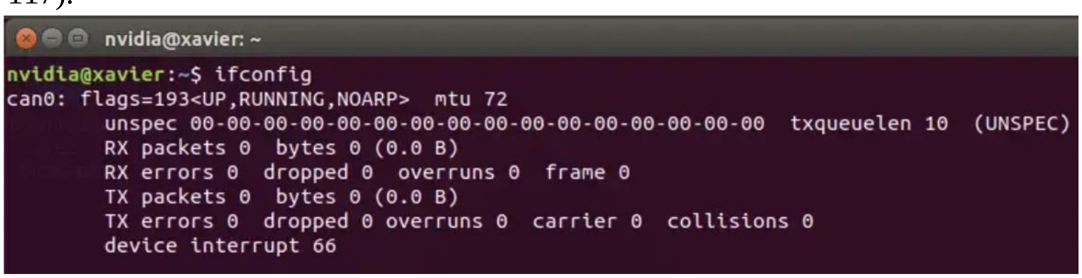


Figure 117. Jetson CAN Software

System Architecture:

Our system architecture can be seen below in Figure 118. It depicts the overall system surrounding the Jetson Xavier. All the colored blocks exiting the Jetson are the different ports that we will be using. As seen in the diagram, there are two C++ classes that we use to talk to the

BMS and MCU. These classes update data stored on the Qt application, which includes RPM, battery charge, temperature, and more. The Qt application will be run on the Jetson Xavier being displayed on the screen. The Jetson has an HDMI port that we plan on using to display the app as well as a USB port we plan on using to receive user input. Overall, this portion of the system is running the GUI.

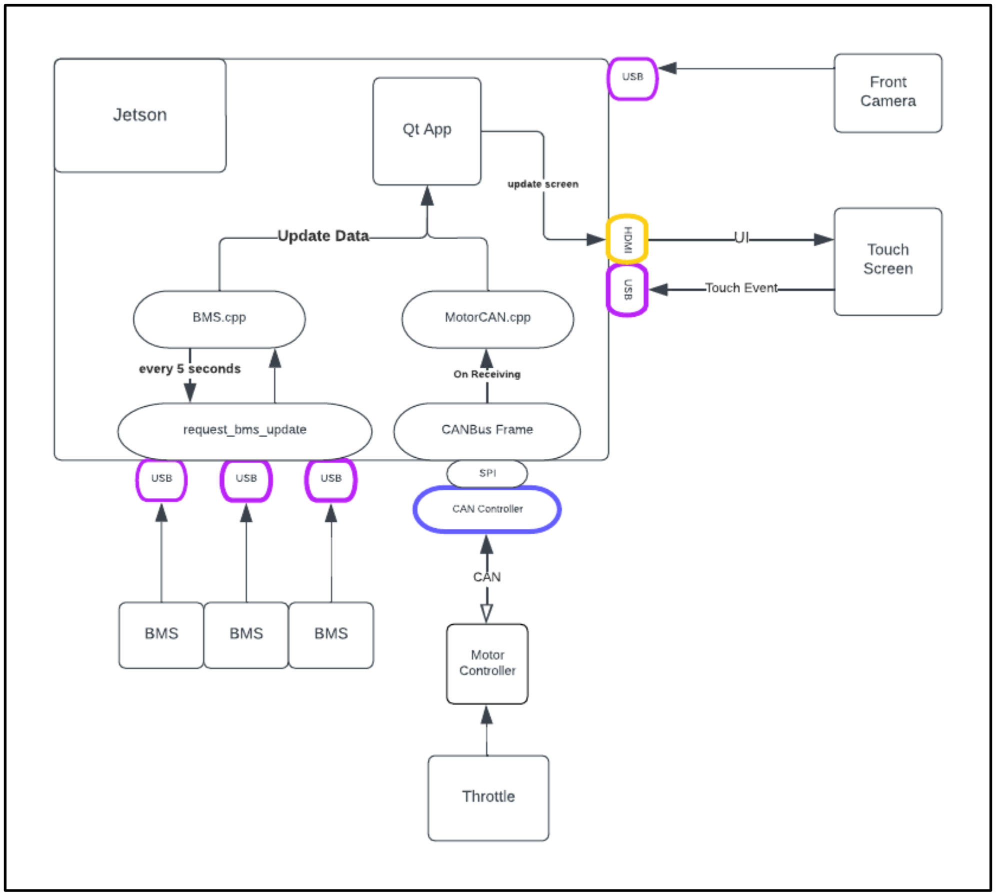


Figure 118. System Architecture

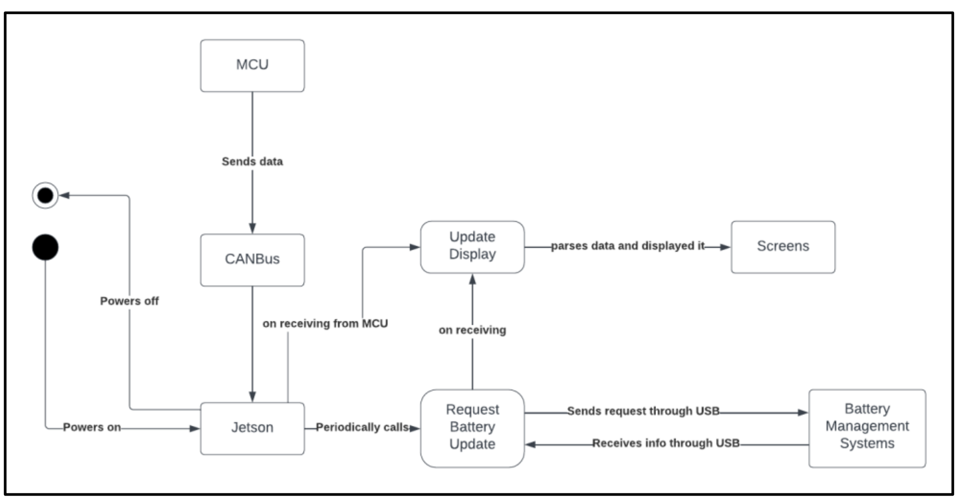


Figure 119. State Diagram

Above Figure 119 depicts the state diagram of the system when it is updating its information from its connected devices. The Jetson periodically sends a request to the BMS which splits into parallel processes which go to each individual connected device and requests an information update.

BMS Connection:

We connected the Jetson to the BMS through the USB ports. Every 5 seconds, the Jetson requests information from all three BMS devices through a c++ class. This request is using the system call to run a command line argument that returns the information in JSON format. The BMS’s output can be seen below in figure X. We then parse the JSON file to retrieve the needed data. The command that we run is from a python module for the BMS called, Daly BMS (See appendix D). Each one of these requests spawns a thread to maximize synchronization. This class will then store the new data before updating the screen. Specific items that will be updated on the screen are the charge of the battery, the battery temperature, and warnings and errors.

```
# daly-bms-cli  -d /dev/ttyUSB0 --soc
{
  "total_voltage": 57.7,
  "current": -11.1,
  "soc_percent": 99.1
}
```

Figure X: Picture of the BMS command line output

MCU Connection:

For our connection to the motor, we used a CAN Bus configuration. On receiving a CAN frame from the MCU, the program parses the frame for the motor speed and motor temperature. Once getting these values, the program then emits the values into the user interface, displaying them dynamically. While the MCU does have the tach and temperature values, it does not have the vehicles speed. For the vehicles speed, we used the GPS coordinates that we received to calculate the vehicles speed. This speed value was evaluated and updated every time the Jetson received GPS coordinates.

Error and Warning Log:

For our error and warning log, we decided to keep it on the right side of the screen as seen below. Both the MCU and BMS units provide their own error codes that are provided in an array. We took these arrays and, for each element, created an error code along with a short description of the error. We also created our own custom error and warning codes. The error codes will begin with either a 'W' for warning or an 'E' for error. Then it would be followed by a 'B' for BMS, a 'M' for MCU, and a 'C' followed by either a 'B' or 'M' for a custom error.

Figure 121. UI Warning and Error Log

Front-end Overview:

The following figures provide a tour of our user interface. Figure 122 is the home page which is the default view. This will be active most commonly. The information displayed on the left side is continuously updating as well as the clock. On the left side there is critical system information displayed such as vehicle speed, motor RPMs, overall battery charge, and temperatures for the motor and battery. Currently the vehicle speed is calculated through the change in GPS coordinate which is obtained through a serial AT command to our Sierra Wireless Airlink GX450. On the right side there is a Navigation app, which currently displays a map that updates with the GPS coordinate. Below that is the Spotify app, which is a custom minimal Spotify client which utilizes the Spotify Web API and the spotifyd daemon to control playback for a logged in Spotify account. The other applications on the right side are Error Log which is shown in Figure 121 and System Info which displays in-depth data from the BMS, such as total current, cell voltage range, and mosfet status.

Figure 122. UI Home Page

Figure 123 shows the center portion of the screen in its engaged state. This occurs when the user touches anywhere within the center section of the screen. This moves the car to this view in a fluid animation, as well as covers the clock and reveals a drop down of "Car Control" options. Currently, this only includes opening the video feed from the camera mounted on the top of the windshield, but in the future could include control of the headlights or other auxiliary systems. The user can tap anywhere but the button to return to the home page shown in Figure 122.

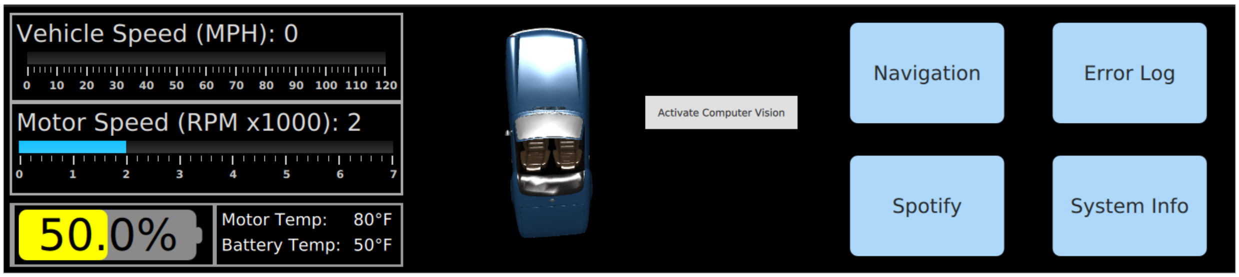


Figure 123. UI Car Menu

When the "Activate Computer Vision" button depicted in Figure Z is touched by the user the Figure 124 or Figure 125 is displayed showing the processed or unprocessed video feed from the windshield camera. In the processed configuration, this would also begin the serial communication of lane center offset to the steering controller. This page spawns a separate thread which continually checks for new frames and sends a signal to the front end when one is received. The processed video shown in Figure 125 is a recorded video generated by a separate python library used for our ADAS experiments. Eventually, we could perform the processing directly in this thread with the OpenCV C++ library for efficiency more suited to live performance. Additionally, we could then take full advantage of the NVIDIA Jetson Xavier graphics processing power using the hardware accelerated functions of the OpenCV library.

Figure 124. UI Unprocessed Dashcam Video

Figure 125. UI Processed Dashcam Video

Software Safety:

We must be sure in the design of this system that we are aware of the ways the software system can malfunction and the effect a malfunction may have on the safe operation of the car. With this in mind, so our design is to "read-only" with our UI system. This means that every other system can run independently of the Jetson, and in most cases where the Jetson encounters a failure the worst-case scenario would be that the dashboard user interface will crash. In this case, however, the car will still be able to operate normally. Additionally, the driver would be able to pull over to the side of the road and connect to the BMS through Bluetooth. This would allow the driver to check on the battery information in real time from their phone.

Dashboard Design:

We have designed a new dashboard setup which includes a digital screen to hold the Graphic User Interface (GUI) which displays system information to the driver. We plan on having 2 analog dials for the speedometer/odometer and tachometer. We also designed the dashboard to have a slot for the screen as well as a set of dials. The screen will be used to display charge and car statistics along with where error alerts will be shown. The dials will be used for different aspects of the car including windshield wipers, wiper fluid, headlights, high beams, and any other unforeseen uses. A digital mockup of the dashboard configuration can be seen in Figure 120.

Figure 126. Dashboard Design

For the digital screen we have selected a 11.9” Capacitive Touch, 320x1480, HDMI, IPS, Toughened Glass screen from Waveshare. This screen has a form factor which is ideal for this dashboard, taking advantage of the surplus of horizontal space while using a small amount of the vertical space, leaving plenty of room below it for the panel of switches and dials.

Advanced Driver Assistance Systems (ADAS):

Overview

Implementing an ADAS system was in the set of early defined ‘stretch goals’ for our team. By the end of this project, we were able to implement this experimental design and engage in early tests of the system.

Lane Assist systems in modern cars are typically engageable embedded systems which process video streams from externally facing cameras into information or action to assist the driver with staying in their lane. This functionality is usually most useful during highway driving of some duration, when the driver may become distracted or bored by the monotonous activity. Lane Assist is an example of the broader category of Advanced Driver Assistance Systems (ADAS). Other examples of ADAS include Adaptive Cruise Control, Adaptive High beams / Headlights, Automatic Parking, and many more. Our system implementation of lane assist includes sensors (cameras, lidar, ultrasonic), actuators (steering motor, warning light), and a control unit.

Any controller for a Lane Assist system must be able to capture a video stream from the front facing camera and process these frames into detected lane lines. Once it understands its position within the lane, it then conditionally warns the user of lane departure and/or “nudges” the wheel to keep the car in the lane. The understanding and action condition check should execute at a consistent rate, so that the system does not lag. This indicates that we should use a system which includes some real-time kernel. Image processing is particularly computationally expensive due to its multidimensional nature. Images are represented in memory as matrices, and image manipulations are performed via matrix operations. This can be exceptionally expensive computationally, especially on hardware that is not optimized to these operations like a general-purpose CPU.

The mechanical portion of the lane-assist system has two design necessities. Primarily, the system must be overridable. If the system malfunctions, it is a critical aspect of the physical design that the operator must maintain control and be able to overpower or disable the system. Secondly, the system must be disengage-able. Most of the time that the car is on the road, the lane assist will not be operating. As a result, it would be advantageous for the operator to not have to back drive the lane-assist motor during manual operation.

We implemented a gear and sprocket system driven by a NEMA34 stepper motor. The system would function by having a large diameter gear fixed to the steering column of the car as well as belt connecting to a smaller drive pulley. The NEMA34 would drive a smaller gear which would have its ‘free-idle’ engaged or disengaged electrically by providing power to the NEMA motor driver. The smaller gear would be the drive gear for the mechanical advantage it offers while still satisfying the desired range of motion for the steering wheel. The stepper motor would be wired to a programmable control board running the lane detection program.

The camera connected to the Lane Assist system will be mounted to the center top of the front windshield. The choice in camera is largely dependent on the choice in controller hardware for several reasons. The Jetson Xavier would likely be able to process about 20-30 frames a second, so we do not need a camera that is capable of frame rates much higher than this. Also some hardware options support MIPI CSI-2 and for some we would use HDMI or USB.

1. Serialization Options
    a. MIPI CSI-2 Camera
        i. Pros: Ultrafast
        ii. Cons: Slightly more expensive
    b. USB
        i. Pros: Cheaper
        ii. Cons: Limited ports

This application doesn’t necessarily need color either, although if we were to display processed output to the GUI then it may be useful. Ideally, the camera should also be rated for automotive applications so that it is not damaged during driving due to vibrations, temperature fluctuations, moisture, debris, etc.

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Appendices:

Appendix A: Drivetrain

Appendix A1: ME1302 PMAC Motor Drawing

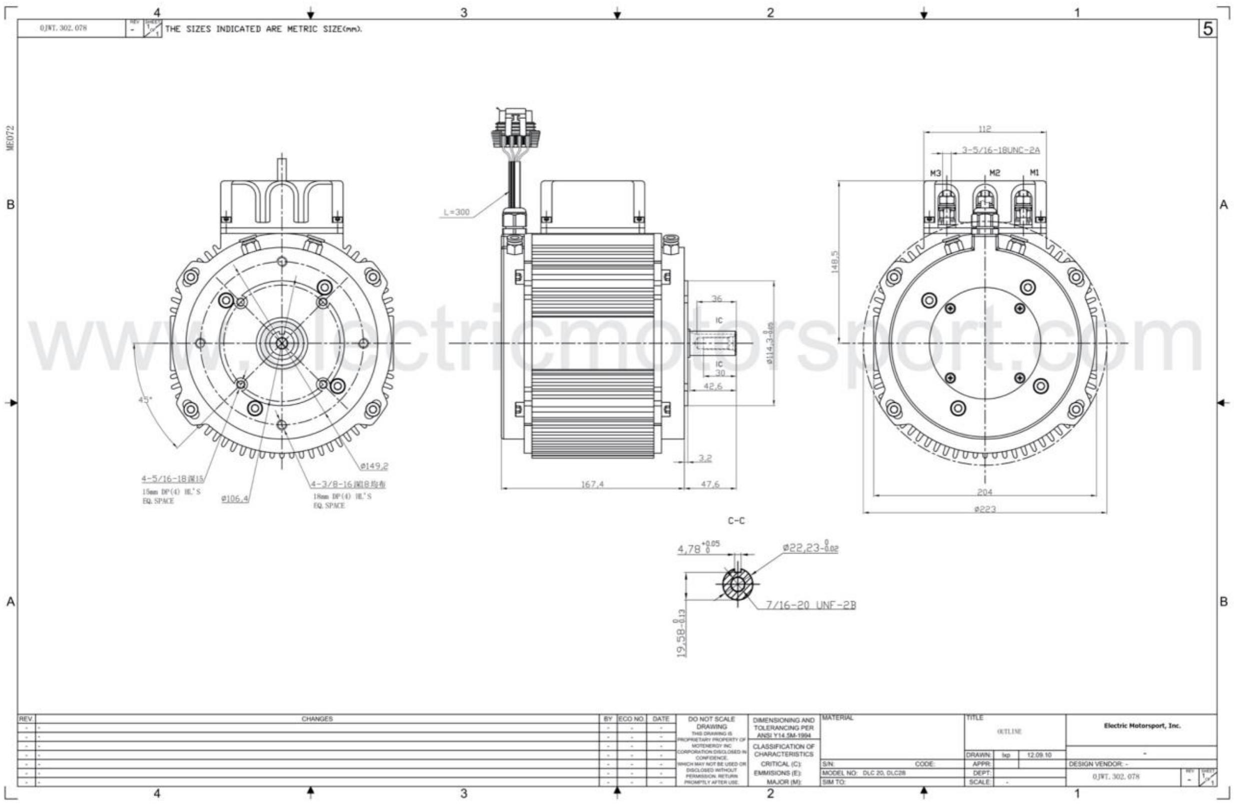


Figure 121.

Appendix A2: Motor Coupling Drawing

Figure 122.

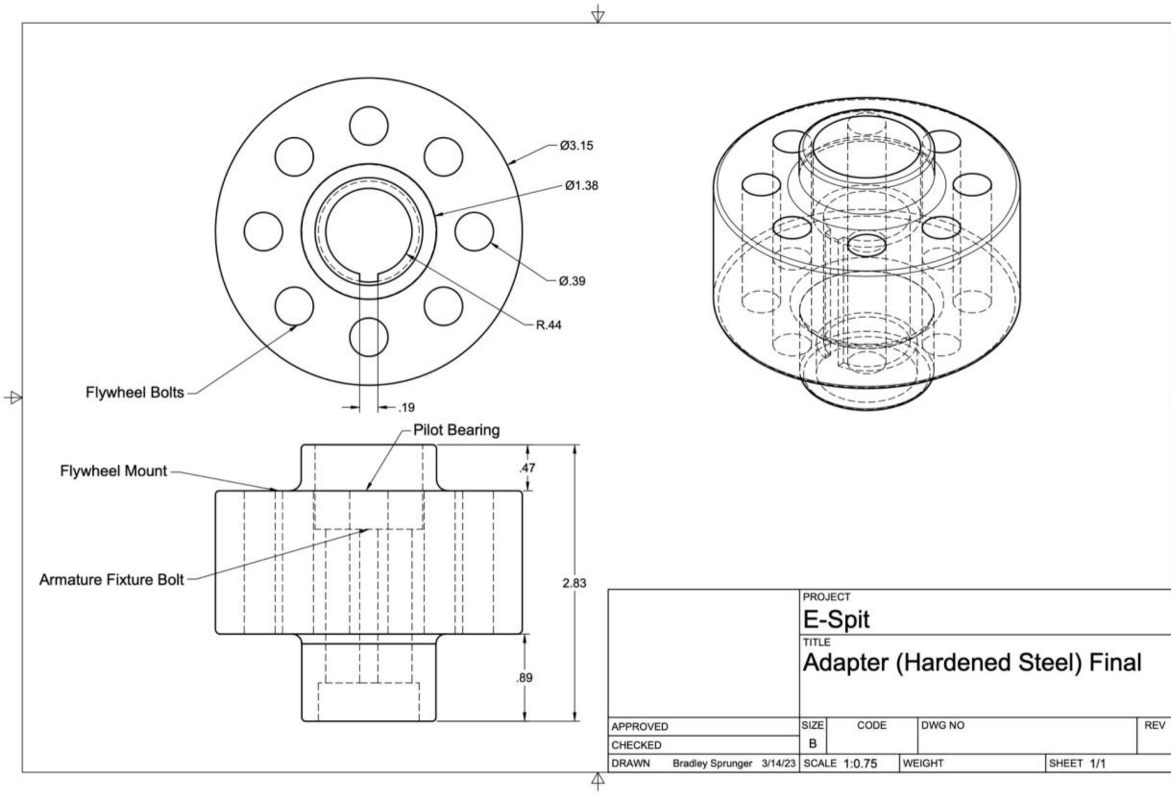


Figure 122.

Appendix A3: Motor Spacer Drawing

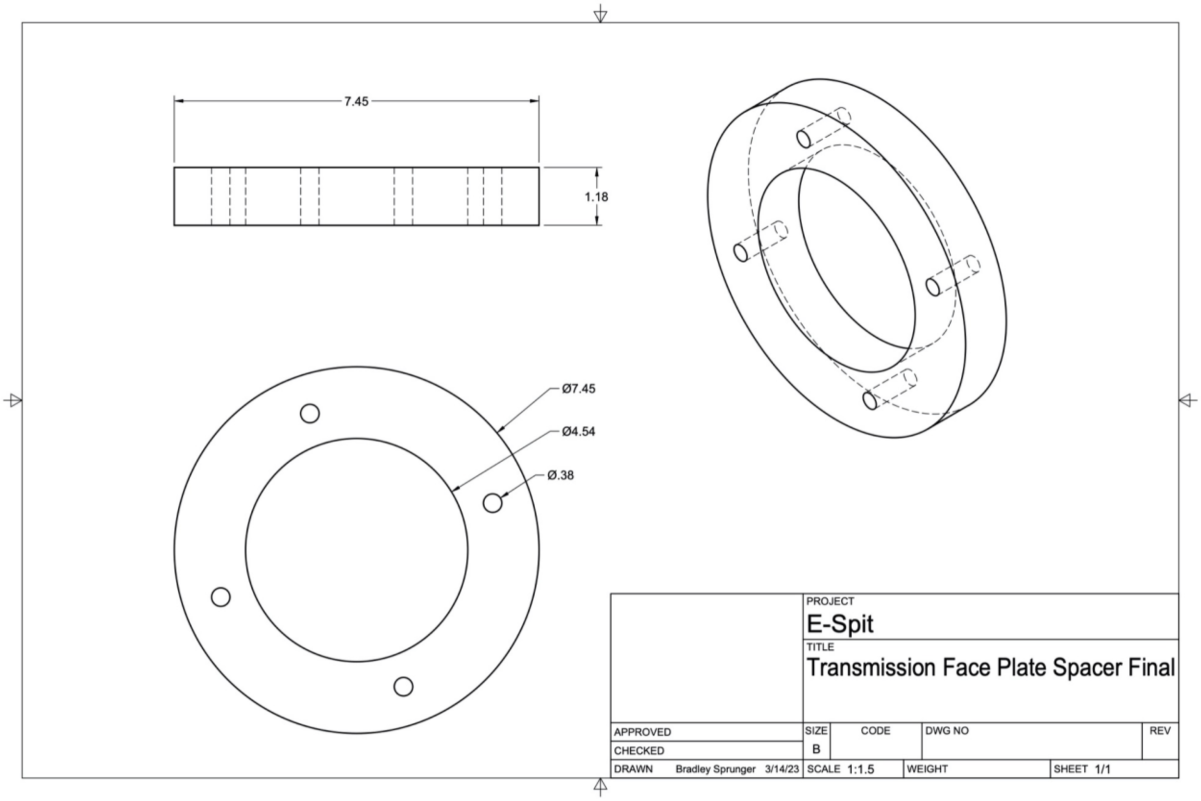

7.45
1.18
Ø7.45
Ø4.54
Ø.38
PROJECT
E-Spit
TITLE
Transmission Face Plate Spacer Final
APPROVED
CHECKED
DRAWN Bradley Sprunger 3/14/23
SIZE B
CODE
DWG NO
REV
SCALE 1:1.5
WEIGHT
SHEET 1/1

Figure 123.

Appendix A4: Transmission Face Plate Drawing

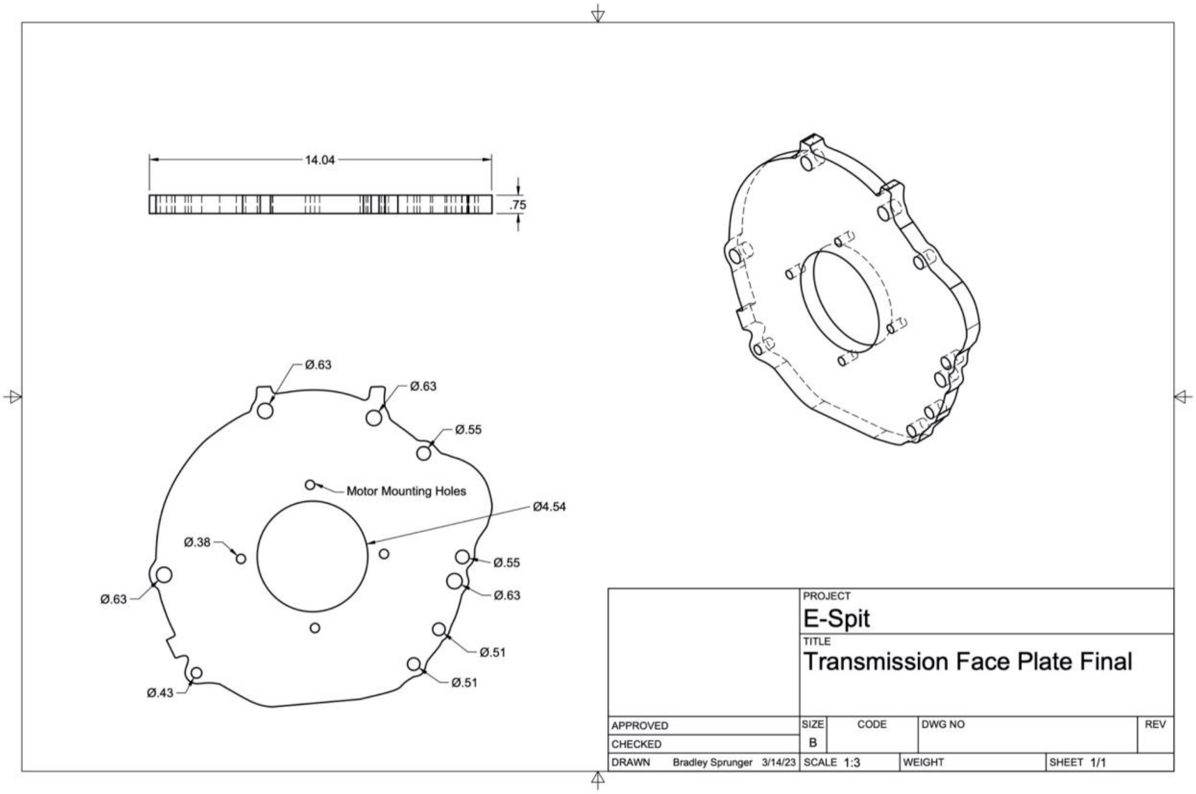


Figure 124.

Appendix A5: Modified Flange Slip Yoke Drawing

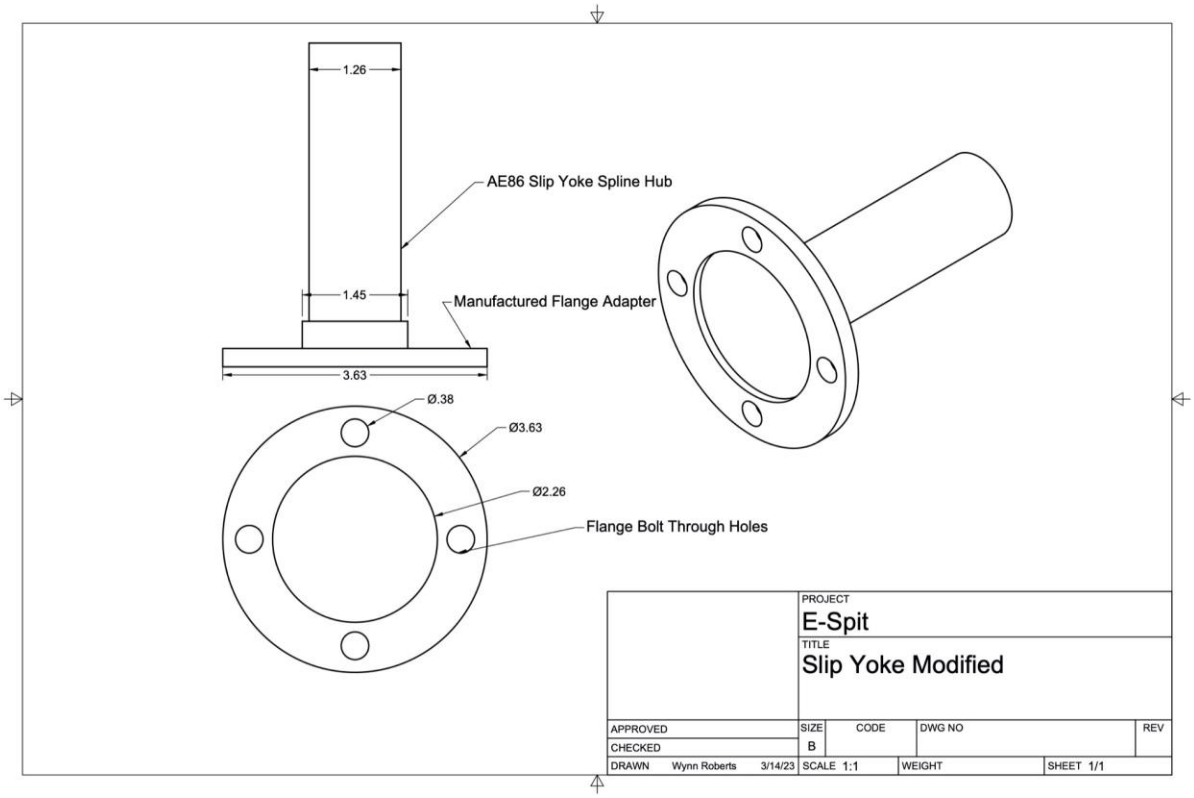
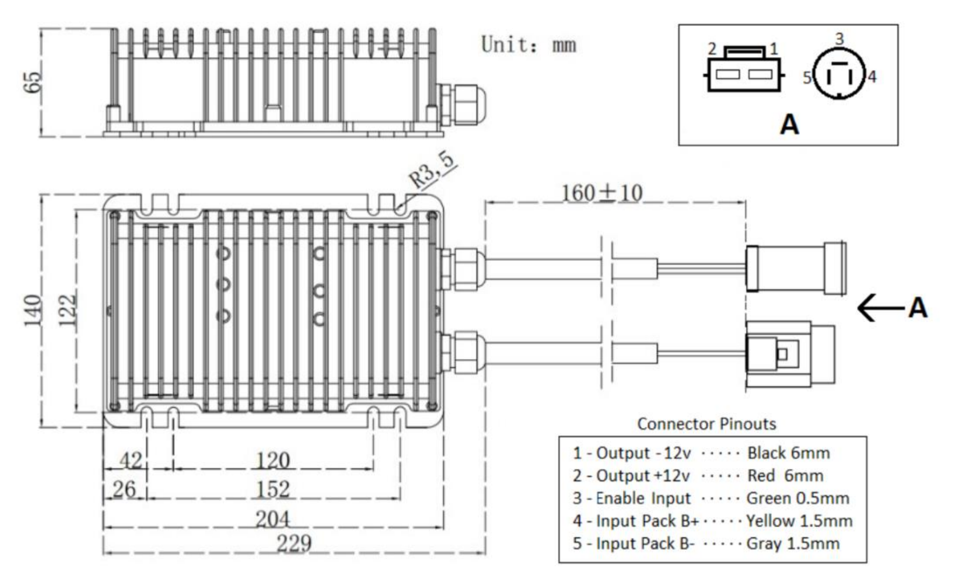


Figure 125.

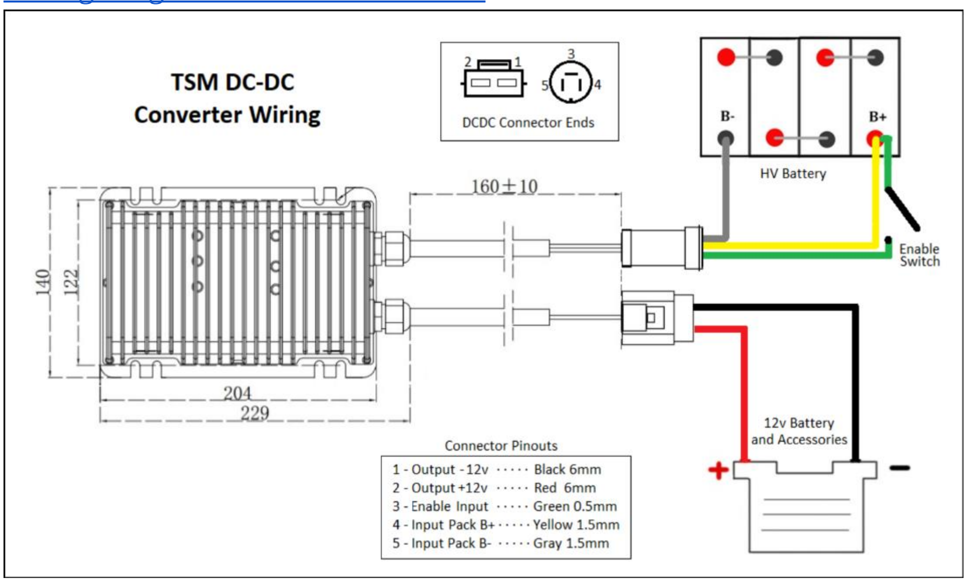
Appendix B: Electrical

Appendix B1: DC-DC Converter Technical Information:

Technical Drawings of DC-DC converter

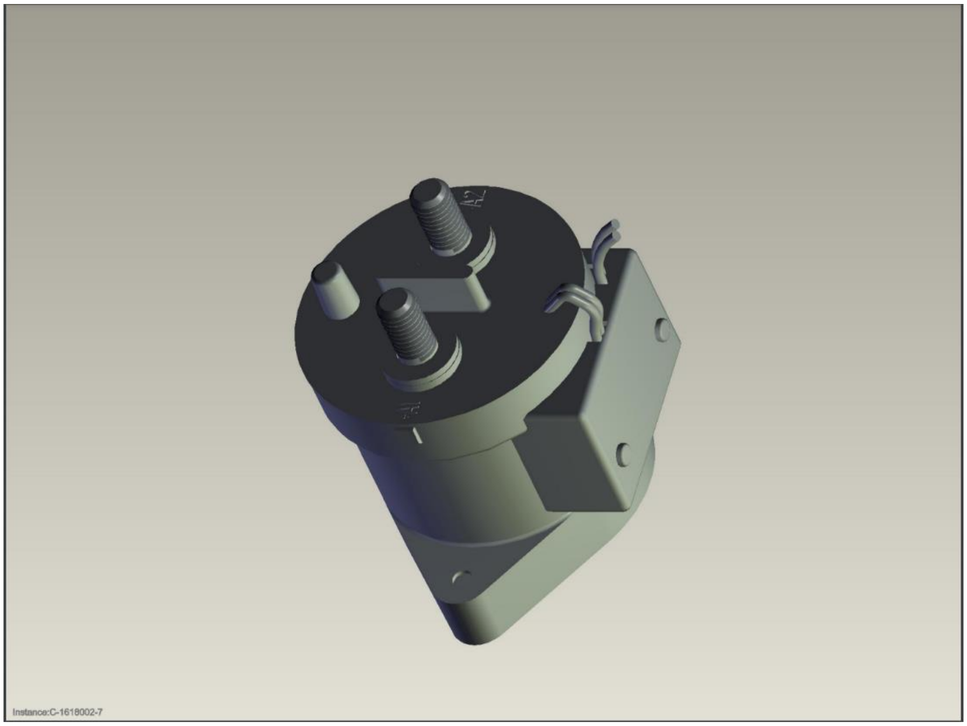


[Wiring Diagram of DC-DC converter]

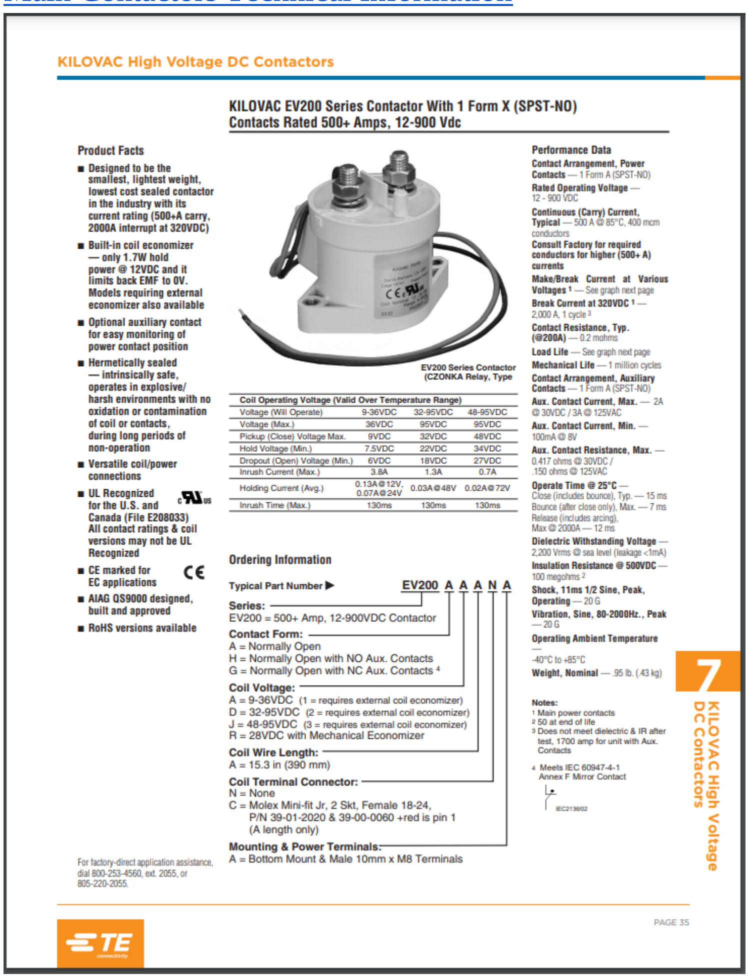


Appendix B2: Main Contactors Technical Information:

[CAD Drawing of Main Contactors]



Main Contactors Technical Information



KILOVAC High Voltage DC Contactors

KILOVAC EV200 Series Contactor With 1 Form X (SPST-NO) Contacts Rated 500+ Amps, 12-900 Vdc

Product Facts

- Designed to be the smallest, lightest weight, lowest cost sealed contactor in the industry with its current rating (500+A carry, 2000A interrupt at 320VDC)
- Built-in coil economizer — only 1.7W hold power @ 12VDC and it limits back EMF to 0V. Models requiring external economizer also available
- Optional auxiliary contact for easy monitoring of power contact position
- Hermetically sealed — intrinsically safe, operates in explosive/ harsh environments with no oxidation or contamination of coil or contacts, during long periods of non-operation
- Versatile coil/power connections
- UL Recognized for the U.S. and Canada (File E208033) All contact ratings & coil versions may not be UL Recognized
- CE marked for EC applications
- AIAG QS9000 designed, built and approved
- RoHS versions available

For factory-direct application assistance, dial 800-253-4560, ext. 2055, or 805-220-2055.

EV200 Series Contactor (CZONKA Relay, Type

Coil Operating Voltage (Valid Over Temperature Range)			
Voltage (Will Operate)	9-36VDC	32-95VDC	48-95VDC
Voltage (Max.)	36VDC	95VDC	95VDC
Pickup (Close) Voltage Max.	9VDC	32VDC	48VDC
Hold Voltage (Min.)	7.5VDC	22VDC	34VDC
Dropout (Open) Voltage (Min.)	6VDC	18VDC	27VDC
Inrush Current (Max.)	3.8A	1.3A	0.7A
Holding Current (Avg.)	0.13A@12V, 0.07A@24V	0.03A@48V	0.02A@72V
Inrush Time (Max.)	130ms	130ms	130ms

Ordering Information

Typical Part Number ▶ EV200 A A A N A

Series:
EV200 = 500+ Amp, 12-900VDC Contactor

Contact Form:
A = Normally Open
H = Normally Open with NO Aux. Contacts
G = Normally Open with NC Aux. Contacts [4]

Coil Voltage:
A = 9-36VDC (1 = requires external coil economizer)
D = 32-95VDC (2 = requires external coil economizer)
J = 48-95VDC (3 = requires external coil economizer)
R = 28VDC with Mechanical Economizer

Coil Wire Length:
A = 15.3 in (390 mm)

Coil Terminal Connector:
N = None
C = Molex Mini-fit Jr, 2 Skt, Female 18-24, P/N 39-01-2020 & 39-00-0060 +red is pin 1 (A length only)

Mounting & Power Terminals:
A = Bottom Mount & Male 10mm x M8 Terminals

Performance Data

Contact Arrangement, Power Contacts — 1 Form A (SPST-NO)
Rated Operating Voltage — 12 - 900 VDC
Continuous (Carry) Current, Typical — 500 A @ 85°C, 400 mcm conductors
Consult Factory for required conductors for higher (500+ A) currents
Make/Break Current at Various Voltages [1] — See graph next page
Break Current at 320VDC [1] — 2,000 A, 1 cycle [3]
Contact Resistance, Typ. (@200A) — 0.2 mohms
Load Life — See graph next page
Mechanical Life — 1 million cycles
Contact Arrangement, Auxiliary Contacts — 1 Form A (SPST-NO)
Aux. Contact Current, Max. — 2A @ 30VDC / 3A @ 125VAC
Aux. Contact Current, Min. — 100mA @ 8V
Aux. Contact Resistance, Max. — 0.417 ohms @ 30VDC / .150 ohms @ 125VAC
Operate Time @ 25°C — Close (includes bounce), Typ. — 15 ms Bounce (after close only), Max. — 7 ms Release (includes arcing), Max @ 2000A — 12 ms
Dielectric Withstanding Voltage — 2,200 Vrms @ sea level (leakage <1mA)
Insulation Resistance @ 500VDC — 100 megohms [2]
Shock, 11ms 1/2 Sine, Peak, Operating — 20 G
Vibration, Sine, 80-2000Hz., Peak — 20 G
Operating Ambient Temperature — -40°C to +85°C
Weight, Nominal — .95 lb. (.43 kg)

Notes:
1 Main power contacts
2 50 at end of life
3 Does not meet dielectric & IR after test, 1700 amp for unit with Aux. Contacts
4 Meets IEC 60947-4-1 Annex F Mirror Contact

IEC2136/02

7 KILOVAC High Voltage DC Contactors

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Additional Technical Information regarding Main Contactors

Tyco Electronics

KILOVAC EV200 Series Contactor With 1 Form X Contacts Rated 500+ Amps, 12-900VDC

Product Facts

- **Designed to be the smallest, lightest weight, lowest cost sealed contactor in the industry with its current rating (500+A carry, 2000A interrupt at 320VDC).**
- **Built-in coil economizer – only 1.7W hold power @ 12VDC and it limits back EMF to 0V. Models requiring extenal economizer also available.**
- **Optional auxiliary contact for easy monitoring of power contact position.**
- **Hermetically sealed – intrinsically safe, operates in explosive/harsh environments with no oxidation or contamination of coils or contacts, including long periods of non-operation.**
- **Versatile coil/power connections.**
- **CE marked for EC applications.**
- **AIAG QS9000 designed, built and approved**

CE

c UL us File E208033

EV200 Series Contactor (CZONKA® Relay, Type III)

Typical EV200 applications include battery switching and back-up, DC voltage power control, circuit protection and safety.

For factory-direct application assistance, dial 800-253-4560, ext. 2055, or 805-220-2055.

Performance Data

Parameter	Units	Value for EV200 Series
Contact Arrangement, power contacts		1 Form X (SPST-NO-DM)
Rated Operating Voltage	VDC	12 - 900
Continuous (Carry) Current, Typical *Consult Factory for required conductors for higher (500+ A) currents*	A	500 @ 85°C, 400 mcm conductors
Make/Break Current at Various Voltages [1]	A	See next page
Break Current at 320VDC [1]	A	2,000, 1 cycle [3]
Contact Resistance, Typ. (@200A)	mohms	0.2
Load Life	Cycles	See next page
Mechanical Life	Cycles	1 million
Contact Arrangement, auxiliary contacts		1 Form A (SPST-NO)
Aux. Contact Current, Max. Aux. Contact Current, Min.	A mA	2A @ 30VDC / 3A @ 125VAC 100mA @ 8V
Aux. Contact Resistance, Max.	ohms	0.417 @ 30VDC / .150 @ 125VAC
Operate Time @ 25°C Close (includes bounce), Typ. Bounce (after close only), Max. Release (includes arcing), Max @ 2000A	 ms ms ms	 15 7 12
Dielectric Withstanding Voltage	Vrms	2,200 @ sea level (leakage <1mA)
Insulation Resistance @ 500VDC	megohms	100 [2]
Shock, 11ms 1/2 sine, peak, operating	G	20
Vibration, sine, 80-2000Hz., peak	G	20
Operating Ambient Temperature	°C	-40 to +85
Weight, Nominal	lb.(kg)	.95 (.43)

[1] Main power contacts
[2] 50 at end of life
[3] Does not meet dielectric & IR after test, 1700 amp for unit with Aux. Contacts

Coil Operating Voltage (valid over temperature range)			
Voltage (will operate)	9-36VDC	32-95VDC	48-95VDC
Voltage (Max.)	36VDC	95VDC	95VDC
Pickup (close) Voltage Max.	9VDC	32VDC	48VDC
Hold Voltage (Min.)	7.5VDC	22VDC	34VDC
Dropout (open) Voltage (Min.)	6VDC	18VDC	27VDC
Inrush Current (Max.)	3.8A	1.3A	0.7A
Holding Current (Avg.)	0.13A@12V, 0.07A@24V	0.03A@48V	0.02A@72V
Inrush Time (Max.)	130ms	130ms	130ms

Part Numbering System

Typical Part Number	EV200	A	A	A	N	A

Series:
EV200 = 500+ Amp, 12-900VDC Contactor

Contact Form:
A = Normally Open H = Normally Open with Aux. Contacts

Coil Voltage:
A = 9-36VDC (1 = requires external coil economizer)
D = 32-95VDC (2 = requires external coil economizer)
J = 48-95VDC (3 = requires external coil economizer)
R = 28VDC with Mechanical Economizer

Coil Wire Length:
A = 15.3 in (390 mm) B = 6.0 in (152 mm)

Coil Terminal Connector:
N = None
B = Yazaki 7282-5558-10 male, 7114-4102-02, 7158-3030-50 +red is pin 2 (B length only)
C = Molex Mini-fit Jr, 2 Ckt, Female 18-24, P/N 39-01-2020 & 39-00-0060 +red is pin 1 (A length only)

Mounting & Power Terminals:
A = Bottom Mount & Male 10mm x M8 Terminals

Catalog EV200--R-TBD
Revised 8-07

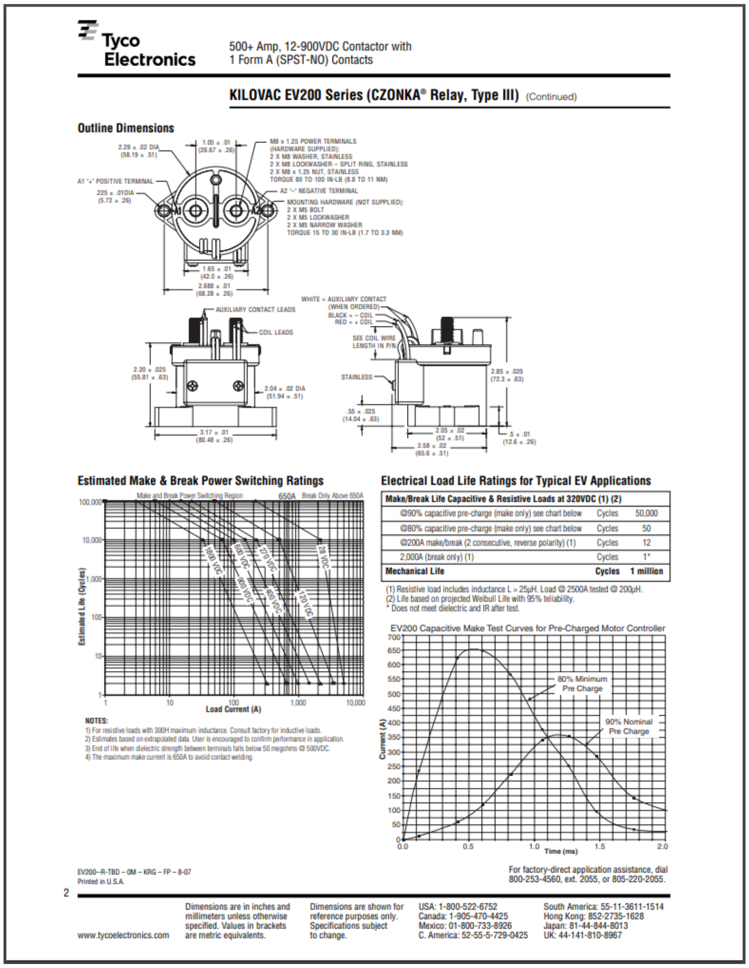
www.tycoelectronics.com

Dimensions are in inches and millimeters unless otherwise specified. Values in brackets are metric equivalents.

Dimensions are shown for reference purposes only. Specifications subject to change.

USA: 1-800-522-6752
Canada: 1-905-470-4425
Mexico: 01-800-733-8926
C. America: 52-55-5-729-0425

South America: 55-11-3611-1514
Hong Kong: 852-2735-1628
Japan: 81-44-844-8013
UK: 44-141-810-8967



Tyco Electronics

500+ Amp, 12-900VDC Contactor with 1 Form A (SPST-NO) Contacts

KILOVAC EV200 Series (CZONKA® Relay, Type III) (Continued)

Outline Dimensions

Estimated Make & Break Power Switching Ratings

NOTES:
1) For resistive loads with 300H maximum inductance. Consult factory for inductive loads.
2) Estimates based on extrapolated data. User is encouraged to confirm performance in application.
3) End of life when dielectric strength between terminals falls below 50 megohms @ 500VDC.
4) The maximum make current is 650A to avoid contact welding.

Electrical Load Life Ratings for Typical EV Applications

Make/Break Life Capacitive & Resistive Loads at 320VDC (1) (2)		
@90% capacitive pre-charge (make only) see chart below	Cycles	50,000
@80% capacitive pre-charge (make only) see chart below	Cycles	50
@200A make/break (2 consecutive, reverse polarity) (1)	Cycles	12
2,000A (break only) (1)	Cycles	1*
Mechanical Life	**Cycles**	**1 million**

(1) Resistive load includes inductance L = 25µH. Load @ 2500A tested @ 200µH.
(2) Life based on projected Weibull Life with 95% teliability.
* Does not meet dielectric and IR after test.

EV200 Capacitive Make Test Curves for Pre-Charged Motor Controller

EV200--R-TBD – 0M – KRG – FP – 8-07
Printed in U.S.A.

For factory-direct application assistance, dial 800-253-4560, ext. 2055, or 805-220-2055.

2

www.tycoelectronics.com

Dimensions are in inches and millimeters unless otherwise specified. Values in brackets are metric equivalents.

Dimensions are shown for reference purposes only. Specifications subject to change.

USA: 1-800-522-6752
Canada: 1-905-470-4425
Mexico: 01-800-733-8926
C. America: 52-55-5-729-0425

South America: 55-11-3611-1514
Hong Kong: 852-2735-1628
Japan: 81-44-844-8013
UK: 44-141-810-8967

Appendix B3: Future Considerations with Ground Fault Isolation System

Ground isolation faults occur in the creation of low resistance paths between the positive and negative terminals of the battery pack as well as between the vehicle chassis and each of the battery terminals. Low resistance paths within the high powered rails of an electric vehicle and the chassis allow extremely high currents where vehicle operators and passengers often come in contact which is extremely dangerous. In order to mitigate this threat we must develop a system to track and identify this phenomena.

There are many strategies as to identify a ground fault, but they are all based around attaching probes to both positive and negative terminals of the battery and another to the chassis. There are devices on the market such as the SIM100 connected this way that will calculate isolation resistance using high impedance values and makes sure they are within the safety standard. A high isolation resistance means that leakage current is kept to a harmless minimum. This method would be extremely simple to implement in our design and however would require us to read the data through CAN communication.

However, another method proposed attaching a connection between the positing and negative terminals of two separate batteries to locating the midpoint. Then attaching a high-impedance resistor from the batteries to ground (Blázquez et al 2019). In the event of a ground fault leakage current will travel across the resistor creating a greater voltage than measured during normal operation (Blázquez et al 2019). In the case of fault current we will see that the lower the isolation resistance is, the higher the grounding resistor voltage will be. However, in the case of a DC current fault, this method will allow us to identify the location of the fault by looking at the polarity of the voltage (Blázquez et al 2019). For an AC current fault, the grounding resistor voltage will give us the frequency of the leakage signal (Blázquez et al 2019). If the operating frequencies of each converter is known we can easily determine which converter is leaking current by matching the frequencies. For our application using this method, we would want to have three monitored grounding resistors between each series configuration in our battery pack.

F. Blázquez, J. M. Guerrero, C. A. Platero, and P. Tian, "Ground Fault Location System for Powertrain of Electric Vehicles," 2019 IEEE 12th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED), Toulouse, France, 2019, pp. 488-492, doi: 10.1109/DEMPED.2019.8864859.

Appendix C: Battery Design

Appendix C1: Battery Technical Information:

Link to LG-MJ-1 18650 Battery Spec Sheet
Sheet attached below:

LG Chem

PRODUCT SPECIFICATION
CONFIDENTIAL

Prepared		*Document No.*	*Date*	*Rev*
LGC MBD/MBDC	Oh, Kyung Su	LRB-PS-CY3450_MJ1	2014-08-22	1

Approved		*Description*
LGC MBD/MBDC	Kim, Dong Myung	Lithium Ion INR18650 MJ1 3500mAh

PRODUCT SPECIFICATION

Rechargeable Lithium Ion Battery Model : INR18650 MJ1 3500mAh

LG Chem

20 YOIDO-DONG YOUNGDUNGPO-GU,

SEOUL 150-721, KOREA

http://www.lgchem.com

Revision History

Revision	Date	Originator	Description
0	2014-04-28	Oh, Kyung Su	- Draft
1	2014-08-22	Oh, Kyung Su	-2.2. Nominal Voltage - 3.63V → 3.635V

Contents

1. General Information

1.1 Scope

This product specification defines the requirements of the rechargeable lithium ion battery of LG Chem.

1.2 Product classification

Cylindrical rechargeable lithium ion battery

1.3 Model name

INR18650 MJ1

2. Nominal Specification

Item	Condition / Note	Specification
2.1 Energy	Std. charge / discharge	Nominal 3500 mAh Minimum 3400 mAh
2.2 Nominal Voltage	Average	3.635V
2.3 Standard Charge (Refer to 4.1.1)	Constant current Constant voltage End current(Cut off)	0.5C (1700mA) 4.2V 50mA
2.4 Max. Charge Voltage		4.2 ± 0.05V
2.5 Max. Charge Current		1.0 C (3400mA)
2.6 Standard Discharge (Refer to 4.1.2)	Constant current End voltage(Cut off)	0.2C (680mA) 2.5V
2.7 Max. Discharge Current		10A
2.8 Weight	Approx.	Max. 49.0 g
2.9 Operating Temperature	Charge Discharge	0 ~ 45℃ -20 ~ 60℃
2.10 Storage Temperature (for shipping state)	1 month 3 month 1 year	-20 ~ 60℃ -20 ~ 45℃ -20 ~ 20℃

3. Appearance and Dimension

3.1 Appearance

There shall be no such defects as deep scratch, crack, rust, discoloration or leakage, which may adversely affect the commercial value of the cell.

3.2 Dimension

Diameter: 18.4 +0.1 / -0.3 mm (Max. 18.5mm)

Height: 65.0 ±0.2mm (Max. 65.2mm)

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4. Performance Specification

4.1 Standard test condition

4.1.1 Standard Charge

Unless otherwise specified, “Standard Charge” shall consist of charging at constant current of 0.5C. The cell shall then be charged at constant voltage of 4.20V while tapering the charge current. Charging shall be terminated when the charging current has tapered to 50mA. For test purposes, charging shall be performed at 23ºC ± 2ºC.

4.1.2 Standard Discharge

“Standard Discharge” shall consist of discharging at a constant current of 0.2C to 2.50V. Discharging is to be performed at 23 ºC ± 2 ºC unless otherwise noted (such as capacity versus temperature).

4.1.3 High Drain rate Charge/discharge condition

Cells shall be charged at constant current of 1,500mA to 4.20V with end current of 100mA. Cells shall be discharged at constant current of 4,000mA to 2.50V. Cells are to rest 10 minutes after charge and 20 minutes after discharge.

4.2 Electrical Specification

Item	Condition	Specification
4.2.1 Initial AC Impedance	Cell shall be measured at 1kHz after charge per 4.1.1.	≤ 40 mΩ, without PTC
4.2.2 Initial Capacity	Cells shall be charged per 4.1.1 and discharged per 4.1.2 within 1h after full charge.	≥ 3400 mAh
4.2.3 Cycle Life	Cells shall be charged and discharged per 4.1.3 400 cycles. A cycle is defined as one charge and one discharge. 401st discharge power shall be measured per 4.1.1 and 4.1.2	≥ 80 % (of C_{min} in 2.1)

4.3 Environmental specification.

Item	Condition		Specification
4.3.1 Storage Characteristics	Cells shall be charged per 4.1.1 and stored in a temperature-controlled environment at 23ºC ± 2ºC for 30 days. After storage, cells shall be discharged per 4.1.2 to obtain the remaining power*.		Power remaining rate ≥ 90% (P_{min} in 2.1)
4.3.2 High Temperature Storage Test	Cells shall be charged per 4.1.1 and stored in a temperature-controlled environment at 60ºC for 1 week. After storage, cells shall be discharged per 4.1.2 and cycled per 4.1.3 for 3 cycles to obtain recovered power**.		No leakage, Power recovery rate ≥ 80%
4.3.3 High Temperature and High Humidity Test	Cells are charged per 4.1.1 and stored at 60ºC (95% RH) for 168 hours. After test, cells are discharged per 4.1.2 and cycled per 4.1.3 for 3 cycles to obtain recovered power.		No leakage, No rust Power recovery rate ≥ 80%
4.3.4 Thermal Shock Test	65ºC (8h) ← 3hrs → -20ºC (8h) for 8 cycles with cells charged per 4.1.1 After test, cells are discharged per 4.1.2 and cycled per 4.1.3 for 3 cycles to obtain recovered power.		No leakage Power recovery rate ≥ 80%
4.3.5 Temperature Dependency of Capacity	Cells shall be charged per 4.1.1 at 23ºC ± 2ºC and discharged per 4.1.2 at the following temperatures.		
	Charge	Discharge	Capacity
	23℃	-10℃ 0℃ 23℃ 60℃	70% of P_{ini} 80% of P_{ini} 100% of P_{ini} 95% of P_{ini}

* Remaining Capacity: After storage, cells shall be discharged with Std. condition (4.1.2) to measure the remaining capacity.
** Recovery Capacity: After storage, cells shall be discharged with fast discharge condition (4.1.3), and then cells shall be charged with std. charge condition (4.1.1), and then discharged with Std. condition (4.1.2). This charge / discharge cycle shall be repeated three times to measure the recovery capacity.

4.4 Mechanical Specification

Item	Condition	Specification
4.4.1 Drop Test	Cells charged per 4.1.1 are dropped onto an wooden floor from 1.0 meter height for 1 cycle, 2 drops from each cell terminal and 1drop from the side of cell can (Total number of drops = 3).	No leakage No temperature rising
4.4.2 Vibration Test	Cells charged per 4.1.1 are vibrated for 90 minutes per each of the three mutually perpendicular axis (x, y, z) with total excursion of 0.8mm, frequency of 10Hz to 55Hz and sweep of 1Hz change per minute	No leakage

4.5 Safety Specification

Item	Condition	Specification
4.5.1 Overcharge Test	Cells are discharged per 4.1.2, and then charged at constant current of 3 times the max. charge condition and constant voltage of 4.2V while tapering the charge current. Charging is continued for 7 hours (Per UL1642).	: No explode, No fire
4.5.2 External Short - Circuiting Test	Cells are charged per 4.1.1, and the positive and negative terminal is connected by a 100mΩ-wire for 1 hour (Per UL1642).	: No explode, No fire
4,5.3 Overdischarge Test	Cells are discharged at constant current of 0.2C to 250% of the minimum capacity.	: No explode, No fire
4.5.4 Heating Test	Cells are charged per 4.1.1 and heated in a circulating air oven at a rate of 5ºC per minute to 130ºC. At 130ºC, oven is to remain for 10 minutes before test is discontinued (Per UL1642).	: No explode, No fire
4.5.5 Impact Test	Cells charged per 4.1.1 are impacted with their longitudinal axis parallel to the flat surface and perpendicular to the longitudinal axis of the 15.8mm diameter bar (Per UL1642).	: No explode, No fire
4.5.6 Crush Test	Cells charged per 4.1.1 are crushed with their longitudinal axis parallel to the flat surface of the crushing apparatus (Per UL1642).	: No explode, No fire

5. Caution

Warning: Using the lithium ion rechargeable battery, mishandling of the battery may cause heat, fire and deterioration in performance. Be sure to observe the following.

5.1 Cautions for Using and Handling

- When using the application equipped with the battery, refer to the user's manual before usage.
- Please read the specific charger manual before charging.
- Charge time should not be longer than specified in the manual.
- When the cell is not charged after long exposure to the charger, discontinue charging.
- Battery must be charged at operating temperature range 0 ~ 45℃.
- Battery must be discharged at operating temperature range -20 ~ 60℃.
- Please check the positive(+) and negative(-) direction before packing.
- When a lead plate or wire is connected to the cell for packing, check out insulation not to short-circuit.
- Battery must be stored separately.
- Battery must be stored in a dry area with low temperature for long-term storage.
- Do not place the battery in direct sunlight or heat.
- Do not use the battery in high static energy environment where the protection device can be damaged.
- When rust or smell is detected on first use, please return the product to the seller immediately.
- The battery must be away from children or pets
- When cell life span shortens after long usage, please exchange to new cells.

5.2 Prohibitions

- Do not use different charger. Do not use cigarette jacks (in cars) for charging.
- Do not charge with constant current more than maximum charge current.
- Do not disassemble or reconstruct the battery.
- Do not throw or cause impact.
- Do not pierce a hole in the battery with sharp things. (such as nail, knife, pencil, drill)
- Do not use with other batteries or cells.
- Do not solder on battery directly.
- Do not press the battery with overload in manufacturing process, especially ultrasonic welding.
- Do not use old and new cells together for packing.
- Do not expose the battery to high heat. (such as fire)
- Do not put the battery into a microwave or high pressure container.
- Do not use the battery reversed.
- Do not connect positive(+) and negative(-) with conductive materials (such as metal, wire)

- Do not allow the battery to be immerged in or wetted with water or sea-water.

5.3 Caution for the battery and the pack

Pack shall meet under condition to maintain battery safety and last long performance of the lithium rechargeable cells.

5.3.1 Installing the battery into the pack

-. The cell should be inspected visually before battery assembly into the pack.

-. Damaged cell should not be used. (Damaged surface, can-distortion, electrolyte-smell)

-. Different Lot Number cells should not be packaged into the same pack.

-. Different types of cells, or same types but different cell maker's should not be used together.

5.3.2 Design of battery pack

-. The battery pack should not be connected easily to any charger other than the dedicated charger.

-. The battery pack has function not to cause external short cut easily.

5.3.3 Charge

-. Charging method is Constant Current-Constant Voltage (CC/CV).

-. Charging should be operating under maximum charge voltage and current which is specified in the product specification. (Article. 2.4, 2.5)

-. The battery should be charged under operating temperature specified in the product specification. (Article. 2.9)

5.3.4 Discharge

-. Discharging method is Constant Current (CC).

(In case of using the battery for mobile equipment, discharging mode could be Constant Power.)

-. Discharging should be operating under maximum discharge current which is specified in the product specification. (Article. 2.7)

-. Discharging should be done by cut off voltage which is specified in the product specification. (Article. 2.6)

-. The battery should be discharged under operating temperature specified in the product specification. (Article. 2.9)

5.3.5 Protection Circuit

-. The protection circuit should be installed in the battery pack, charger.

-. Charger or pack should have voltage sensing system to control over charge or discharge in order to maintain the battery's normal operating mode and protect cell imbalance.

-. Charger or pack should have warning system for over temperature, over voltage and over current.

6.EXCLUSION OF LIABILITY

THE WARRANTY SHALL NOT COVER DEFECTS CAUSED BY NORMAL WEAR AND TEAR, INADEQUATE MAINTENANCE, HANDLING, STORAGER FAULTY REPAIR, MODIFICATION TO THE BATTERY OR PACK BY A THIRD PARTY OTHER THAN LGC OR LGC'S AGENT APPROVED BY LGC, FAILURE TO OBSERVE THE PRODUCT SPECIFICATION PROVIDED HEREIN OR IMPROPER USE OR INSTALLATION, INCLUDING BUT NOT LIMITED TO, THE FOLLOWING:

-. DAMAGE DURING TRANSPORT OR STORAGE

-. INCORRECT INSTALLATION OF BATTERY INTO PACK OR MAINTENANCE

-. USE OF BATTERY OR PACK IN INAPPROPRIATE ENVIRONMENT

-. IMPROPER, INADEQUATE, OR INCORRECT CHARGE, DISCHARGE OR PRODUCTION CIRCUIT OTHER THAN STIPULATED HEREIN

-. INCORRECT USE OR INAPPROPRIATE USE

-. INSUFFICIENT VENTILATION

-. IGNORING APPLICABLE SAFETY WARNINGS AND INSTRUCTIONS

-. ALTERING OR ATTEMPTED REPAIRS BY UNAUTHORIZED PERSONNEL

-. IN CASE OF FORCE MAJEURE (LIGHTENING, STORM, FLOOD, FIRE, EARTHQUAKE, ETC.)

THERE ARE NO WARRANTIES – IMPLIED OR EXPRESS – OTHER THAN THOSE STIPULATED HEREIN. LG CHEM SHALL NOT BE LIABLE FOR ANY CONSEQUENTIAL OR INDIRECT DAMAGES ARISING OR IN CONNECTION WITH THE PRODUCT SPECIFICATION, BATTERY OR PACK.

Appendix D: Software

Appendix D1: Link to Github Organization:

https://github.com/Electric-Spitfire

Appendix E: General

Appendix E1: Link to Project Website:

https://www.electricspitfire.com/

Appendix E2: Link to Project Critical Path Analysis Board:

Link to Project Critical Path Analysis Board

Appendix E3: Link to Gantt Chart:

Link to Gantt Chart