# Final Design Report

## *Electric Conversion of a 1979 Volkswagen Bus*

## December 17, 2020


**Colorado School of Mines**
**Capstone project S20-25**
**Team Re-Volt**
Gracie Cole, *Project Manager, Fundraising Lead*
Andrew Wood, *Assistant Project Manager & Power Systems Lead*
Layton Blankenship, *Fundraising Specialist*
Cesar Chacon, *Technical Specialist*
Mason Elliott, *Technical Specialist*
Luke Greenidge, *Technical Specialist*
Dylan Greenman, *Technical Specialist*
Loren Griffeth, *Fabrication Lead*
Tim Helmer, *User Interface Lead*
Brandon Horgan, *Technical Specialist*
Evie Oglesby, *Technical Specialist*
Max Porter, *Drive Systems Lead*
Garrett Shirley, *Embedded Systems & Overall Systems Leads*
Erin Smethers, *Communications & Documentation Leads*
Alex Vogel, *Cooling Lead*

# Table of Contents

**0.0 Acknowledgments** **4**

**1.0 Introduction** **5**

1.1 Disclaimer 5
1.2 Background 5
1.3 Stakeholders 5
1.4 Glass Box Diagram 6
1.5 Vehicle Constraints 7
1.6 Design Requirements & Solution Summary 9
1.7 Design Overview 10
1.8 Concerns from Previous Design Reviews 10
1.9 Chosen Components 11

**2.0 Components** **12**

2.1 Motor 12
2.2 Batteries 16
2.3 Pedals 19
2.4 Dash 20

**3.0 Systems** **21**

3.1 Power System 21
3.1.1 Overview 21
3.1.2 The Battery Management System (BMS) 21
3.1.3 The Onboard Charger 22
3.1.4 The 12 V Battery 23
3.1.5 The 12 V Battery Charger 23
3.2 Embedded System 23
3.2.1 Overview 23
3.2.2 Changes Made 24
3.2.3 Common Design Features 24
3.2.4 User Interface Node 25
3.2.5 Temperature Node 26
3.2.6 Relay Node 28
3.2.7 Connection “Node” 29
3.2.8 Next Steps 30
3.3 Cooling System 30
3.3.1 Coolant Choices 30
3.3.2 Component Selection 31
3.3.3 Air Flow Analysis 32
3.3.4 Thermal Load Calculations 33

**4.0 Conversion Planning** **34**
4.1 Proven Component Compatibility Through Testing 34
4.2 Fabrication 35
4.3 Safe Conversion Protocols 36
4.4 Emergency Safety 37
4.5 Legal Considerations 38
4.6 Budget Breakdown 39
4.7 Fundraising/Marketing 39

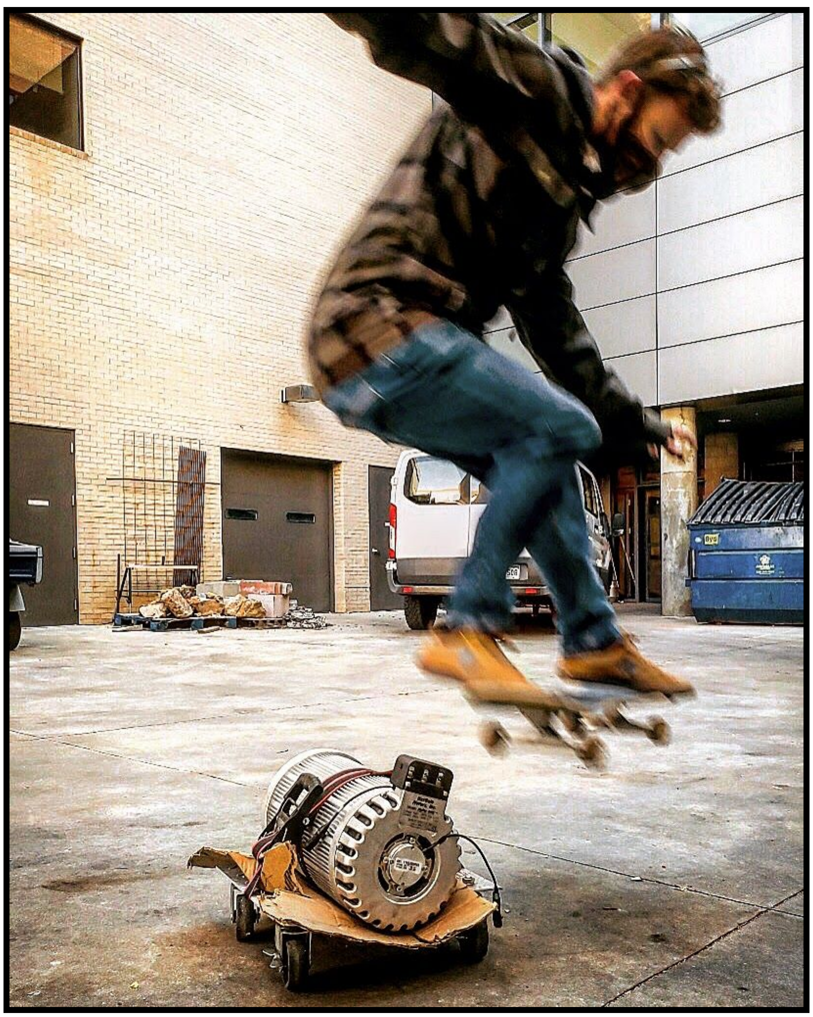
**5.0 Conclusion** **40**
5.1 Detailed Design Critique 40
5.2 Lessons Learned 41
5.3 Final Steps 41

**6.0 Appendixes** **42**

**7.0 Work Cited** **43**

# 0.0 Acknowledgments

The Re-Volt team would like to thank our Project Advisor, Dr. Yosef Allam, for empowering us to take independent ownership of this project and offering support whenever and however needed. Our Technical Advisors offered critical insights, challenged us to explore technical considerations, and provided professional oversight in the design process; these advisors include Dr. Christopher Coulston, Dr. Chuck Stone, Dr. Jeffrey Ackerman, and Professor Steve Richardson. The Colorado School of Mines ensured we had plenty of student personpower to carry the load of such a big project and demanding undertaking, and provided work space, some tools, and a bit of funding. Lastly, we would like to thank the clients, Kevin and Gracie Cole, who took notable strides to prevent blood sugar lows and provided a compelling commitment—financially and personally—to see this project through to success. The clients would like to thank the Re-Volt team for their work ethic, attention to detail, and integrity throughout the project.



# 1.0 Introduction

## 1.1 Disclaimer

This *Final Design Report* has been prepared by students at Colorado School of Mines (CSM) and presents a final design for an electric conversion of a 1979 Volkswagen (VW) bus. This *Final Design Report,* as part of the CSM Senior Design course, is strictly informational; as such, the authors, staff and university assume no responsibility for the use that any person or group makes of the information presented therein, or devices, systems and calculations resulting thereof.

## 1.2 Background

In engineering it is paramount to research existing solutions before beginning the design process. This approach helps refine the design and prevent unnecessary mistakes. Electric vehicle (EV) conversions are not new, but have changed considerably over time. In the early 1900s, people desired electric cars due to the reduced noise and vibrations. By 1900, electric cars represented one third of all vehicles in New York City [1]. Advancements in internal combustion engine (ICE) design surpassed the advancements in battery research and the ICE became the more popular choice for many years. Within the past few decades, that has changed, especially after John B. Goodenough's invention of the lithium battery [2]. With this invention, EVs have gained in popularity and EV conversions can improve the reliability of a classic vehicle, as well as reduce noise and vibrations.

Initial research consisted of sourcing information on existing VW bus EV conversions. A variety of commercial-off-the-shelf (COTS) kits were found that are specifically made to convert a VW bus to fully electric power. These kits are appealing and greatly simplify the build, but the trade-off is the hefty price tag attached. Not only are these kits expensive, they also provide very few options for power output and range. The COTS kits typically come with either lower power output motors than what the clients desire, or the battery range would not fulfill our mileage requirement. Thus, it was decided that each component for the conversion would be selected individually, in order to meet the clients' requirements, while ensuring compatibility of the components working together. The initial design process is over, and the Re-Volt team has started working toward the implementation of the electric conversion.

## 1.3 Stakeholders

The primary stakeholders in this project are the clients, Kevin and Gracie Cole. They both own the bus and originated the idea for the project. They are also the ones funding the project. Gracie is a fellow Re-Volt team member and is the Project Manager. There are a number of secondary stakeholders including the Re-Volt team, other motorists, and local and state governments. Each team member is a stakeholder because of the opportunity to develop and demonstrate marketable skills during the completion of the project. Other motorists and the governments were identified as stakeholders because of their need for the bus to be safe, reliable, and not impede the flow and safety of traffic.

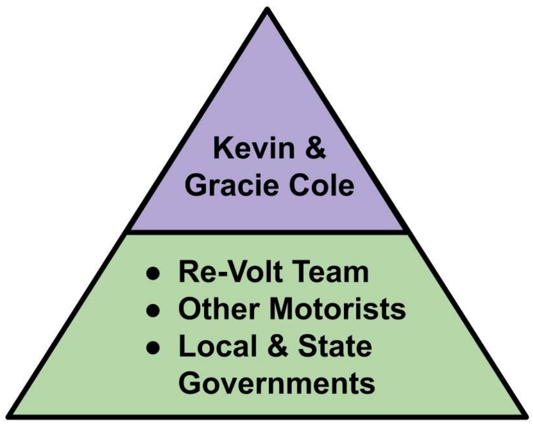



***Figure 1:*** *Primary and Secondary Stakeholders*

## 1.4 Black Box and Glass Box Diagrams

---

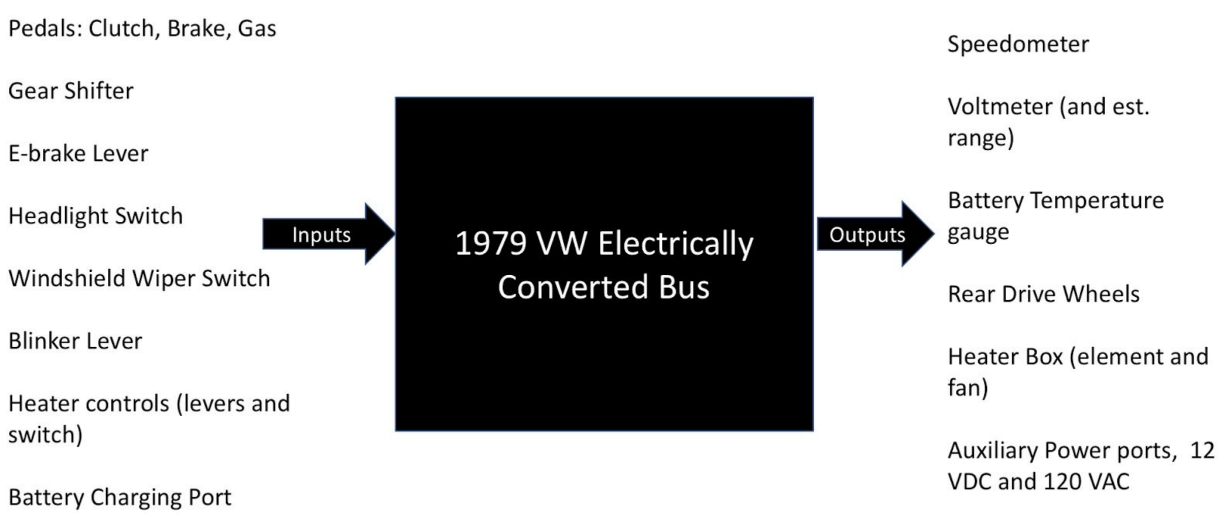



***Figure 2:*** *Black Box of 1979 VW Bus*

The Black Box diagram (**Figure 2**) was compiled from background research and experience with electric car conversions. From that same research, the Black Box diagram was expanded to the following Glass Box diagram (**Figure 3**).

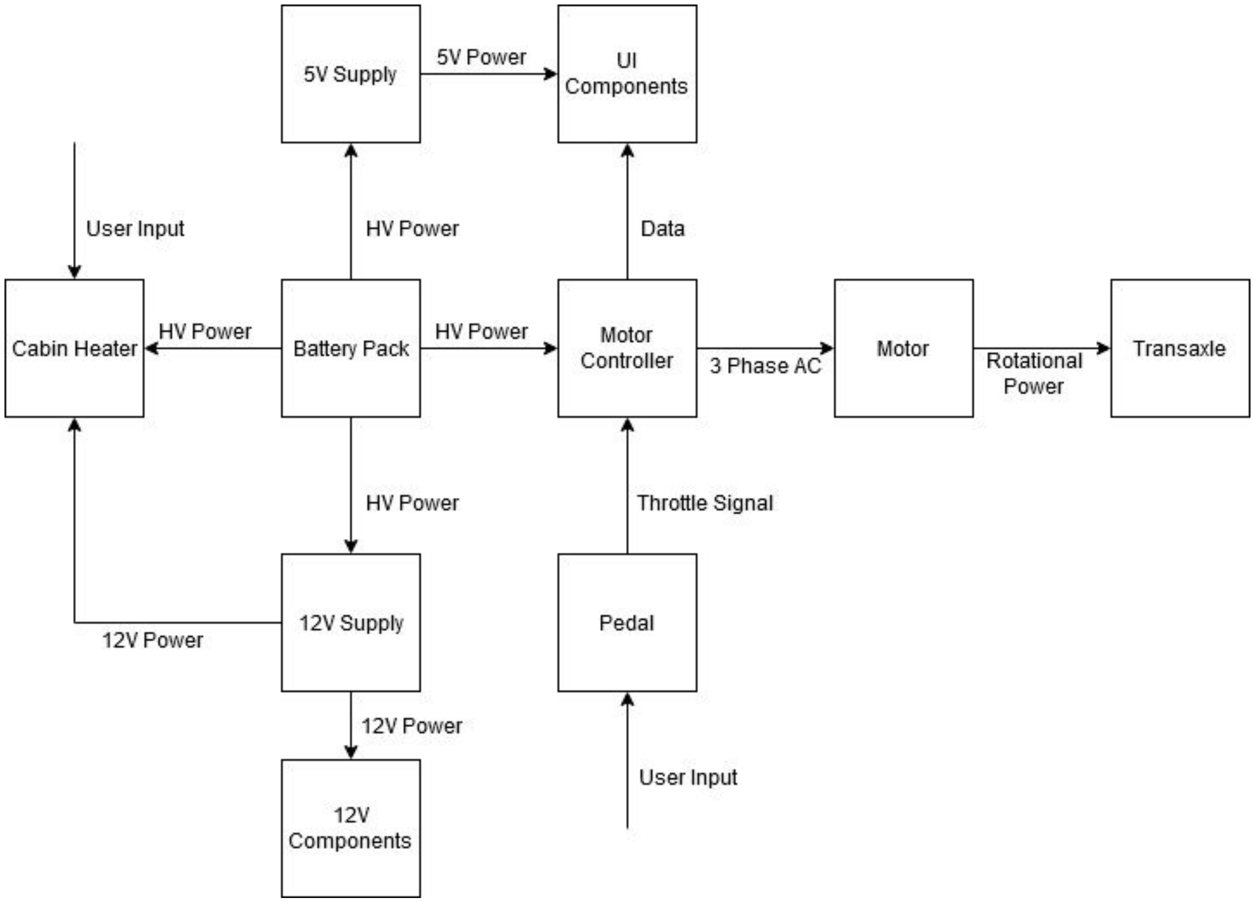



***Figure 3:*** *Glass Box of Electric 1979 VW Bus*

The components in **Figure 3** were the ones that the team identified as crucial to any potential design. Certain aspects of this diagram are subject to change depending on the specific component chosen. For example, if it becomes clear to the team that a DC motor would be the best choice, then the motor controller would supply pulse width modulated (PWM) DC power to the motor rather than a three phase AC power. Similarly the actual data received from the motor controller may have to be changed to a format that the user interface components can use, so there may be an additional block added between the two existing ones.

## 1.5 Vehicle Constraints

An integral decision to be made was whether or not to keep the existing transaxle. Ultimately, it was decided that it would be best to use the existing transaxle, primarily for budgetary considerations, but also in the interest of simplifying the conversion itself. The existing transmission was fully rebuilt in early 2019. The complex interface between the motor and axles dissuaded the team from exploring options to modify it. Reliable information on how much power the transmission can handle was not found, but general consensus amongst existing technical information suggests that the differential would be the weak link in the drivetrain system [3]. Failure of the transmission would most likely occur as a result of impact from rough shifting, which would not occur in an electric motor conversion. By retaining the transmission, the bus would have the ability to start up a hill in second gear, third gear would be used for all-around driving, while fourth gear would be ideal for highway driving speeds.

The new EV motor will reuse the factory Volkswagen engine mounts. The fabrication team fabricated an aluminum motor mount that sits on the stock engine cross member and bolts to the stock engine mount, ***Figure 4***. Electric motors do not have the same amount of vibration produced as a combustion engine, but isolating mounts will still be used. The use of a polyurethane isolator will allow for solid motor mounting, and will reduce most harsh vibrations transferred from the powertrain and drivetrain. These isolators will also prevent any material corrosion issues when mating an aluminum crossmember to the steel VW engine mounts.

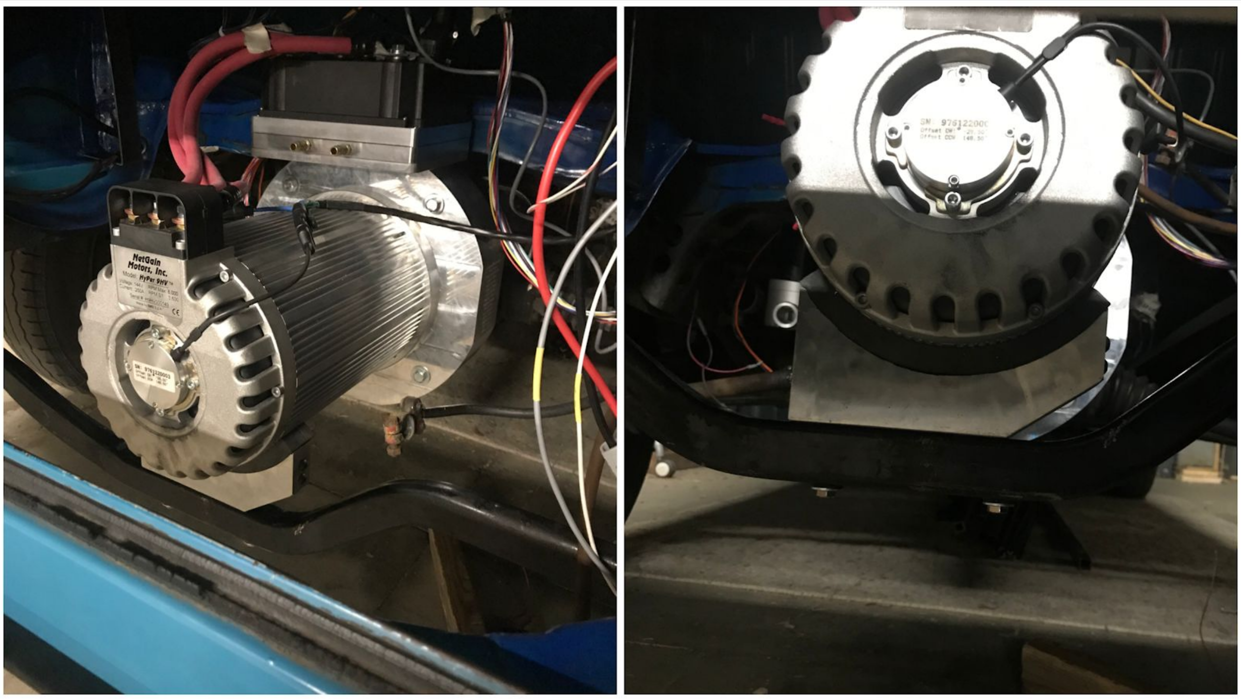


***Figure 4:*** *New Motor Mount using Original VW Cross Bar*

The driveability of the bus is not only affected by power but also vehicle weight. The classic bus is relatively light compared to modern vehicles at 3100 pounds but has a gross vehicle weight rating (GVWR) of 5093 lbs [X]. The weight difference allows approximately 2000 pounds of passengers, cargo, and conversion components (e.g. batteries) that can be added safely and legally. The suspension and braking systems on the bus are designed to handle this gross vehicle weight and the bus may not legally exceed the GVWR. The suspension and braking system may be modified for the clients' comfort and for modernization but are not strictly necessary; the following suspension and braking considerations should be assessed after completion of the conversion, as it is possible only some considerations—if any—will lead to modifications. The brakes could be augmented with new stock components or updated with modern technology. The suspension should be checked for wheel alignment and adjusted accordingly. The ride height and spring ratios may be adjusted if the base weight is significantly changed, per client feedback. Anti-roll bars can be adjusted for body roll adjustment, with a variety of aftermarket and stock solutions available. The body roll will be affected by the total vehicle weight after the conversion, as well as the center of gravity and weight distribution. The SOLIDWORKS model of the bus, and weighing it pre- and post-conversion will help us determine how handling will be affected by weight distribution.

Another important design constraint was the clients' desire to retain certain functional features of the bus. The spare tire and all usual service items need to be accessible. Another functional feature of the bus is the interior camping capability. This functionality includes a custom-made storage box in the rear of the bus that doubles as a bed platform. While this space could potentially house batteries or battery management systems, the client has expressed the preference to use the majority of this space for storage while camping, if possible. The bus has sufficient battery storage space within the cargo space of the vehicle, and the batteries do not need to be placed under the bus in order to retain camping capability.

## 1.6 Design Overview

***Table 1:*** *Design Requirements and Solutions*

| Requirement Type | Minimum Standard | Desired | Solution | Main Component(s) Selected |
|---|---|---|---|---|
| **Range (miles)** | 250 | 350+ | 229<br>+ range gained from regenerative braking | 18 Tesla Model S batteries in 3p6s<br>Total 95.2 kWh |
| **Highway cruising speed (mph)** | 70 | 80 | 75<br>+ improved acceleration | NetGain HyPer 9 motor provides 120 horsepower |
| **Recharge time** | 10 hrs (220 V) | 30 min. (supercharger) | 13 hrs for 0% to 100% charge at Level 2 (will decrease charge time with future addition of 2nd charger) | Elcon UHF 6.6 kW onboard charger + J1772 charge port |
| **Drive type** | RWD | AWD | RWD | — |
| **Cost** | $20,000 | $12,000 | $35,760.31<br>(client approved) | — |
| **Braking** | Existing drum brakes | Regenerative + disc braking | Regenerative + existing drum brakes (option to upgrade brakes in future) | NetGain HyPer 9 motor includes regenerative braking capability |
| **Defrost** | No Change | Defrost | Defrost | Dryer Heating Element (replacement for Kenmore dryer) |
| **Cabin Heat** | Option to add | Cabin heater | Cabin heater | |
| **Camping Capabilities** | Retain interior camping capabilities (plus fridge) | Retain interior camping capabilities (plus fridge) | Retain interior camping capabilities (plus fridge) | Client built custom camping storage box and bed platform |
| **USB** | Option to add | USB Charger | Two USB charging ports<br>+ two 12 V ports | E-Bro 4.2A Dual USB Charger Socket Blue LED with waterproof spring cover |
| **Headlights** | No Change | Brighter/LED headlights | LED headlights | LED Light Street H6024 LED Conversion Kit |
| **Seat Heater** | No Change | Seat Heater | No change | — |

In order for this design to be successful, a vast number of things needed to be done. These include: replace the stock engine with an electric motor, add the high capacity battery pack used to power the motor, add a system that power the stock 12 V components and the ones added, redo the various user interfaces to reflect the new powertrain (gas pedal, dashboard display, etc), ensure that the stock suspension and braking components can deal with the additional weight added by the batteries, physically mount the various components in reliable ways, route the new wiring as needed in ways that ensure its longevity, amongst many other things.

The general overall design of this project is as follows. The stock gas powered engine is replaced with an electric motor of a similar power output. That motor is then mounted to the stock transaxle through the use of some adapter plate and shaft coupling, as well as an additional motor mount that works with the stock motor mount. That motor is controlled by some motor controller that outputs the necessary power to drive the motor that is converted from a high voltage battery pack. That high voltage battery pack is charged and monitored by a charger and battery management system. The stock user interface components are changed to be able to deal with the new power train of the bus. When applicable and possible, existing industry standards are used to ensure that the clients are able to use this bus with existing EV infrastructure. The design of this conversion will comply with all relevant laws and regulations, to ensure the clients will have no legal liabilities. This report details the design specifics.

## 1.7 Concerns from Previous Design Reviews

---

The largest concern from the Preliminary Design Review (PDR) was the cooling system, which was largely ignored during the first phase of design. The technical advisors expressed much concern about both motor and battery cooling, which resulted in the team placing much greater importance on the cooling system, and creating a whole subsystem team devoted to it. The second major concern expressed in the PDR was the safety aspect of the high-voltage (HV) system. The advisors were concerned about the safety implications of the high-power electronics that will be present in the bus. The team intends to address this by researching current HV cable and safety standards in automobiles, and implement these safety measures in the conversion of the bus.

## 1.8 Chosen Components

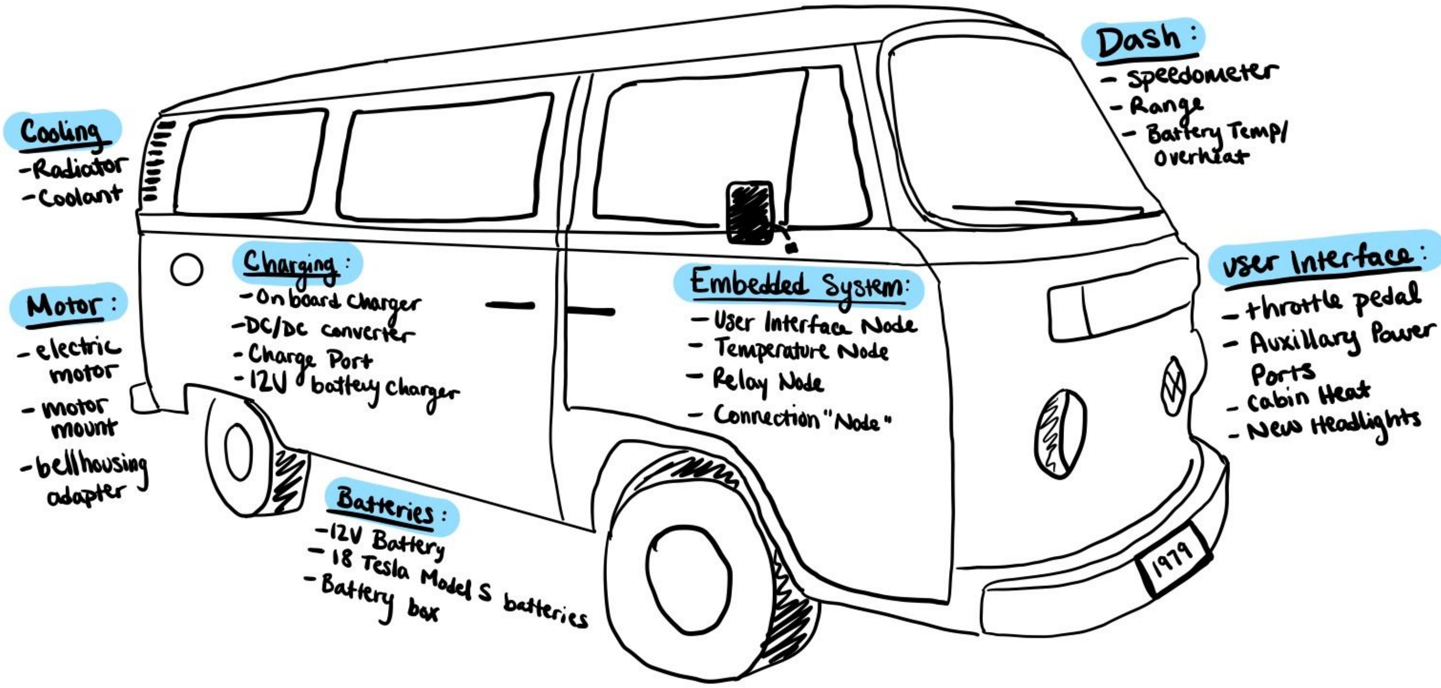



***Figure 5:*** *System Overview*

The new motor that we have picked to power the bus is a NetGain HyPer 9. This motor was chosen because of its balance of price and efficiency. It produces more power and torque than the stock bus motor and has been used in previous conversions with the stock transmission. The motor and controller have been ordered.

The original accelerator pedal controlled the engine throttle with a cable; however, the electric motor controller requires an electronic signal to operate properly. To retain the original gas pedal in the cab, a simple cable-operated, HGM throttle position sensor has been selected to allow for seamless operation with the motor controller.

When equipped with a gas engine, the dash displays certain information that is pertinent to internal combustion. With a new, electric motor, the dash has different data to display than before; the dash panel and the displays available, will be changed as a part of the conversion. The small battery monitoring display will be purchased from EV West and allows the client to monitor the battery's state of charge. LED indicator lights will be used for warnings similar to a check engine light on an ICE vehicle. This new battery monitor display was chosen due to how nicely it fits in the dash dimensions and the simplicity of the output display.

# 2.0 Components

## 2.1 Motor

---

A vital component of a vehicle conversion from gas to electric is the electric motor itself. Both motor efficiency and regenerative braking capabilities factored into the motor selection. Three motors were considered for the bus: the Tesla Model S motor, the Curtis HPEVS, and the NetGain HyPer 9. All three of these motors are capable of regenerative braking, and come ready with their respective motor controllers. Tesla is a very well known and innovative electric vehicle manufacturer that has become a forerunner in the modern electric vehicle industry. As such, Tesla's reputation warranted consideration of implementing its Model S motor in this conversion. The Curtis HPEVS motor is a very popular choice among existing EV conversions and is therefore very well documented, researched, and offers simple, bolt-on, 'plug and play' integration. Lastly, the HyPer 9 motor from NetGain is also a common choice for EV conversions and boasts very high efficiency at an economic price, making it the third and final motor considered. The nominal performance of the motor was evaluated using an equation that estimates the quarter-mile elapsed time. The formula is:

$$elapsed\ time = 5.825\sqrt[3]{\frac{vehicle\ weight}{motor\ horsepower}}$$

The estimated elapsed time and trap speed served as metrics for the theoretical performance of the bus, which were then compared to the published quarter-mile times for the Volkswagen Tiguan, the clients' secondary vehicle. The comparison of the estimated VW bus performance against the Tiguan was reported as a relative percentage, allowing the clients to compare the driving experience of the fully converted bus to another vehicle driven regularly.

**Option 1:** Tesla motor

> The Tesla motor was almost immediately disqualified, as it would require extensive fabrication to install. It offers a high power output (362 hp) and high efficiency, but its inability to be installed with a simple bellhousing adapter added unnecessary cost and complexity. The power and efficiency offered by the Tesla motor is more than offset by the additional installation complexity, which would likely extend the timeframe of the project well beyond the timeline available to the team.

**Option 2:** Curtis HPEVS motor

> The Curtis HPEVS motor has the advantage that it is quite user-friendly. Simple bolt-together adapters and a well-documented controller make the Curtis motor one of the most popular motors for EV conversions. The downside of the Curtis motor is that it has the lowest maximum power of any of the motor options, as well as the lowest efficiency (0.88), which is important if the bus is to meet the clients' goal of a 250-mile

range. Lower efficiency means that performance of the bus may be compromised in demanding driving situations, such as highway on-ramps or mountain passes.

**Option 3:** NetGain HyPer 9 motor

The NetGain HyPer 9 is not capable of as much output power as the Tesla motor, but it produces 30 more horsepower than the Curtis motor, allowing the bus to keep up with traffic in all driving situations while remaining simple to adapt to the bus drivetrain. The HyPer 9 is capable of 120 horsepower, which should allow the bus to accelerate 0-60 mph in under 9 seconds and complete a quarter mile in approximately 17 seconds, which is similar to the clients' secondary vehicle, a 2012 Volkswagen Tiguan [5]. Additionally, the HyPer 9 motor uses a permanent magnet design which is significantly more efficient than the Curtis motor. The HyPer 9 is rated at 94% efficiency, which is a 6% increase over the Curtis, translating to approximately 16 miles more range from the same energy storage capacity [6]. The downside of the HyPer 9 is that its high torque output of 173 ft-lbs risks damage to the succeeding drivetrain components - namely the transaxle, which was originally designed for a mere 70 horsepower ICE. This can be solved by programming the controller to limit the output torque to 200 N-m (145 ft-lbs). Fortunately, due to the nature of the torque vs. rpm curve of the motor, the torque will only be limited until 4000 rpm, at which point the unmodified torque curve falls under 200 N-m limit and the motor will be able to achieve its maximum power rating (120 hp) from 4000 rpm to 6000 rpm. ***Figure 6*** shows the unmodified and modified torque and horsepower curves, and how the performance will be affected by the electronic limiting. This solution will allow the bus to have maximum power and efficiency without risking breakage of the original transaxle. For all of these reasons, the team and client determined the NetGain HyPer 9 motor to be the optimal choice.

The NetGain HyPer 9 (***Figure 6***) motor is capable of 120 horsepower, which should allow the bus to accelerate 0-60 mph in under 9 seconds and complete a quarter mile in approximately 17 seconds, which is similar to the 2012 VW Tiguan giving us an acceleration of 100% Tiguan [7]. This is a significant improvement over the bus' current acceleration of 41% Tiguan. Additionally, the HyPer 9 motor uses a permanent magnet design which is significantly more efficient than the ICE, and is rated at 94% efficiency [7]. The downside of the HyPer 9 is that its high torque output of 173 ft-lbs risks damage to the succeeding drivetrain components—namely the transaxle, which was originally designed for a mere 70-horsepower ICE. This problem can be solved by programming the controller to limit the output torque to 200 N-m (145 ft-lbs). Fortunately, due to the nature of the torque vs. rpm curve of the motor, the torque will only be limited until 4000 rpm, at which point the unmodified torque curve falls under 200 N-m limit and the motor will be able to achieve its maximum power rating (120 hp) from 4000 rpm to 6000 rpm. ***Figure 7*** shows the unmodified and modified torque and horsepower curves, and how the performance will be affected by the electronic limiting. This solution will allow the bus to have maximum power and efficiency without risking breakage of the original transaxle. For all of these reasons, the team and clients determined the NetGain HyPer 9 motor to be the optimal choice.

***Figure6:*** *HyPer 9 Motor and Controller*

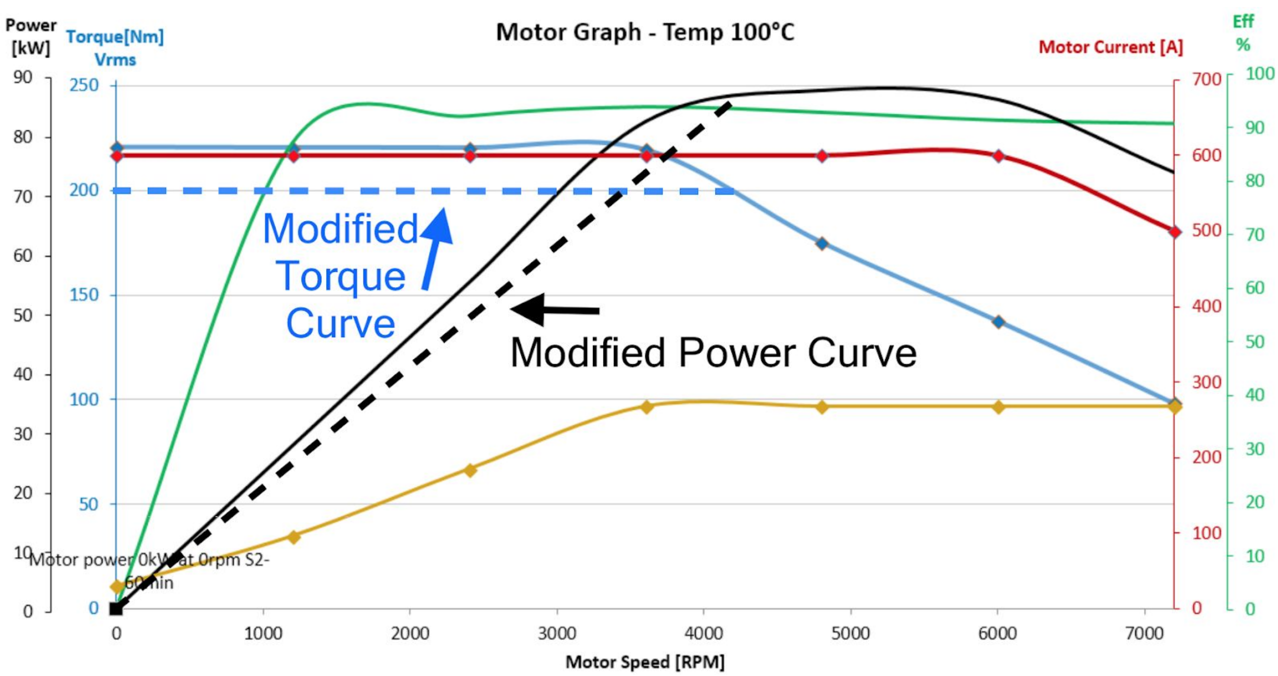



***Figure 7:*** *HyPer 9 modified torque and horsepower curves [9]*

Once the HyPer 9 motor was selected, the task was to determine how to mate the manual gearbox to the electric motor. EV West and other companies manufacture bellhousing kits for this purpose (see ***Figure 8***). The kits range from $700-$1100, which seemed excessive for such a simple part. After research, it was decided that the team's fabrication abilities and access to the school's machine shop afforded the option of machining the bellhousing adapter in-house (see ***Figure 9***). Material cost for a suitable aluminum billet was priced at roughly $300. Once this piece was machined, the Fabrication Team made a splined shaft that connects the drivetrain assembly to the output shaft of the electric motor. The original VW bus flywheel will be bolted onto the shaft, then the clutch and pressure plate will be bolted to the flywheel. This leaves us with the same result as if we had bought a kit without having to pay for a machine's and machinist's time. With those components assembled, an optimally affordable solution will be achieved, mating the electric motor with the transaxle and drivetrain.

The motor, shaft adapter, bellhousing adapter, and controller have been installed and wired. The drivetrain has been tested at low speed by lifting the rear axle off of the ground and rotating the wheels in different gears and actuating the clutch. All appears to be in working order however a true test will consist of 0 mph to 60 mph acceleration and 60 mph to 0 mph braking times as well as overall street driveability. The throttle and regen braking will be celebrated to the client's preference throughout testing.

***Figure 8:*** *EV West Adapter Plate [10]*

***Figure 9:*** *Custom Manufactured Adapter Plate*

## 2.2 Batteries

In an EV, perhaps the second most critical component behind the motor itself is the battery array. In addition to supplying the necessary power to drive the motor, the batteries also power auxiliary components such as interior lights, 12 V chargers, dash gauges, etc. Similar to how a gas vehicle's range is limited by the capacity of the fuel tank, an EV's range is limited by the total power capacity of its battery pack. The capacity of the pack is determined by the Voltage and output Ampere-hours of the total pack. The efficiency of the motor has a significant effect on range, as well. A more efficient motor will make better use of the power provided by the batteries, allowing the car to go further. ***Figure 10*** shows that the battery pack will consist of 3 Tesla Model S battery modules in parallel with 6 sets of these in series for a total of 18 Tesla Model S battery modules. This dictates the battery pack's voltage range.

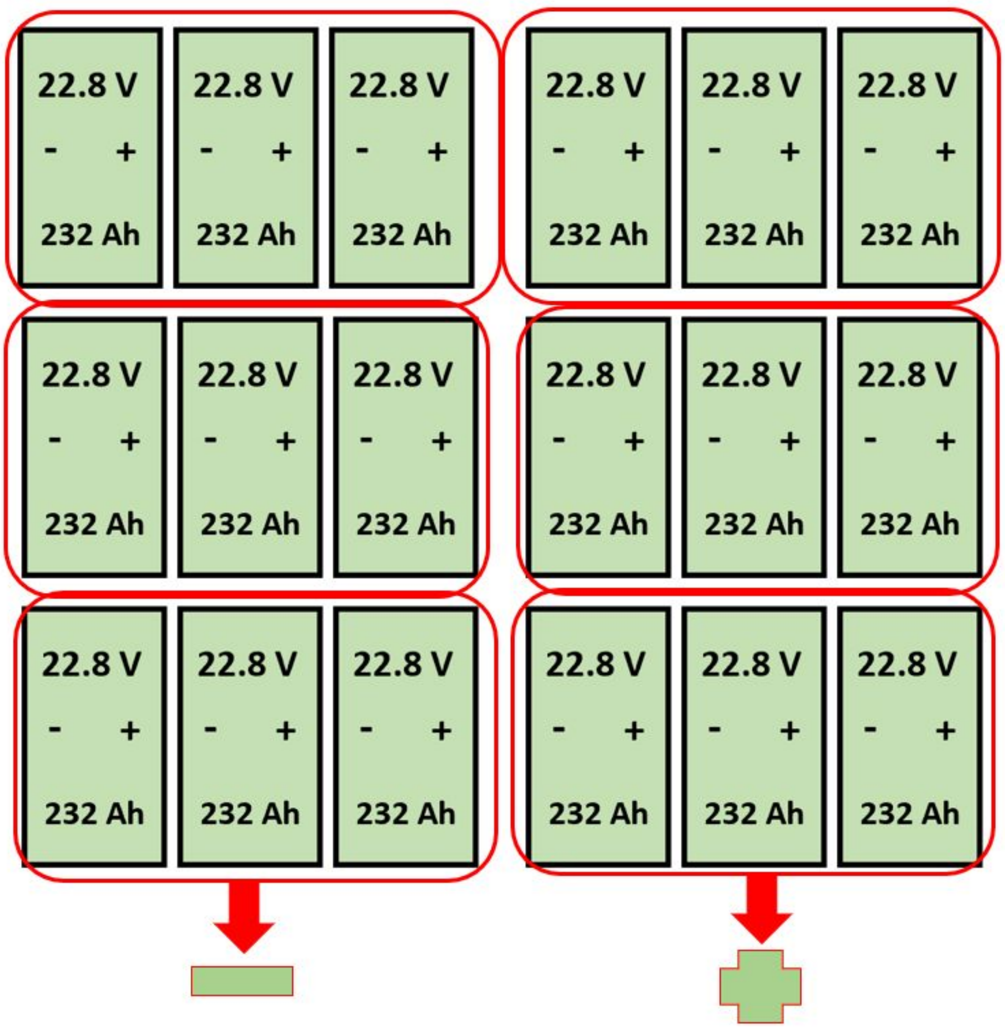



***Figure 10****: Bus battery pack configuration*

Given that the discharge cut off voltage for each module is 19.8 V, nominal voltage is 22.8 V, and charge cut off is 25.2 V we can calculate the voltage range for the battery pack below.

$$V_{min} = 6*19.8\ V = 118.8\ V$$

$$V_{nominal} = 6*22.8\ V = 136.8\ V$$

$$V_{max} = 6*25.2\ V = 151.2\ V$$

Similarly, the total current discharge can be calculated by summing the individual current discharges for the three modules in parallel.

$$I = 232+232+232\ Ah = 696\ Ah$$

With the total current discharge and nominal voltage of the battery pack, the capacity of the battery pack can be calculated by multiplying the discharge and voltage.

$$E = 136.8\ V * 696\ Ah$$

$$E = 95.2\ kWh$$

With the capacity of the battery pack obtained above, the total distance the bus will be able to drive is 229 miles. To calculate this, the team calculated the power consumption of the bus making several assumptions. We assumed the bus has a velocity (*v*) of 26.8 m/s, a total system efficiency ( $\eta$ ) of 0.85, a rolling resistance coefficient ($C_R$) of 0.02, a total mass ( $M_v$ ) of 1590 kg, and an frontal area ( $A$ ) of 2.6 m$^2$. Using these assumptions, the power consumption was calculated to be 25 kW, shown below.

$$Consumption\ (W) = \eta^{-1} * (0.5 * C_D * A * \rho * v^2 + C_R * M_v * g) * v$$

$$Consumption\ (W) = (0.85)^{-1} * (0.5 * 0.42 * 2.6 * 1.225 * 26.8 * 26.8 + 0.02 * 1590 * 9.81) * 26.8$$

$$Consumption\ (W) \ = \ 24972\ W$$

Because the team assumed a velocity of 26.8 m/s (60 mph), the calculation of energy consumption is 416 Wh/mile, resulting in a range of 229 miles before accounting for the extra range obtained through regenerative braking.

$$\frac{24982\ W}{1} * \frac{1\ hr}{60\ miles} \ = \ 416.4\ Wh/mile$$

$$\frac{95.2\ kWh}{1} * \frac{1 mile}{0.4164\ kWh} \ = \ 229\ miles$$

The project will require use of American Wire Gauge size 000, which allows up to 239 amps for power transmission connecting the battery modules to other components [7]. This wire specification allows the voltage and current needs to be met safely.

If the client decides to add additional battery packs in the future to increase the range of the bus, these battery packs can be added over the motor in the engine compartment. This space allows for the addition of up to eight supplemental Tesla model S packs.

The physical implementation configuration of the battery pack can be seen in ***Figure 11***. Each color represents a set of three in parallel for a total 3p6s configuration. This spatial configuration was chosen because it allows the client to retain the camping box while keeping the batteries within the bus. The most recent progress of the battery enclosure can be seen in ***Figure 12.***

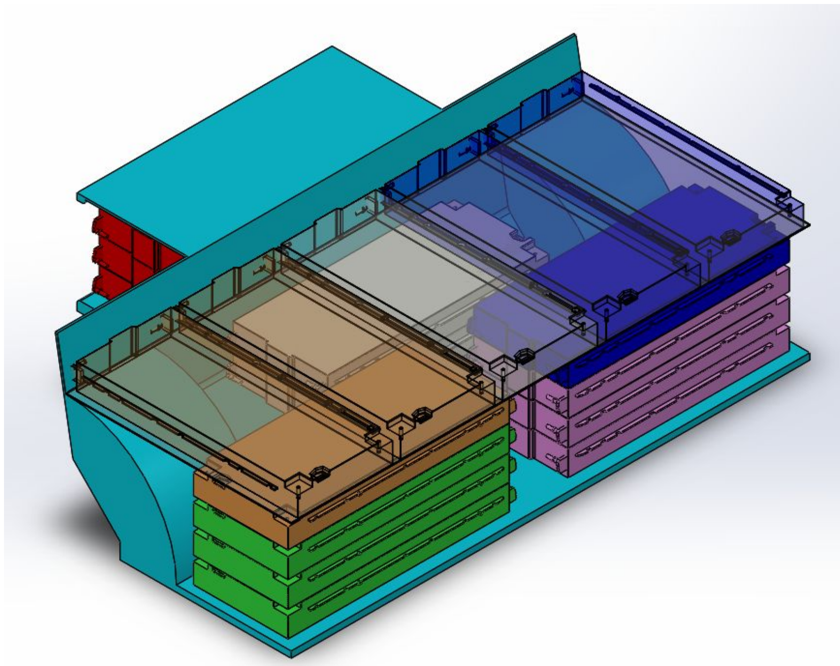


***Figure 11:*** *Battery configuration*

***Figure 12:*** *Battery Enclosure Progress*

## 2.3 Pedals

Electric conversion of a vintage vehicle presents many esoteric challenges. One challenge is adapting the throttle assembly to work with an electric motor. While the brake and clutch pedals will remain the same, the throttle pedal must be modified to ensure proper control of the vehicle with its new power source. As with most vintage vehicles, the throttle pedal is attached to a cable which actuates the throttle body valve inside the engine. This valve controls how much air/fuel mixture is allowed into the engine, which modulates the revolutions per minute of the engine, ultimately controlling the acceleration of the vehicle.

When the system is converted to electric power, the aforementioned throttle cable no longer can directly connect to the electric motor because the motor controller uses an electronic signal instead of an analog one. Thus, a new, cable-operated throttle position sensor (TPS) will be retrofitted into the vehicle, allowing the user to press on the stock gas pedal and send an appropriate signal to the motor controller, ***Figure 13***. The way this TPS works is by connecting it to a 5 V source; there is a variable resistor that is actuated by an external cable. When the variable resistor's value is changed by the position of the cable, an output voltage between 0 and 5 Vdc is transmitted to the motor controller. This signal enables the motor controller to determine how much power to send to the motor.

The TPS that will be used for this function will be a high-quality unit from HGM Electronics. This specific component was selected because it has a very simple interface with the motor controller, a streamlined mounting system, and this component will allow the stock gas pedal to be retained in the vehicle. Retaining the original gas pedal was a strong preference of the clients, and they are glad a stealthy solution was devised.


***Figure 13:*** *Cable-operated TPS sensor [11]*

The existing clutch and brake pedals will be retained, as they will continue to operate with the same mechanisms as before the conversion.

## 2.4 Dash

Once the old gas engine is replaced with an electric motor, there will be different, vital information for the driver to track while driving. The dashboard display that came in a stock VW bus includes an oil light, charging light, fuel gauge, and more. With an electric motor, however, much of this information is no longer relevant.

An EV has different information to display to the user than a gas-powered vehicle. As such, the dash will be modified to accommodate new information, specifically the status of battery charge. The dash will also be modified to include alarm lights that turn on when batteries overheat or another electrical fault occurs. Filling the rightmost dash gauge port will be a TBS Expert Pro Battery Monitor display, as modeled in ***Figure 14**.* The new display will provide critical battery life status for the driver while retaining the stock features of the dash cluster. Previously, the only item in that rightmost gauge cluster was an aftermarket thermometer which no longer functioned. The previous design included fabricating an entire new dash panel in order to accommodate a 7" LCD screen, to display a wider variety of system data, but this smaller display option (which was discovered by the client late in the design process) aligns more consistently with clients' goal of retaining the stock look and simplicity of features. Additionally, it was discovered late in the design process that there would be extreme difficulty getting the various conversion systems to communicate with the LCD screen in a way that would be helpful for the user. Thus, the round TBS Expert Pro proved to be the best option.


***Figure 14:*** *The original dash cluster with TBS Expert Pro Battery Monitor [11]*

In addition to the new display, there will be two USB charging ports, capable of 2.1 A each, added to the underside of the dash panel, facilitating charging of a variety of devices. The original heater controls will be retained, but the functions for the new heater will be controlled with simple switches added to the lower edge of the dash, below the gauge cluster and alongside the USB ports and headlight switches.

# 3.0 Systems

## 3.1 Power System

### 3.1.1 Overview

Each component is described more thoroughly below. The Power Systems subsystem is comprised of the motor, the motor controller, batteries, and the 12 Vdc converter, the 12 V battery, the 12 V battery charger, and the onboard charger. As stated earlier, the team has chosen the NetGain HyPer 9 motor and the HyperDrive X144 motor controller to pair with it. This motor is recommended to be air-cooled from the manufacturer, and the motor controller also uses a liquid-cooled chill plate that will be used to maximize the performance of the system. The batteries that have been chosen are the Tesla Model S battery packs, to be used in a configuration of three in parallel, then 6 sets of three in series, to achieve the ideal capacity of 95.2 kWh. The 12 Vdc step down was purchased from Elcon to pair with a new 12 V battery and 12 V charger. All of these components interact with each other through the embedded system.

### 3.1.2 The Battery Management System (BMS)

After many long discussions with companies like ZElectric and Evolve Electric, and project advisors, the Dilithium Battery Management System (BMS) has been chosen for this project. This system has the capability to manage parallel strings of many cells. The dilithium bms uses two units to control the charge levels: the BMS Controller (BMSC) and the BMS Satellite (BMSS). This will give the controller the expanded capacity needed to manage three parallel strings of six series Tesla Model S battery packs. This setup can be seen in the figure below, taken from the dilithium BMS user manual.

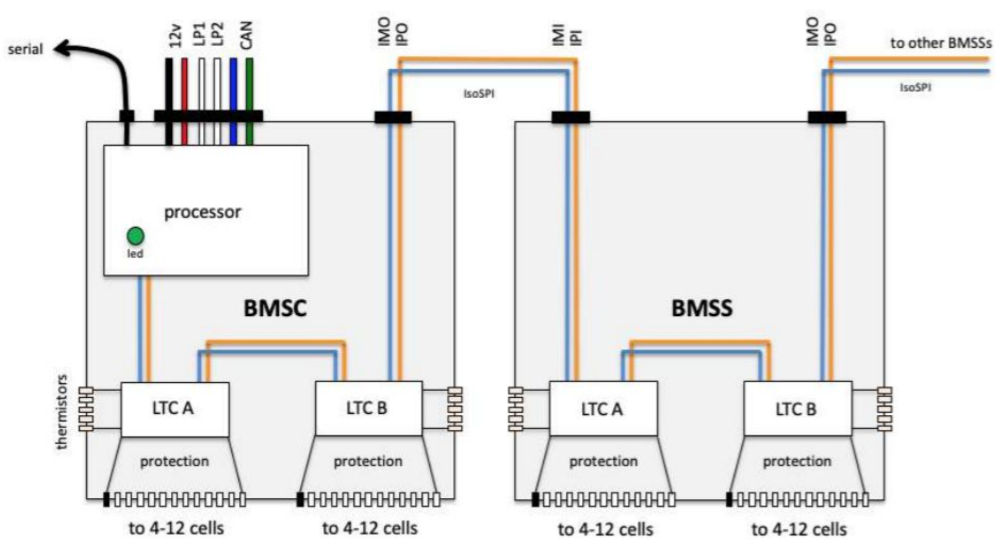



***Figure 15:*** *The Dilithium BMS wiring diagram [12]*

The BMSC is shown on the left, connecting to the BMSS on the right. Each Linear Technologies LTC6811 (or pin compatible LTC6804) multicell battery monitor chip (LTC port) can support 4-12 cells in series, so the 3p6s setup will use three LTC ports. Shown below is an example of the LTC ports supporting cells in parallel.

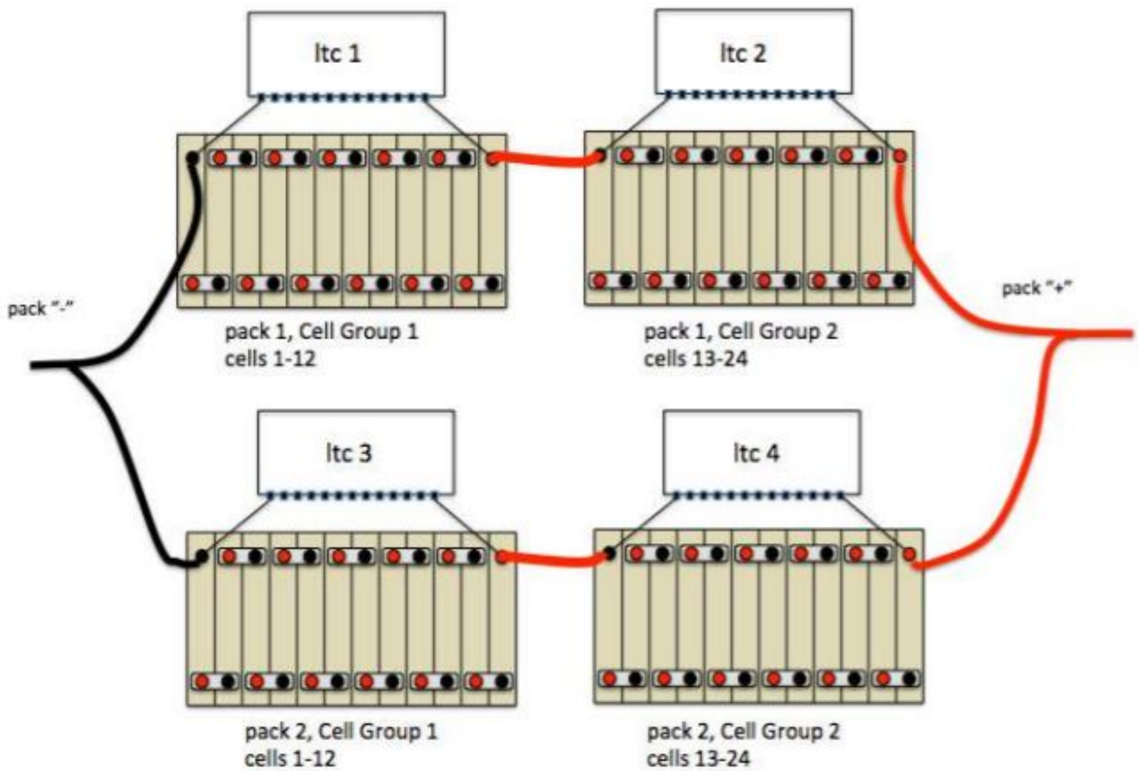



***Figure 16:*** *Dilithium BMS supporting a parallel configuration of cells through the LTC ports [12]*

Since an LTC port can only handle individual cells, the 444-cell Model S battery packs will need a supplemental BMS to act as a single LTC-managed cell. The BMS was connected directly to each battery pack to communicate without interruptions.

### 3.1.3 The Onboard Charger

For the onboard charger the initial plan to go with the Elcon PFC5000 was changed and the team ended up going with the Elcon UHF 6.6 kW charger. There were a few reasons for the change. First when ordering the PFC5000 it was discovered that it was going to be soon discontinued and that the UHF 6.6kW was the charger most similar to the PFC5000. The benefits of switching to the UHF charger are that it is more efficient than the PFC which is great for the project. It also works with the CANbus system that is being planned into our system. The price of the two chargers is comparable, making the more efficient UHF charger the best choice.

### 3.1.4 The 12 V Battery

Since there is no longer a need for engine starting, the large, flooded lead-acid battery originally equipped on the bus was replaced with a smaller, lighter and cheaper sealed lead-acid 12 V battery. The 12 V battery's most important purpose is to provide 12 V power to close the main contactor to enable the HV components. The battery will also provide a buffer between the 12 Vdc converter and the 12 V system, absorbing power spikes and powering the 12 V components even if the 12 Vdc converter is disabled.

### 3.1.5 The 12 V Battery Charger

The 12 V battery charger will keep the 12 V battery charged while the HV system is active and the bus is "on". This will ensure that the battery will be able to provide the needed power to enable the HV systems the next time the bus is turned "on".

## 3.2 Embedded System

### 3.2.1 Overview

As indicated in the intermediate design review, this project had a need for a custom embedded system to be developed for it. Since that design review, the responsibilities of the embedded system have been changed to reflect the current state of the project. The largest one of these changes relates to the use of a COTS display, and the implementation of the CANBus network. The following responsibilities of the embedded system have been identified:

1. Display necessary errors using the stock dashboard display (over temperature, under voltage, a generic "check engine" notification)
2. Control the battery cooling system based on information received from the battery management system
3. Control the cabin air heater based on inputs from the user
4. Monitor the temperatures of components in the engine bay, and control the cooling system as needed

As with the previous design review, in the interest of not taking up an excessive amount of this report with details on the embedded system, a supplementary report has been included as Appendixes D through G. As such, this section of this report will only have a relatively surface level view of the embedded system.

### 3.2.2 Changes Made

As previously mentioned, changes have been made to the embedded system designed for this project. The largest change deals with the user interface node and what it must be capable of. The main change to this node is the removal of the screen used to display the necessary information for the user. By choosing a COTS display, the main way of communication with the user has been removed, and a substitute was needed. This substitute is described in greater detail in a later section.

The second change made relates to the use of a CANBus network with the embedded nodes. At the time that each node was designed, it was believed that the CAN module built into each microcontroller was capable of natively communicating on CANBus. After reviewing the datasheet in greater depth as well as numerous technical briefs and forum discussions, that belief has been proved false. Specifically, in addition to the CAN module on the microcontroller (MCU), there needed to be a CAN transceiver on each embedded node. The combination of the MCU and that separate transceiver is what allows for communication over CAN. While this is something that in hindsight should have been discovered when designing the nodes, it is far too late for a redesign and rebuild of the system. Fortunately, while this specific issue was not foreseen, the idea that implementing CANBus communications in the embedded system would prove difficult was. As such, during the design of the system, a backup communication method was always kept in mind. This backup uses basic serial communication via the UART modules on the MCUs to exchange information. Additionally, with the use of a COTS display, the UI node does not need to actually be capable of gathering data over CAN. This communication method is described in greater detail in the supplemental report.

There are several components however that need to be able to communicate over CAN. These are the BMS, the battery charger, and the motor controller. Those have a CANBus network in place that they can use. Thankfully those 3 components are in close proximity and should not require much setup to use the CANbus network.

### 3.2.3 Common Design Features

For ease of development and installation, each embedded node features a number of common features. These common features are as follows:

1. Each node takes in 12 V power and communication lines as its inputs. That 12 V power is then converted to 5 V power by converters on each node. This was chosen as the bus already needed a 12 V supply that could be easily tapped into. Additionally, a separate 5V supply would require extra routing of wires that while possible was viewed as unnecessary.
2. Each node uses the same style of wiring harness for power and communication. This takes the form of a fully shielded assembly of 2 pairs of twisted pair wiring. This assembly allows for 12 V and communication to be sent to any node, with shielding in place to protect against noise introduced by the various switching components inside of the bus.

3. Each node uses the same microcontroller, a PIC18F26K83. This was chosen as it was believed that it could natively communicate over CANBus. As mentioned, that belief turned out to be false, but the MCU has multiple UART modules that can be used for communication instead. Related to this, each node uses the same programming setup to minimize cost and development time.
4. Common components were used between each design. This was done to minimize the work that was spent on choosing components and developing the bills of materials for each node. Additionally, it allowed for bulk pricing on certain components which helped minimize the overall cost of the system.
5. Each node utilizes a simple LED indicator to allow for a visual signal of whether the node is receiving power. Currently each LED has the full rated current going to them which produces an almost blinding level of light. Before final installation, those LEDs will have their current limiting resistors changed with ones of a much higher resistance.
6. When possible, the lower power and sleep modes of the MCU will be used to lower power consumption.

### 3.2.4 User Interface Node

The user interface node has the following responsibilities:

1. Read the inputs from the heater controls, and send their state to the cabin air heater node.
2. Gather any errors found in the bus and display them on the dashboard using the stock indicators.
3. Periodically check each node on the network to make sure that it is active and functioning

In the communication network, this node acts as something of a “master” device and the other nodes as something of “slave” devices. This was done as it avoids having to allow each node to control another, and several team members have experience with this type of communication network.

In order for the node to control the stock indicators, a separate MCU is used. This MCU takes the form of a former development board used in the EENG383 class at Colorado School of Mines. That board is used to drive a number of LEDs that have replaced the stock indicator lamps on the dashboard. That board was chosen due to how readily available it was, and the teams experience using it. In the event that the board cannot supply enough current to power the maximum number of LEDs that could be on at once, a COTS LED driving board will take its place.

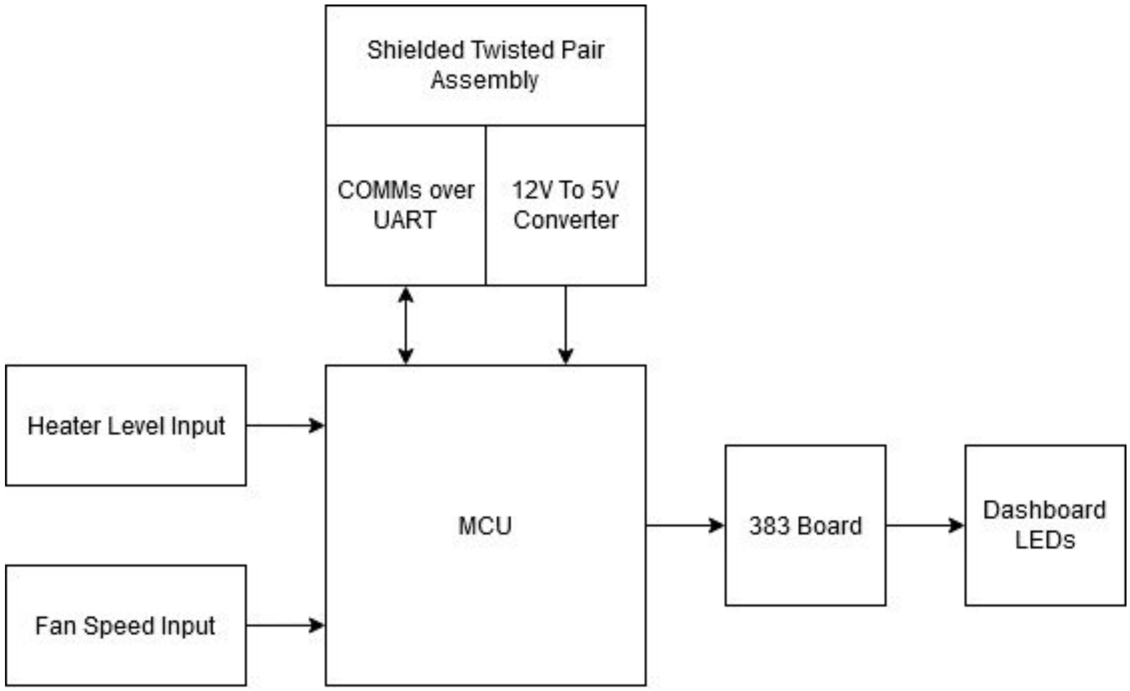



***Figure 17:*** *User Interface Node Block Diagram*

The heater level input takes the form of a 4-position rotary switch. The switch selection options are: off, 1, 2, 3, with 3 being the maximum heat level. The fan speed input takes the form of a rotary potentiometer. In the interest of safety, the heater level input is only sent to the heater node if the fan speed input is above a threshold of 25% of the maximum speed. This threshold, combined with the use of a thermal fuse on the heating element itself will help ensure that the heater is operated safely.

This node has been fully designed and built, and the programming for it has been 75% complete as of the writing of this report. The team is confident that it will be fully developed and ready for installation well before the design showcase.

### 3.2.5 Temperature Node

The temperature nodes responsibilities remain unchanged from the previous design reviews. The are as follows:

1. Monitor temperatures at four points via an analog temperature sensor
2. Report to the UI node in the event that a single temperature rises above a preset threshold

What has changed is the number of them being used. The battery management system is capable of using the thermistors built into the Tesla battery packs and using the temperatures of those to drive up to 2 outputs. Due to that, the number of these nodes in use has decreased from 5 to 1. That 1 node will be in the engine bay and will be used mainly to monitor the temperatures of the motor controller and the high voltage DC converter.

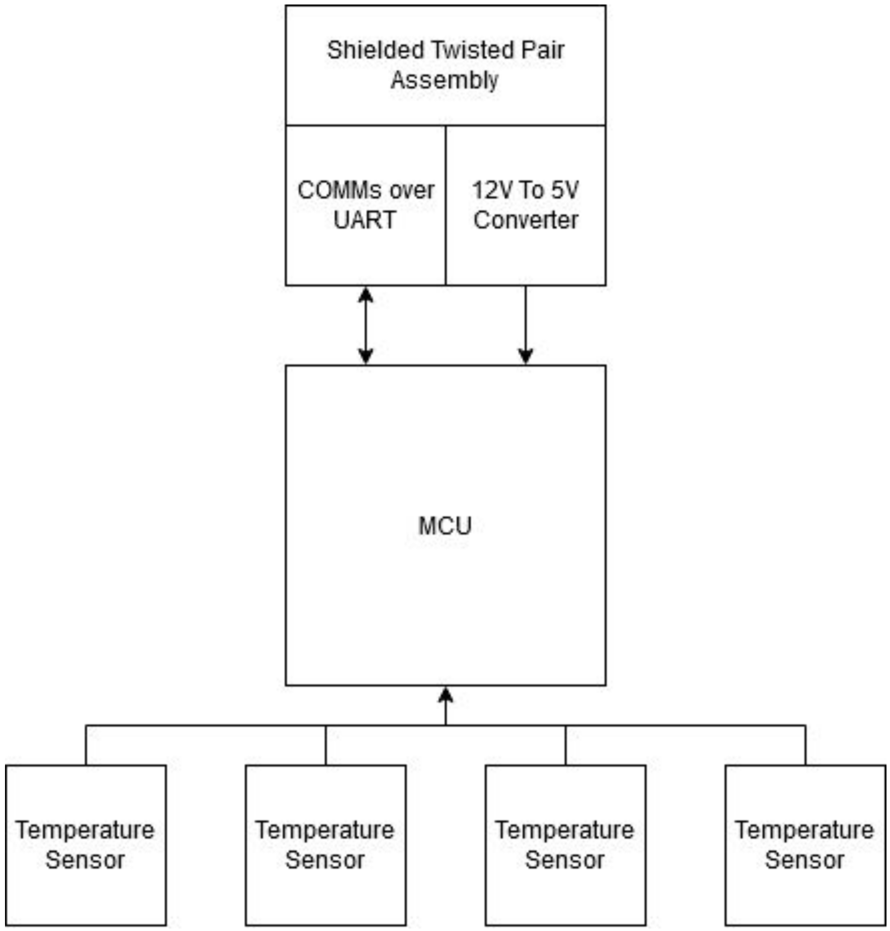



***Figure 18:*** *Temperature Node Block Diagram*

The temperature sensors used are basic analog temperature sensors, specifically the Analog Devices TMP36. This sensor was chosen as it just outputs a basic voltage of 10 mV/°C that is converted to a discrete value by the MCUs analog to digital converter (ADC). In the datasheet for the sensor, it specifies that a 0.1 μF capacitor should be added between its supply voltage inputs. Due to the fact that the sensors themselves are not located on the node circuit board, they actually have two of these capacitors. The first is on the circuit board right by the connectors that lead to the sensors. The second is soldered to the sensor leads themselves, with care taken to ensure that no connection is made to the output pin. These two capacitors ensure that the sensor has a stable voltage supply that is resistant to ambient noise.

The temperature node itself will mainly communicate with the battery cooling system node. This is because it will be monitoring the temperature of components that can be cooled by that system. Currently the idea of the temperature node communicating with the UI node is under consideration. While it is logically possible, there are concerns over if enough pins are available on the circuit board itself to facilitate this communication.

Currently the node has been fully designed and assembled. Basic code has been developed that allows for the reading of the four sensors and storing their readings in a buffer. The average of those values in that buffer is considered the current temperature of that sensor. They are read at a rate of 1 Hz. This sample rate was chosen as they are reading temperatures of physical devices. Those temperatures are not going to be changing very fast compared to the speed of the MCU, so a 1 Hz sample rate allows for plenty of time to complete a reading and to perform the minimal math that is required. As with the UI node, the team is confident that the node will be fully developed and ready for installation well before the design showcase.

### 3.2.6 Relay Node

As stated in the previous design review, one node was designed for use in both the battery cooling and cabin air heating systems. Each node is capable of controlling the following components: four relays powered by a 12 V coil with a maximum coil current of 500 mA, two constant speed constant direction 12 Vdc motors with a maximum current of 10 A each, and two variable speed variable direction 12 Vdc motors with a maximum continuous current of 12 A each and a maximum peak current of 80 A. The variable speed motors are controlled by a COTS motor controller. Each relay output features a flyback protection diode to avoid voltage spikes from de-energizing the inductive loads.

The node used in the cabin air heater will communicate with the UI node when the heater inputs have changed state. The cooling node however will function completely independently of the rest of the embedded system. It will turn on the cooling system to 100% power when the battery management system drives one of its outputs high. That output will be read via a pull down resistor added to the node discreetly. Essentially this means that the cooling system uses a bang-bang control system, which while crude will be more than sufficient for this project with the proper tuning.

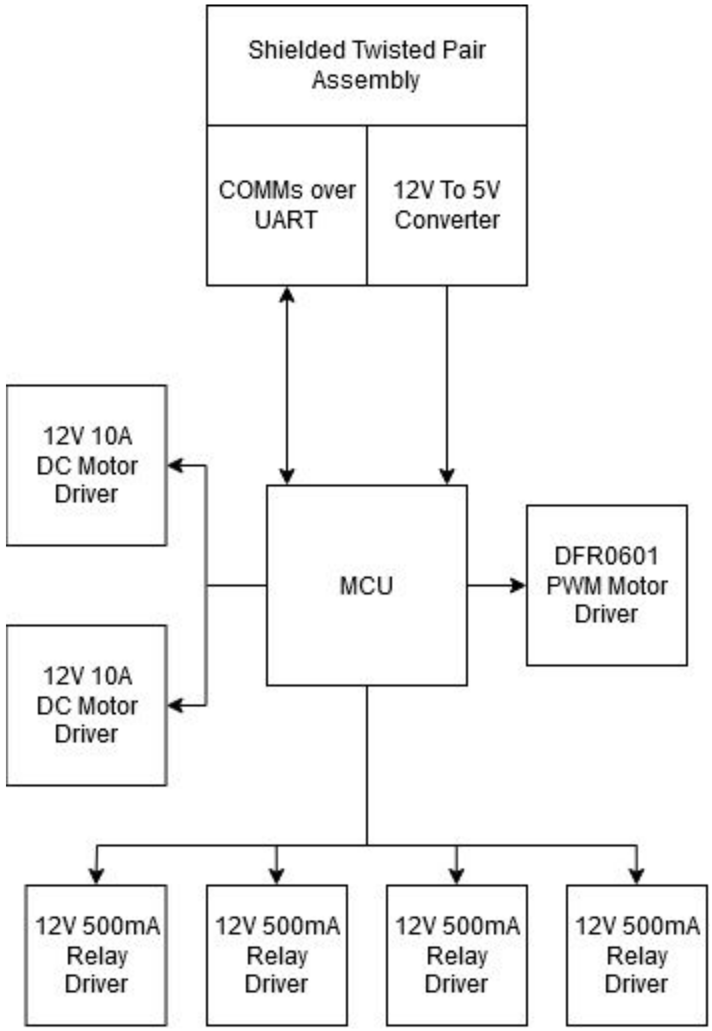



***Figure 19:*** *Relay Node Block Diagram*

Currently, the code for the heating node is 90% complete. What is left is just implementing the communication protocol designed which is expected to be relatively easy to complete. The code for the cooling node has not been started, but it is believed that it will be almost trivial to develop. Due to the use of the same circuit for each node, the code from one can be reused in the other with little changes needing to be made. As with the other nodes, the team is confident that both will be complete in time for the design showcase.

### 3.2.7 Connection "Node"

Due to the changes made with regards to the CANBus network, the connection node mentioned in the previous design review will not be used. Instead, the UI node will be wired directly to the temperature and heating nodes. The cooling node as mentioned exists entirely independent of the rest of the system. In order for the battery management system, motor controller, and battery charger to be able to communicate on CAN, they will be wired together with the necessary termination resistors to build a small self contained CANBus network.

### 3.2.8 Next Steps

As previously stated, each node needs to have its code fully developed. Most of the work has been done on this, with little remaining. The team is confident that that code will be developed without much trouble in the coming week. Once each node has been fully programmed and proven to work outside of the bus, they will be installed within it. Following that, their functionality will again be verified before the project is completed. If needed, the various thresholds used for the temperature monitoring capabilities will be changed as determined by experimental data.

A test plan for each node has been created and is ready for implementation. It relies on the use of the RobotFramework test automation framework as well as a Python library backend. This framework was decided on due to the experience of several team members with it, as well as its ease of use and development. Each node has a number of tests that give them a certain input. Through the use of several pieces of test equipment, the output of each node will be compared to what is expected of them. This test framework will allow for rapid testing of each node and quick troubleshooting of any unwanted effects.

It is expected that this section will be seen as somewhat lighter than others. Again, a supplement has been included with this report that goes into far greater detail which should alleviate any concerns.

## 3.3 Cooling System

---

### 3.3.1 Coolant Choices

Due to the desired high steady state performance of the bus, the team has selected liquid cooling to allow a higher steady state power consumption without overheating. The team considered three standard choices for the type of coolant for the loop. The three that were compared are water alone, ethylene glycol, and propylene glycol. The benefit to using water would be its accessibility: it would be easy to obtain and add to the system. Water's downsides are its corrosive interactions with surrounding materials, and having the highest freezing point of all three of the solutions. Ethylene glycol's advantages are its low freezing point, high boiling point, high heat transfer capabilities, and its non-corrosive qualities. The disadvantages, however, are that it is flammable and poisonous if ingested; the toxicity makes this risky, because it happens to have a sweet smell, which may attract children and animals. Propylene glycol's upsides are its low freezing point, non-poisonous quality (the FDA approved it for use in food), and it is non-corrosive. The downsides are its slight flammability at high temperatures, and it is slightly more expensive than Ethylene glycol, though both are fairly inexpensive. Because the coolant pump that was selected is designed for automotive use, automotive ethylene glycol will be used to prolong the life of the pump and avoid unexpected issues with coolant compatibility.

### 3.3.2 Component Selection

As the client desires the bus to keep up with traffic in all driving situations, the team decided that thermal throttling of the drive system would be detrimental to the driving experience. Therefore, when designing the cooling system for the bus, components were selected that would allow the bus to perform to its full potential in all climates and driving situations. The battery packs and the motor controller will be liquid-cooled in order to limit operating temperatures during demanding driving situations. The cooling system includes a coolant loop comprising the battery packs, the motor controller, a pump, a small automotive radiator, and an option for a coolant heater. The Champion Drag Racing Aluminum Radiator Module was selected because of its heat rejection capabilities and its size compatibility with the motor bay.

The option for the 2.2 kW engine coolant heater is included to heat the battery packs above their minimum operating temperature to allow the batteries to function correctly when operating in low ambient temperatures. To circulate the coolant, a 20 gpm, 84 W electric coolant pump was selected, which will be able to pump the coolant through the entire cooling system.

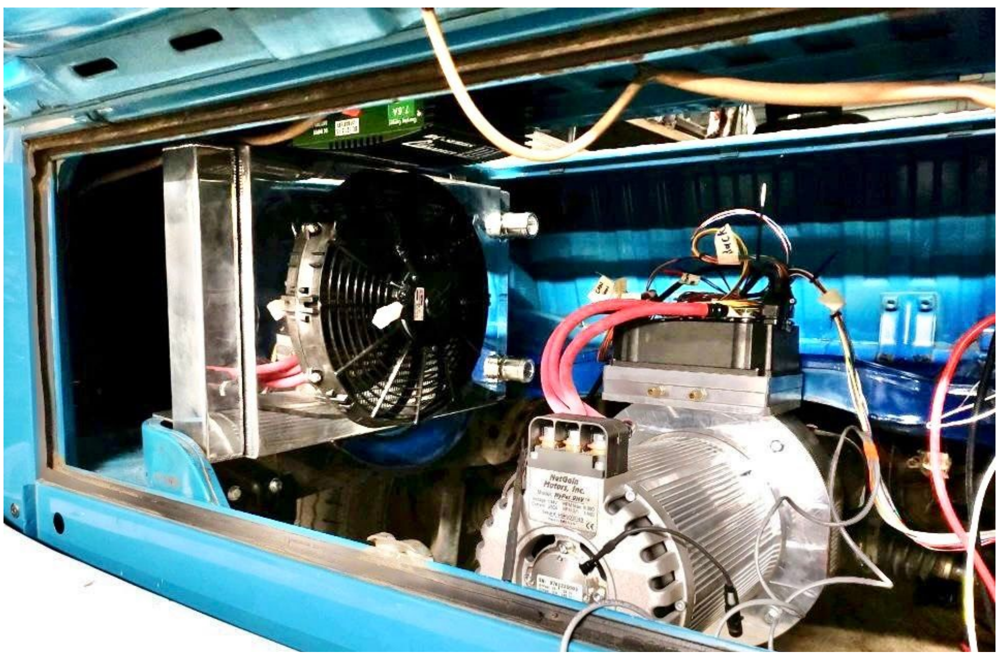


***Figure 20:*** *Radiator Mounting Location*

The ε-NTU method was used to analyze the performance of the cooling system, using an effectiveness value of 0.4 for the radiator (determined by an experimental study conducted by Lamar University) [9]. The details of this analysis can be seen in Appendix A. The cooling system's goal is to keep the batteries below their maximum normal operating temperature of 130°F, even at maximum power (allowing the bus to climb steep grades while loaded with gear, without de-rate). At the motor's rated power, the cooling system needs to reject approximately 4600 W of heat from the batteries, and about 300 W from the motor controller, totalling 4.92 kW. The radiator is a small dragster radiator with a 1400 cfm fan. The radiator is sized such that the cooling capacity will allow the bus to operate at full throttle continuously as long as the ambient temperature is below 103°F. At temperatures above 103°F, the motor controller will de-rate and reduce power consumption to allow the cooling system to keep up.

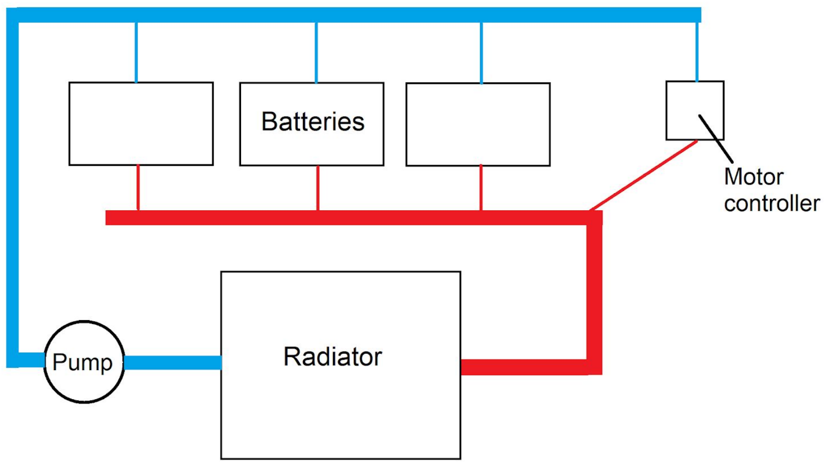



***Figure 21:*** *Cooling system loop configuration*

### 3.3.3 Air Flow Analysis

A SolidWorks simulation was performed to better understand the passive air flow cooling while driving. On average, the air flow through the undercarriage of the bus was approximately 0-3 mph higher than the driving velocity, as shown in ***Figure 22.*** This profile was just under the front bumper (about 6 inches under the baseboard). The air flow around the sides of the bus varied more, and was around 5-15 mph lower than the driving velocity. The side profile is an average of approximately 4 inches off the side of the bus. Full air profiles at 30, 40, 50, 60, 70, and 80 mph can be found in Appendixes B and C. The goal of these simulations is to determine if the air flow into the motor bay would be adequate for cooling both the motor and radiator. These simulations show that there is proper convective air flow where cooling is needed. Analysis was not performed at slow speeds (like stop and go traffic) because the motor will be off when the vehicle is not moving, and therefore will not generate heat.

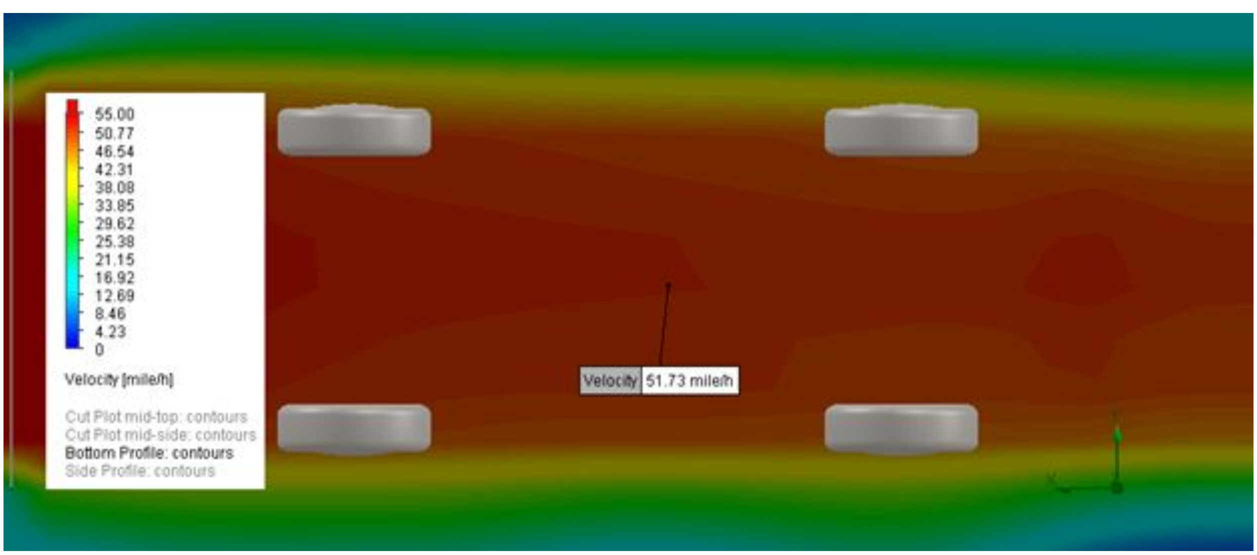


*__Figure 22:__ Bus air flow 6 inches below baseboard profile at 50 mph*

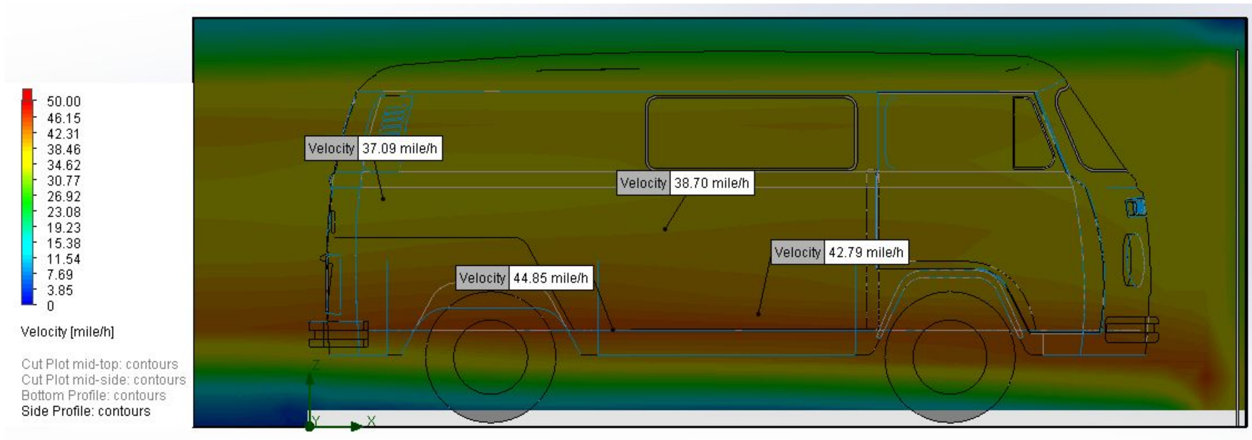



*__Figure 23:__ Bus air flow side profile at 50 mph, 4 inches off side face*

### 3.3.4 Thermal Load Calculations

It is important to calculate the thermal conditions of the battery pack in the two cases where it is generating heat. These cases are:

1. **Heat on recharge**—The cooling system will be active when the batteries are charging. This will keep the batteries below their maximum charging temperature, and allow higher charging power by dissipating the heat generated during faster charging.
2. **Heat on discharge**—The cooling system will dissipate the heat generated by the batteries under heavy load, which will allow the bus to drive at high speeds without overheating, even when driving fully loaded.

When considering thermal conditions, the important factor is the heat generated; in the case of the battery pack, this comes in the form of watts generated. Since the battery cells in a Tesla Model S module are 3.4-A batteries, the power dissipated by a single cell is approximately 1.0 W, assuming an internal resistance of 100 mΩ [10]. With 444 battery cells in a single module, each module dissipates approximately 513 W of heat. In the team's final battery configuration there are 18 modules, thus the cooling system will need to dissipate 9200 W of heat.

$$P = I^2 * R$$

$$P_{cell} = (3.4)^2 * 0.1 = 1.16\ W$$

$$P_{module} = P_{cell} * 444 = 513\ W$$

$$P_{pack} = P_{module} * 18 = 9239\ W$$

The type of battery charger used will determine the amount of heat generated. Specifically, the more current the charger is capable of outputting in a smaller time frame, the more heat will be generated. Assuming the batteries are being charged at the maximum amount for a standard level two charger station the cooling system will need to dissipate roughly 20 kW. This number comes from an output current and voltage of 80 A and 240 V from the onboard charger. With this much heat being introduced into the system the batteries will be providing power to the fans to run the cooling system. This will allow the batteries to charge safely and maintain safe operating temperatures.

$$P = V * I = 80 * 240 = 19200\ W$$

# 4.0 Conversion Planning

## 4.1 Proven Component Compatibility Through Testing

---

From conversations amongst the team as well as with external parties, there was concern about potential compatibility issues with the parts selected. The chief concern was whether or not the Tesla batteries will function with a non-Tesla motor and controller. These concerns were raised by people with EV Conversion knowledge however other conversions had already been accomplished with these battery modules, motor controller, and motor before we started.

As stated, the largest concern with component compatibility relates to the batteries. Ideally, there would just be a positive and negative terminal on the battery pack that power can be either taken from or given to. What differs our conversion from previous conversions with these components is the use of three packs of batteries in parallel. When using batteries in parallel, especially lithium-based ones, special care must be taken to ensure that no one pack is delivering most of the current. One existing EV conversion that has tackled this problem is the VW Bus being converted by EV West [13], which is using the same motor and controller as this project, and is also powered by Tesla Model S battery packs. From the precedent set by their success, the following can be determined:

1. The motor and controller chosen have no issues interfacing with each other
2. The controller is able to interface with the Tesla batteries in some way

The team contacted Zelectric Motors, another VW electric conversion company, who offered insights that an easy and effective way to manage the Tesla batteries is with the Dilithium BMS distributed by EV West. Relying on precedent and professional technical recommendation, the team concluded that this combination of parts would lead to a successful project. By relying on precedent and industry contacts, the team moves forward with confidence to overcome unforeseen issues.

Some component compatibility has been tested. The motor has spun powered by the batteries and the drivetrain has been assembled in the bus. The drivetrain has been tested at low speeds but has yet to complete 0 mph to 60 mph as well as 60 mph to 0 mph testing.

## 4.2 Testing Procedures

Along with the calculations that were done last semester for the initial choices of each component, the Re-Volt team has also devised testing plans and procedures for each subsystem to ensure the safety and longevity of the bus' functionality. The test plans and results are summarized in Appendix I. Additionally, technical approval for the calculations that informed certain design decisions was provided by the Re-Volt Technical Advisors (professors at Colorado School of Mines), and are included as Technical Advisor Approvals in Appendix J.

## 4.3 Fabrication

While planning out our selected components for the driveline, our team knew a decent amount of fabrication would be necessary to make everything fit in the bus. At a minimum the conversion would need brackets to mount: radiator, cooling fans, motor controller unit, batteries, throttle position sensor, and a charging port. These are all relatively simple ideas that could be designed with packaging being of most concern. Space inside the bus would be optimized since about 90% of the listed components can be mounted in the engine bay rather than in the passenger compartment.

During the team's research of motors, we noticed the few companies that produce conversion kits sell several adapters to make the motor bolt up to the existing transmission. Although convenient, these adapters come with a steep price tag and are custom made to order which could result in possible installation delays. One adapter allows the VW flywheel to bolt onto the electric motor so that the clutch assembly can still be utilized. This component could be easily created on the manual lathe and mill in a few days. The larger adapter would be used to extend the bellhousing of the transmission. It would need to enclose the flywheel and clutch assembly while also providing the exact spacing for the clutch pedal to disengage the clutch correctly. This would be a critical component and a bit more challenging to make on the CNC mill, but our team was confident that it could be made within our abilities. The team decided based on given design and cost of raw materials that these adapters could be machined at the school, ***Figure 24***. They were produced by the team for under half the cost of the name brand adapters.

***Figure 24:*** *Bellhousing Adapter Machining Process*

## 4.4 Safe Conversion Protocols

---

Throughout this project there has been a large number of concerns related to safety. These are not without reason, the total battery pack is expected to contain over 95.2 kWh of energy which is over 300 MJ. For a frame of reference, if all of that energy were to be dissipated instantaneously it would be similar to a kilogram of TNT exploding [14]. While it can be safely assumed that such a scenario would never happen, the sheer amount of energy stored in the bus should be a cause for concern. As such, safety has been the top priority of each part of this design from the very beginning. Safety has been incorporated not just into the final design, but the steps that must be taken to complete it.

The largest concern is the potential for an electric arc when dealing with the batteries. A single battery pack can have a voltage of up to 24 V and can deliver a maximum current of 1.5 kA if they were to be shorted. From experience amongst team members, a process like stick welding uses currents on the order of 100-200 A for standard ⅛" electrodes. That amount of current if allowed to flow through a piece of metal has great potential to instantly spot weld it in place. Additionally, there are concerns over electrical safety with relation to people. The human body has a dry skin-to-skin resistance of approximately 100 kΩ [15], which at that voltage would allow for under a microamp of current to flow. However, for the full nominal voltage of the battery pack of 144 V, that increases up to over a microamp and only more so if the person in question has, say, sweaty hands. In short, while the voltages present in this system are far below the AC voltages that would be encountered by the average electrician, they are still more than capable of causing bodily harm to team members.

These hazards have been mitigated by the use of proper safety equipment. For protection against electrical arcs with tools, a set of cheaper wrenches have been coated in multiple layers of PlastiDip to add a degree of electrical insulation. Thankfully, due to the comparatively low voltages in this system, a full set of lineman's tools was not needed. To protect team members who are working with the batteries, a pair of Class 00 electrical insulating gloves was purchased. These gloves are rated to 500 Vac and 750 Vdc [16], well above the range expected to be encountered in this project. Additionally, when working with the batteries, team members have been instructed to keep one hand behind their back. The goal of this practice is to lower the chance that someone touches a piece of grounded equipment when working on a battery, causing a short circuit. By having only one pair of gloves, this requires that only one person be working on the batteries at a time. The goal of this is to have only one person who could be injured at a time.

In the designs themselves, special attention has been paid to potential causes of arcs of short circuits. To minimize these risks, liberal use of insulating rubber sheeting has been used.

Other safety concerns have been dealt with through the use of industry and OSHA safety standards where possible. These include but are not limited to: use of eye and ear protection when necessary, usage of closed toed footwear when working with heavy materials, and other things of that nature. The COVID-19 pandemic has introduced other concerns with regards to the potential spread of the virus. When working in person, all team members are expected to wear some sort of facial covering and expected to maintain the appropriate distance between people. These efforts have proven worthwhile. Earlier this semester, a team member tested positive for the virus. Thankfully, due to the safety procedures in place, no one else on the team was infected and minimal work time was lost.

## 4.5 Emergency Safety

A primary safety concern with electric and hybrid vehicles is the possibility of electrocution to first responders and individuals conducting maintenance. The bus will be outfitted with "ELECTRIC VEHICLE" and "HIGH VOLTAGE" safety decals to notify first responders in the event of an emergency. These decals, seen in ***Figure 25***, will also notify anyone who may not be familiar with its power source and is performing maintenance on the bus.

***Figure 25:*** *High voltage sticker on charging port cap*

In collaboration with the Department of Energy and the National Fire Protection Association, the National Highway Traffic Safety Administration (NHTSA) had developed safety measures regarding electrical vehicles in the event of a crash. While NHTSA does not see electric vehicles as more dangerous than gas powered vehicles, electric vehicles do have certain attributes that need to be known for anyone coming in contact. The clients will be familiar with NHTSA procedures for operation, storage, and post-accident protocols [17].

The bus will be equipped with a Class C fire extinguisher incase of electrical fires. A Class C fire extinguisher uses carbon dioxide or a dry chemical that separates the fuel source, heat, and oxygen to extinguish the fire. The fire extinguisher will be located with the motor in the back of the vehicle [18].


***Figure 26:*** *Gigavac 400 A disconnect [19]*

In order to ensure safety while working on components downstream of the battery, a high voltage disconnect will be incorporated, seen in ***Figure 26***. This will ensure the ability to work safely on the vehicle's electronics with the batteries installed. In the case of an accident and the passengers are unable to reach the high voltage disconnect, an inertial cutoff switch will be installed as well. An inertial cutoff switch from a Smart EV is being implemented. The high voltage wiring will be done in accordance with SAE standards including the use of orange high voltage split looms to surround cables.

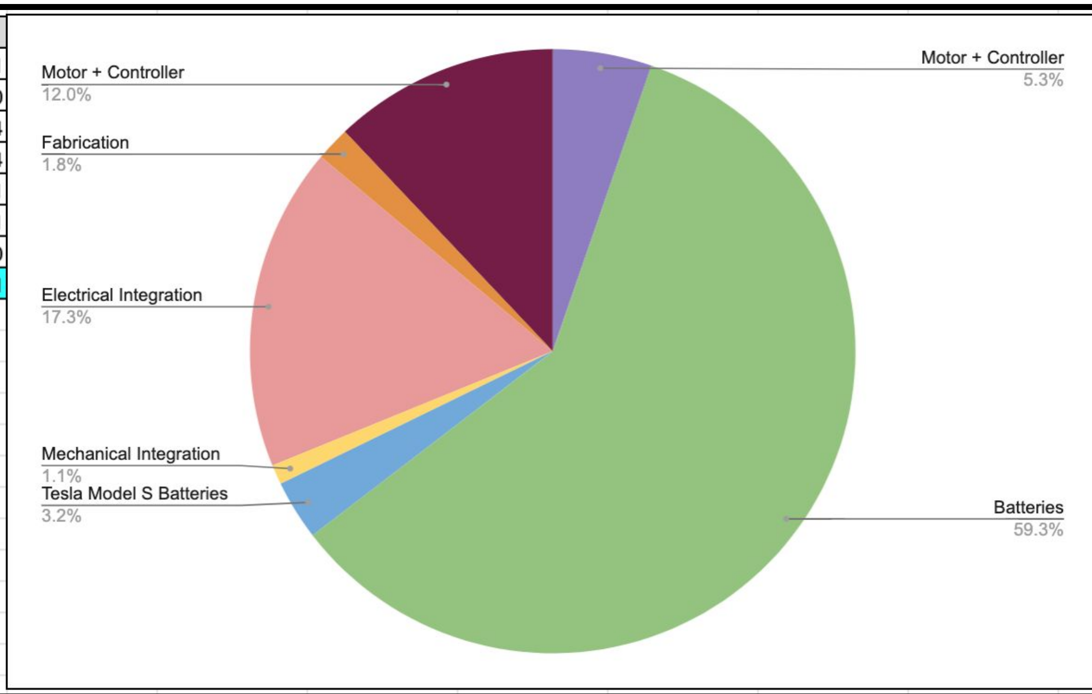
## 4.6 Legal Considerations

In order to maintain the vehicle's legal status and allow it to be driven on public roads, it must be registered with the Colorado Department of Motor Vehicles (DMV) as an EV after the conversion is complete. The DMV lays out a few legal requirements for converting a vehicle into an electrical vehicle, as well as some benefits. Firstly, the total weight of the bus must not exceed the original gross vehicle weight rating (GVWR). Secondly, when replacing an engine, the new engine must be the same year or newer. This is assumed to be true, as well, for electric motors (vs. ICE). Lastly, the vehicle must have a new VIN inspection and be issued a new title reflecting the new "fuel" type. As a reward, the state government of Colorado offers a tax credit to those who convert vehicles from gas to electric before the end of year 2020. This reward and its stipulations are defined under Income 69, *Innovative Motor Vehicle Credit* [18], in the Colorado Department of Revenue tax code, and payment depends on both the year the conversion is done and the vehicle's GVWR.

## 4.7 Budget Breakdown

During the initial client meeting, the budget was set to $15,000-$20,000. This low estimate served to challenge the team to be resourceful and creative. However, after the batteries were chosen and the clients expressed their strong desire to meet the 250-mile driving range for road trips, it was decided the budget would be increased. Currently, the estimated total cost is $35,760. This money is sourced from the CSM Capstone Foundation, crowdsourced donations,

| Categorical Breakdown | |
|---|---|
| Optional Add-ons | $1,887.81 |
| Batteries | $21,166.50 |
| Cooling System | $1,141.24 |
| Mechanical Integration | $377.14 |
| Electrical Integration | $6,177.01 |
| Fabrication | $653.31 |
| Motor + Controller | $4,300.00 |
| **PROJECT TOTAL** | **$35,760.31** |




selling the existing ICE and combustion-related components, and the clients' personal financing.

***Figure 27:*** *The budget pie*

The hefty funding required to obtain eighteen batteries is due to the number of batteries in this design to meet the clients' requirements for mileage range (250+ miles). Funding for batteries has driven the fundraising efforts, as battery costs are nearly 60% of the total project cost. Appendix H is the detailed Bill of Materials for the project.

## 4.8 Fundraising/Marketing

With fundraising efforts being difficult due to the outbreak of COVID-19, the clients obtained sufficient personal funding for the project. Fundraising efforts were geared to help ease the financial burden on the clients while maintaining social distance mandates. Difficulties with fundraising were anticipated after the lockdown last spring. Not only has it been difficult to host events while trying to maintain social distancing, but with the economic uncertainty, it has been hard to convince people to donate. While the semester started off strong with an on-campus "open house" and multiple other fundraising prospects planned, it quickly became clear that local businesses whom we hoped to partner with for fundraising events were unwilling to host us at their locations as COVID-19 numbers continued to rise. Earth Treks Golden was the most receptive to our partnership idea and was willing to give us discounted day passes for donors. However, they could not help with hosting an event of any type. It quickly became apparent that the fundraising team's efforts would be better utilized with fabrication and installation.

While helping with component installation, the fundraising team has also been working to create the Re-Volt photo books, t-shirts, and engraved metal plaques for top tier donors. Photo books for the $250 donors, tshirts for the $500 donors, and engraved metal plaques with the names of the $1000 donors will be mounted in the motor bay.

Though we only hosted one event on campus, it was a huge success. We received a substantial donation as a direct result and many Mines students and faculty were able to learn about the project. Re-Volt has become a very well known senior design project in the Mines community. Over 50 new Instagram followers were gained during the on-campus "open house" and our Instagram account gained over 300 followers in the last three months.

# 5.0 Conclusion

## 5.1 Detailed Design Critique

---

With a project of this size, scope, and cost, every decision made must be the correct one. In order to meet this requirement, each decision was ruthlessly critiqued by both the clients, the team members making it, when possible the projects technical advisors, and when possible industry experts. One of the things that the team relied on most from the start of the project was precedent set by previous conversions. When done by professional companies such as EVWest and Zelectric, companies with a degree of legal liability for their work, the decisions and designs that they chose were chosen by the team. When precedent didn't exist, those same companies proved invaluable due to the input and advice they were able to give.

One key example of this is the battery configuration. As seen in both the preliminary and intermediate design review, the batteries were configured as having 3 strings of batteries, with each string having 6 batteries connected in series. After conferring with both the companies mentioned, the team learned that there were serious safety issues with that design. Those companies were able to give us insight as to how to fix those issues, with the end result being a reworking of the battery configuration. This is just one example of where the team critiqued a design decision that was made, and came to a different conclusion than expected. When precedent didn't exist for a decision, a precedent was set only with the input of industry experts.

## 5.2 Lessons Learned

---

This project has proven to be a learning experience for everyone involved. Most team members came into this project with little idea of what even went into an EV conversion, let alone what needed to be done on this specific one. All team members were able to grow their skills in doing in depth research on specific tasks. Most team members were able to expand their knowledge and skills in various fabrication techniques.

As far as specific lessons that can be given to other EV conversions, it is hoped that all of the work that has been done on this project will be turned into an open source guide on how this conversion was done. By making it open source, it allows for other groups who are considering similar conversions to see what was successful and what was not. As previously stated, precedent was used for a large number of decisions in this project. It is hoped by all team members that the precedents that were set in this project can be used by others.

One of the key lessons learned is that for a project of this scale, the fine details are some of the most important ones. While it is known that it is easy to get bogged down in the details of a project and lose sight of the bigger picture, those details are what make up the big picture. Despite the amount of work that was done by the team in the previous semester, it was truly only scratching the surface of what needed to be done. If the goal of the capstone program is to have the first semester be planning the project and the second semester executing that plan, then for a project of this magnitude much more planning should have been done. In this project, the first semester was mainly just giving a rough idea of what needed to be done. This past semester has shown that a rough idea did not have anywhere the number of fine details that needed to be decided.

## 5.3 Final Steps

---

The final steps for this electric bus conversion will be working with the clients to develop a user manual that fits all of their needs. This will include basic diagrams of all systems, charge instructions, what warning lights or key sounds to look out for, information to convey to anyone working on the vehicle, and general guidance for safe operation.

In addition to a user manual, the team will be compiling the varying reports, photos, and work log from the past year to open source. Open sourcing the project has been a main goal since the project was brought to the team by the client. The goal will be to share what we have learned from component selection and physical conversion with anyone looking to meet similar electric conversion goals as us. This will be shared on our website (revoltswagen.com).

# 6.0 Appendixes

Appendix A: ε-NTU Heat Transfer Calculations

---

$$Q_{reject} := (4620\ W + 300\ W) \cdot 1 = (4.92 \cdot 10^{3})\ W$$

$$T_{h.in} := 130\ °F$$

$$\varepsilon_{radiator} := 0.4$$

$$V_{air} := 1400\ \frac{ft^{3}}{min}$$

$$\rho_{air} := 1.225\ \frac{kg}{m^{3}}$$

$$m_{dot} := V_{air} \cdot \rho_{air}$$

$$Cp_{air} := 1006\ \frac{J}{kg \cdot K}$$

$$C_{min} := 1006\ \frac{J}{kg \cdot K} \cdot m_{dot}$$

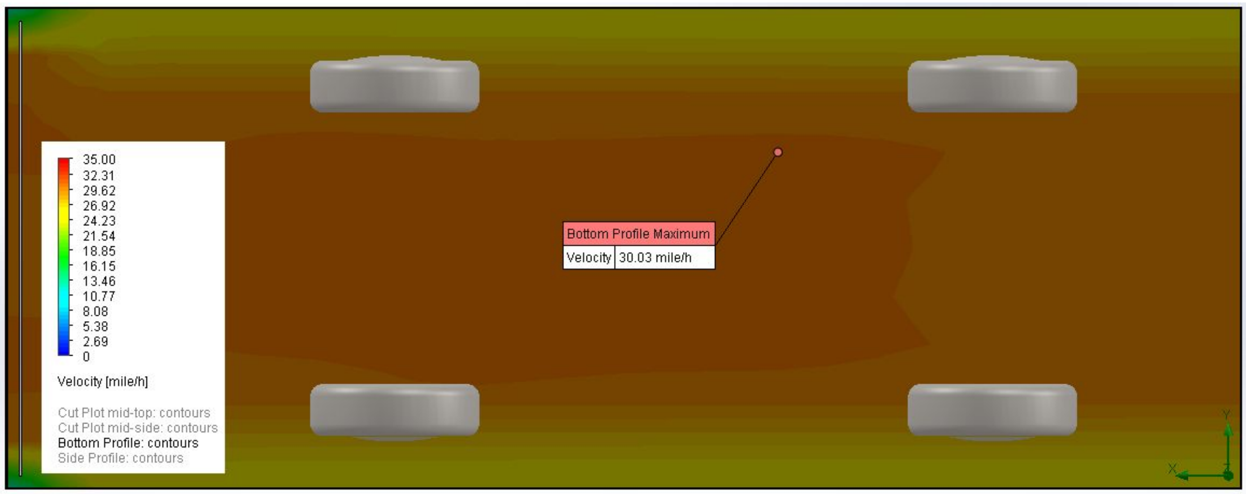
The equation below is reorganized from the $\varepsilon$-NTU heat transfer method to solve for the maximum ambient temperature before thermal de-rate begins.

$$T_{c.in} := T_{h.in} - \frac{Q_{reject}}{\varepsilon_{radiator} \cdot C_{min}} = 102.809\ °F$$

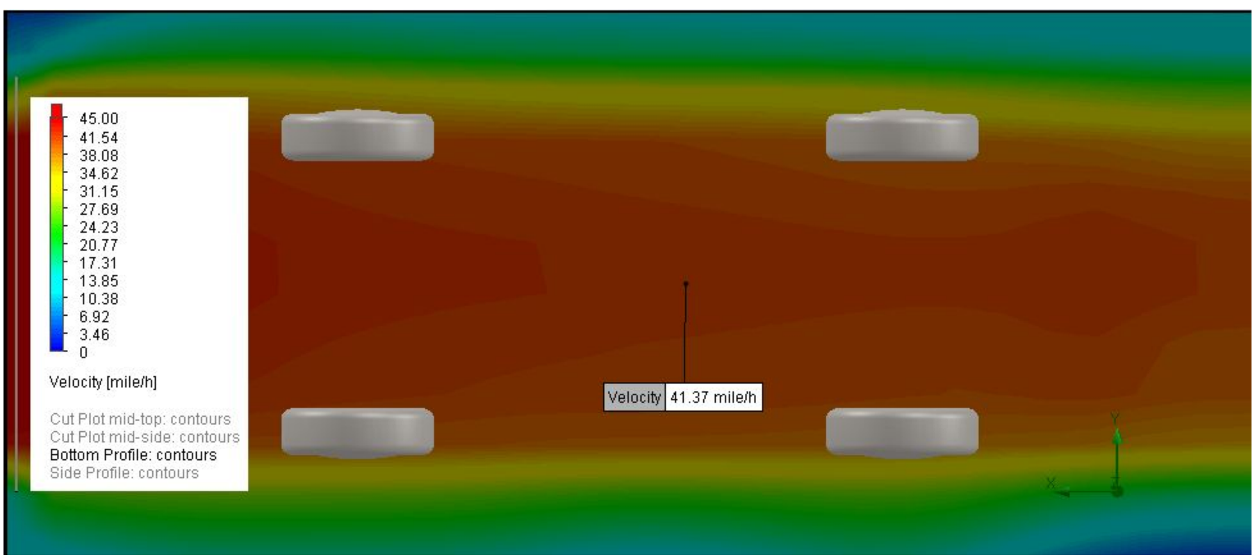
# Appendix B: Bottom Air Flow Profiles

---

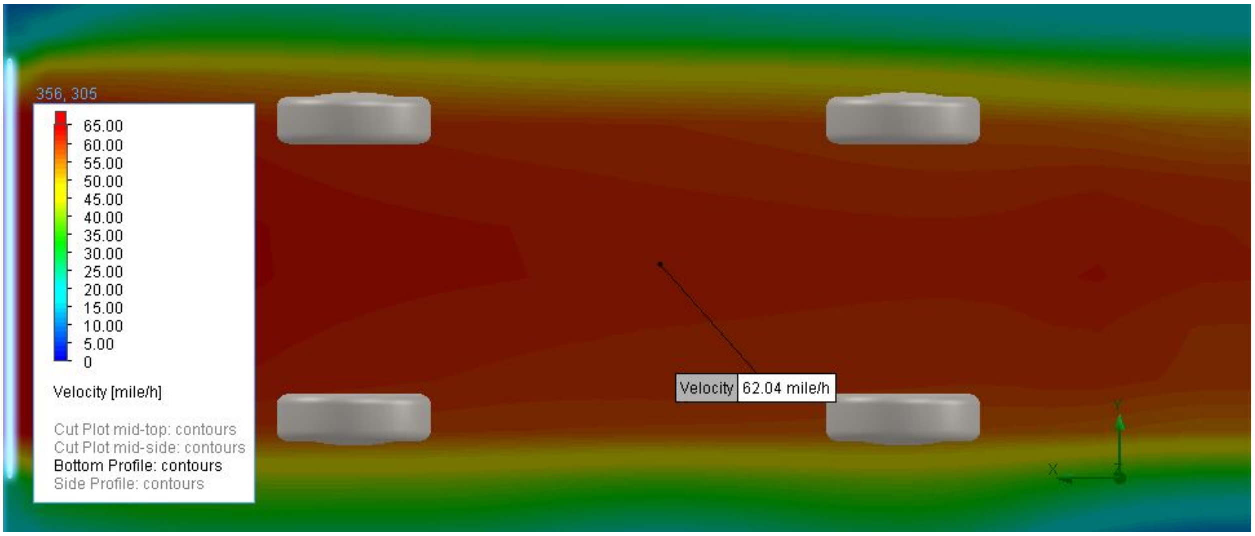
### Bottom Profile:  30mph



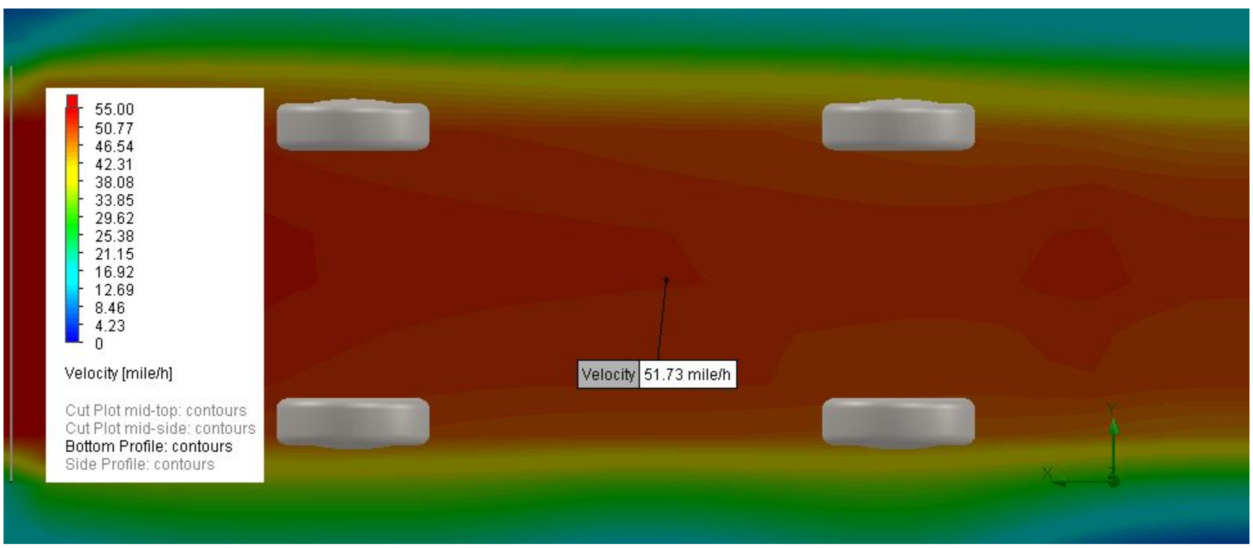

### Bottom Profile:  40mph



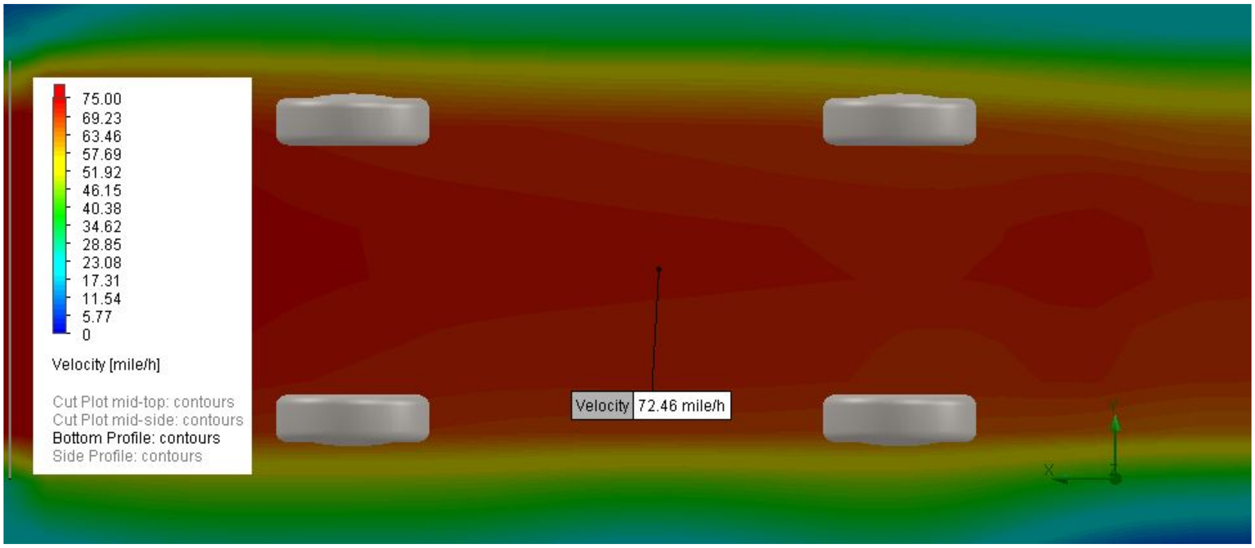
**Bottom Profile:  50mph**



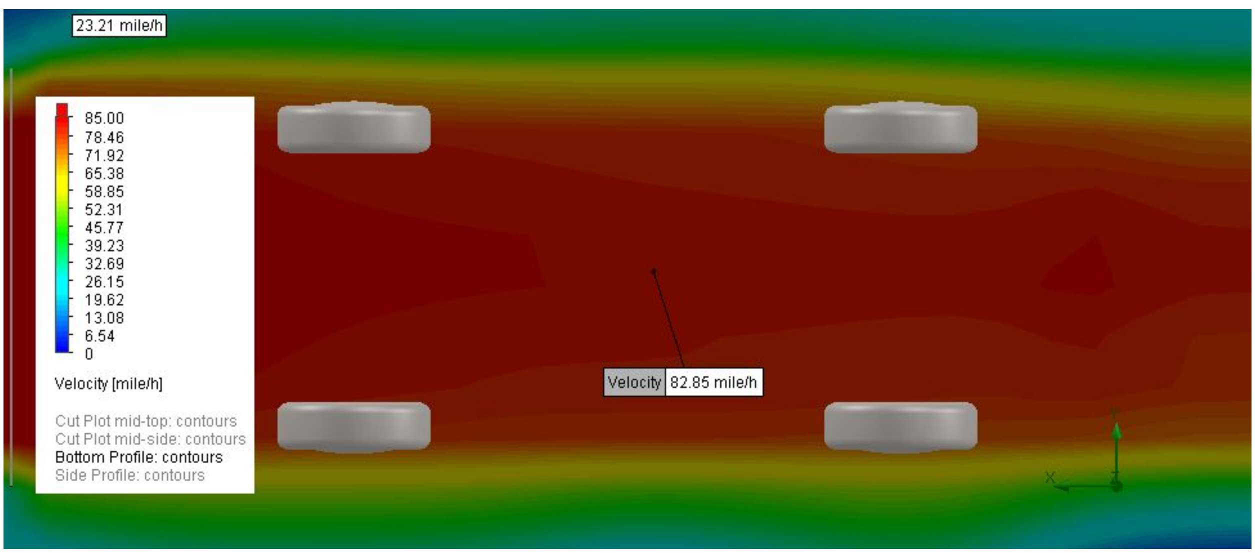

**Bottom Profile:  60mph**



**Bottom Profile:  70mph**



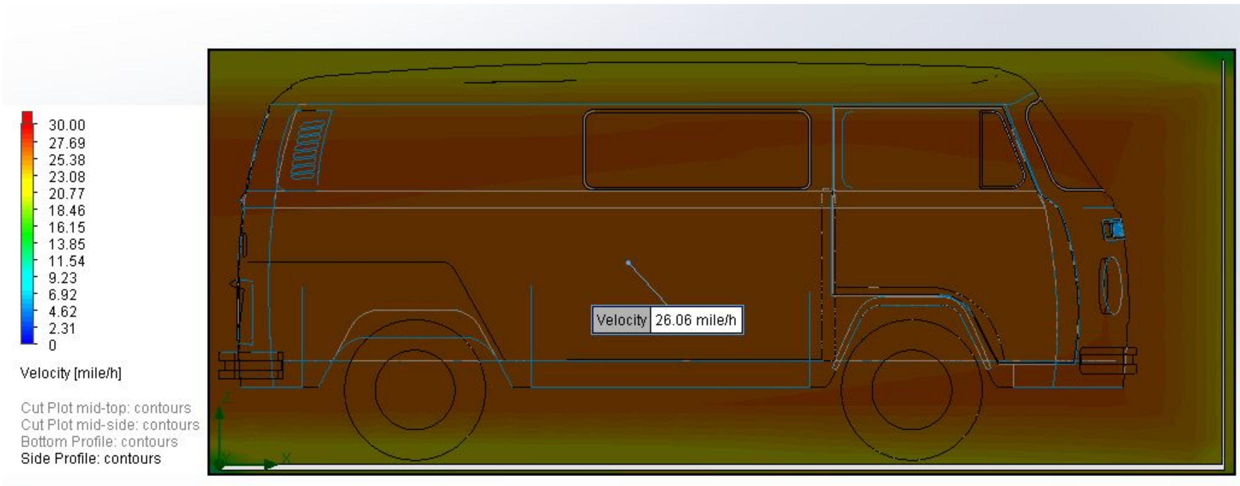

**Bottom Profile:  80mph**



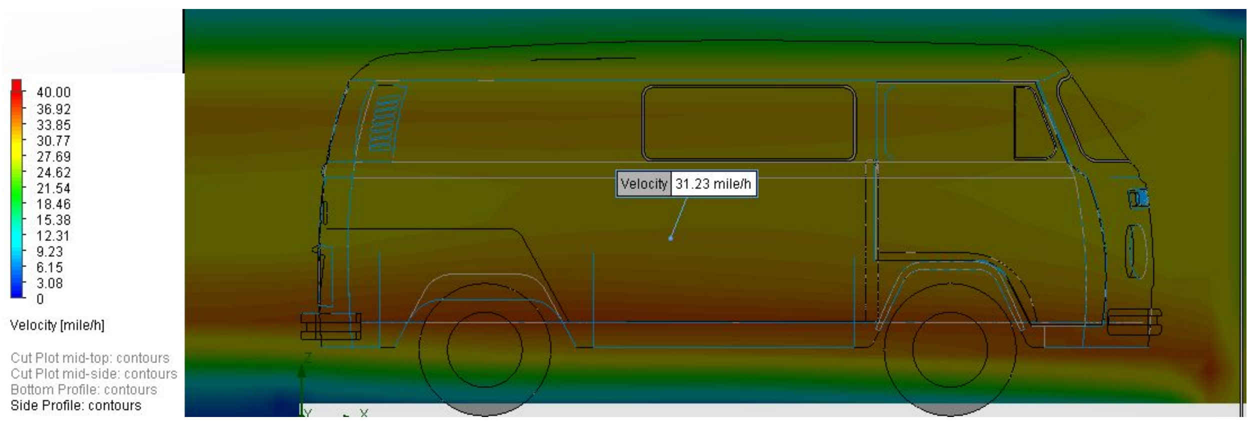
# Appendix C: Side Air Flow Profiles

---

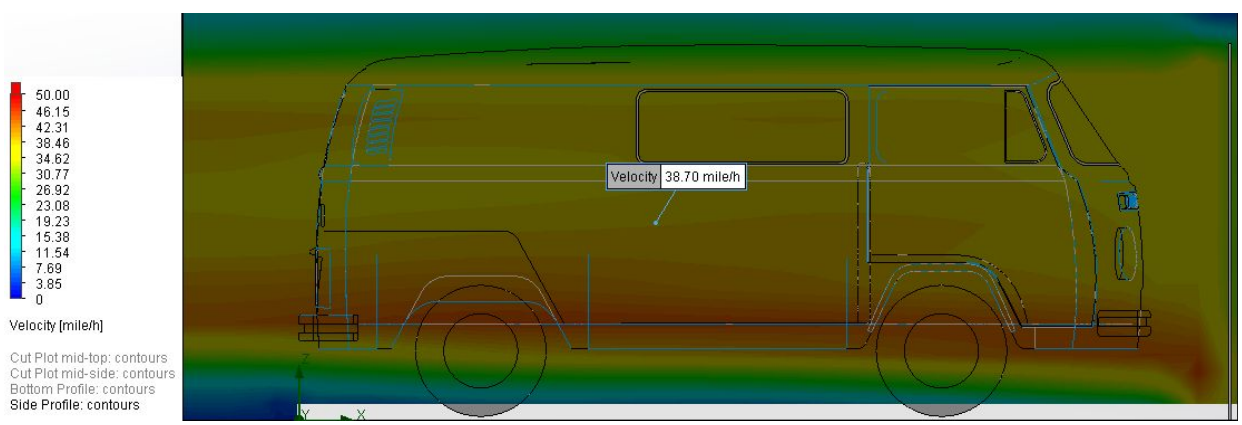
### Side profile – 30mph



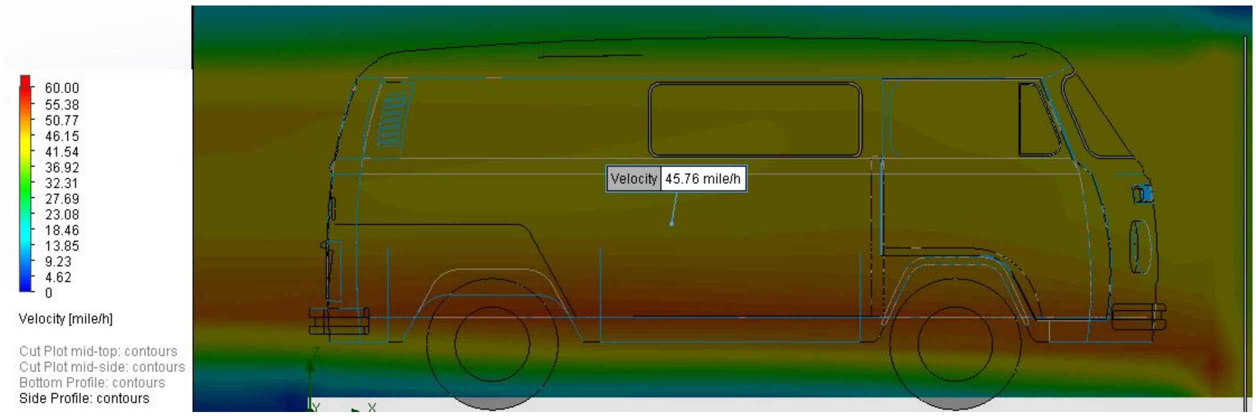

### Side profile – 40mph




### Side profile – 50mph

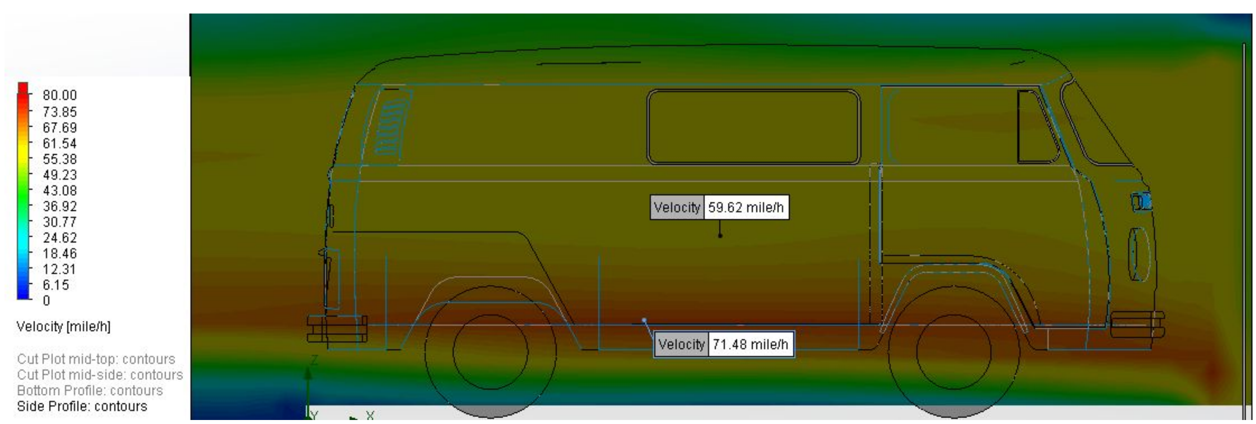


## Side profile – 60mph




## Side profile – 70mph


## Side profile – 80mph



# Appendix D: Embedded Systems Report and Bill of Materials

# ReVolt FDRt Embedded Systems Supplementary Report

Garrett Shirley

November 24, 2020

## Contents

**1 Background** **2**

**2 System Responsibilities** **3**

**3 Communication Specification** **5**
3.1 Physical Layer Description . . . . . 5
3.2 Software Layer Description . . . . . 5

**4 User Interface Node** **6**
4.1 Schematic Design . . . . . 6
4.2 Parts Selection . . . . . 7
4.3 Software . . . . . 7

**5 Temperature Nodes** **8**
5.1 Schematic Design . . . . . 8
5.2 Parts Selection . . . . . 8
5.3 Software . . . . . 9

**6 Relay Node** **10**
6.1 Schematic Design . . . . . 10
6.2 Parts Selection . . . . . 12
6.3 PCB Design . . . . . 12
6.4 Software . . . . . 13

**7 Connection Node** **14**

**8 Next Steps** **14**

**9 Lessons Learned** **14**

# 1 Background

This document is intended to act as a supplement to the ReVolt project's Final Design Review Report (FDRt). This document was chosen to be separate from the FDRt so as not to overload the FDRt with an excessive amount of detail on the design of the necessary embedded systems. As a result, this document has been written by and for people with somewhat of a background in embedded systems, and some terms/concepts may be used without an explanation of their meaning/purpose. This document should have included with it a number of schematics and bills of materials in PDF form as well, as it is intended to describe their design and the parts chosen for them. Note, only non-passive devices will be explained in depth. The reasoning behind the majority of passive devices chosen is their cost, their size, and if they are automotive rated.

It has been established that there is a need for some sort of an embedded system for this project. Previously a report was made that indicated this, and the approach that would be used. In the intermediate design review another supplemental report was written detailing the designs of the embedded system. This report is intended to show what changes have been made to the overall embedded system since then, as well as the current state of the system. All nodes have been fully assembled and proven to work, with most of the code needed for them having been written. Currently a test plan has been developed for each node that uses the RobotFramework automated test framework. Once all code has been fully developed, and each node passes its full test suite, they will be installed in the bus. For installation, special consideration has been made towards reducing the overall EMI noise that may affect the nodes. There are many devices in the engine bay that use high frequency switching supplies to perform their duties, so it is expected that the bus itself will be a somewhat noisy environment.

## 2 System Responsibilities

The responsibilities of the embedded system have changed considerably since the intermediate design review. The main cause of this is the use of a COTS screen, rather than the team developing their own. This is a change that occurred rather late in the project that while not ideal at the time turned out to be a blessing in disguise. That blessing comes from the next major change that was made, which is the scrapping of the CANBus network for the custom designed nodes.

When the nodes were originally being developed, it was assumed that the MCU's built in CAN module allowed for the MCU to communicate over CAN with no other components. This assumption was false. Upon reviewing the datasheet in greater depth, as well as a number of forum posts from other uses, it was discovered that a separate CAN transceiver IC is needed for CAN communication. To put it simply, the MCU's built in CAN module outputs two signals, CANTX and CANRX. Those signals then need to be passed to a transceiver that then turns them into the CANH and CANL signals that actually makeup the CANBus. This is something that in hindsight should have been discovered when the nodes were being designed. Had it been known, the designs could have easily incorporated the CAN transceiver IC. A popular CAN transceiver appears to be the Microchip MCP2551, adding this to each node would have been trivial. What this all adds up to is that without some sort of serial to CAN module, the embedded system cannot communicate over CAN. That means that if a COTS screen was not used, then the custom one being developed would have no way of getting the information it needed. In the current state of the project, all that will be communicating over CAN is the motor controller, the battery management system, and the onboard battery charger.

Thankfully, while this specific issue was not foreseen, the designers of the embedded system had a hunch that implementing CAN on the MCU's would not be without problems. Because of that, from their inception, a backup communication plan for the embedded system has been kept in mind. This backup communication system uses the UART modules available on each MCU. This new communication system will be detailed in a later section.

The new responsibilities of the embedded system are as follows:

1. Display necessary errors using the stock dashboard display (over temperature, under voltage, a generic "check engine" notification)
2. Control the battery cooling system based on information received from the battery management system
3. Control the cabin air heater based on inputs from the user
4. Monitor the temperatures of components in the engine bay, and control the cooling system as needed

While the specific responsibilities of the overall system has changed, the fulfillment of those responsibilities has not. The specific nodes in use has not changed, although the number of temperature nodes has been reduced from 5 to 1. This is because the battery modules have built in thermistors that are monitored by the battery management system. Because of this, only 1 temperature node is needed. It is located in the engine bay, and monitors the temperature of components within it. The responsibilities of each node can be seen below:

1. **User Interface Node**, this node is responsible for getting inputs from the user and displaying any errors within the bus using the stock dashboard indicator lights.
2. **Temperature Node**, this node is responsible for monitoring the temperatures of components in the engine bay. Based on those temperatures, it will control the battery cooling system in conjunction with the battery management system. While it is only planned to use one of these, the team has the ability to have up to 5 total in the bus. With each node being able to read up to 4 sensors, it is believed this this will be more than sufficient.
3. **Battery Cooling System Node**, this node is responsible for controlling the battery cooling system. It uses the design of the "relay node" that was described in the previous design review. In the interest of simplicity and ease of development, the control system used is just basic bang-bang control.
4. **Cabin Air Heater Node**, this node is responsible for controlling the cabin air heater. As with the battery cooling system node, it uses the design of the same "relay node".

In addition to the components need for their specific functionalities, each node has the following common components:

1. 1 12 Vdc to 5 Vdc converter. The decision was made to transmit 12 V power and convert it to 5 V on each board as that allows for more efficient transmission of power and remains unchanged. However, following technical feedback from the previous design review, the converters wattage has been reduced as needed. This is to ensure that the minimum load requirements of the converters are always met by each node. This has been verified in that when the nodes are given full 12 V power without any devices attached they have appropriate voltages and function as expected.

2. 2 2-pin terminal blocks. Each node has a 2-pin terminal block that is used to supply them with the 12 V power they need to function. The other 2-pin terminal block is used for communication. As previously stated, it was intended for each node to communicate over CANBus. This block will now be used to transmit and receive the UART signals from each node.

3. 1 PIC18F26K83 MCU. This MCU was chosen as it is available at a low cost in a footprint that is easy to work with (SSOP), and there is a large amount of experience with PIC18 processors among the team. The MCU has proven to have every peripheral that is needed, including multiple UART modules.

4. 1 PicKit3/4 debug header. The MCU needs to be programmed, and the easiest way to do that with PIC18 devices is via a 6 pin debug header. Team members already posses multiple PicKit3 debuggers, so it makes sense to use them in this project.

5. 4 M3 sized mounting holes. The PCBs need to be mounted to some part of the bus. 4 mounting holes was chosen as the PCBs is rectangular and will allow for each corner to be mounted. Additionally, the size of the hole was chosen as it is the same size that is used on the variable speed motor driver that is part of the relay nodes. Earlier this semester, the question of what size should the mounting hardware be for the electronics was given to the fabrication team. The answer given was whatever would be the most consistent, the choice of M3 hardware has fulfilled that.

6. 1 Green LED indicator. This is used to give a visual indicator of whether power is being delivered to the node and is a first check for any troubleshooting.

7. Test points. All nodes have spots to test 5V power, GND, and data lines. Additional test points have been added to appropriate signals.

8. 1 Pushbutton used to reset the MCUs when needed. This has mainly been used when developing the code for them. When each node is installed in the bus, it is planned to remove these button so as to not cause any unintended resets.

Additionally, the schematics were designed to have as many common parts as possible to help keep the cost low and improve portability between designs. What follows is a detailed explanation of new communication strategy, followed by explanations of the nodes themselves. Unless otherwise stated, the designs of the PCBs were done to minimize any interruption to the ground plane. Additionally, liberal use of silkscreen identifiers was done to ensure that it is clear what connections go where.

# 3 Communication Specification

As previously stated, rather than a CANBus network, the nodes communicate using basic serial communication.

## 3.1 Physical Layer Description

The physical design of the communication has changed significantly due to the change in communication protocols. The largest part of this change is that rather than using the multi-master serial bus that CAN uses, the new communication protocol uses an explicit master-slave relation between the nodes. Specifically, the UI node is the master for the heating node, and the temperature node is the master of the battery cooling node.

The nodes themselves are connected using a standard shielded cable assembly. That assembly has 2 pairs of twisted pair wires, that combined with the shielding within the cable itself should reduce the effects of any EMI.

The specific serial communication used is fairly standard: 8 data bits, 1 start bit, 1 stop bit, but with an added bit for even parity. The parity bit is used as part of a new error checking scheme that is done in software.

## 3.2 Software Layer Description

One of the main disadvantages of serial communication vs. CANBus is that serial communication has no built in error checking capabilities. This disadvantage has been rectified in the software layer of the communication system.

A valid message for this communication system is as follows: a character indicating which node the message is intended for ('H' for the heating node, 'T' for the temperature node, 'C' for the cooling node), a character indicating what peripheral is being controlled by the message ('f' for a fan, 'p' for a pump, 'h' for a heater), a character indicating what state the peripheral should be in ('0' for off, '1' for on, additional characters for varying levels of on), a newline character as the message terminator (ASCII 0x0A). An example of a valid message is "Cf1\n". That message would instruct the cooling node to fully turn on the radiator fan.

Whenever a slave device receives a message it will send back a single character to the master device. If the message was valid and was successfully executed, an acknowledge character will be sent (ASCII 0x06). If it was not valid or executed successfully, a bell character will be sent (ASCII 0x07). These two characters were chosen as they will never be part of an actual message and are built into the ASCII standard. Additionally, the UART modules on the MCU have a flag that is set whenever a parity error occurs. If that flag is set, the bell character will be sent to indicate that the message was not properly received. In the event that a master device receives a bell character, the original message will be resent. This will occur up to 5 times, if it is not successful at that point then an error will be displayed on the dashboard.

It is believed that this communication strategy will allow for robust transmission of data within the embedded system. Although no data should actually be transmitted, just commands as to what each node should be doing. Because each node will only be wired to another, no wiring diagram of the overall system has been included. In the event that multiple temperature nodes are added to the system, each one will be able to control the cooling system. This strategy makes heavy use of software for error checking, and it is believed that it will be an appropriate substitute for the CANBus network.

# 4 User Interface Node

## 4.1 Schematic Design

As a reminder, the user interface node is responsible for handling all inputs from the user and displaying any errors on the dashboard display. The schematic for this node is the file **ui_node_rev_idr.pdf**, the bill of materials is **ui_node_bom.pdf**, and the PCB design (without the copper fills for clarity) is **ui_pcb_no_fill.pdf**. The figure below shows a block diagram of the node.

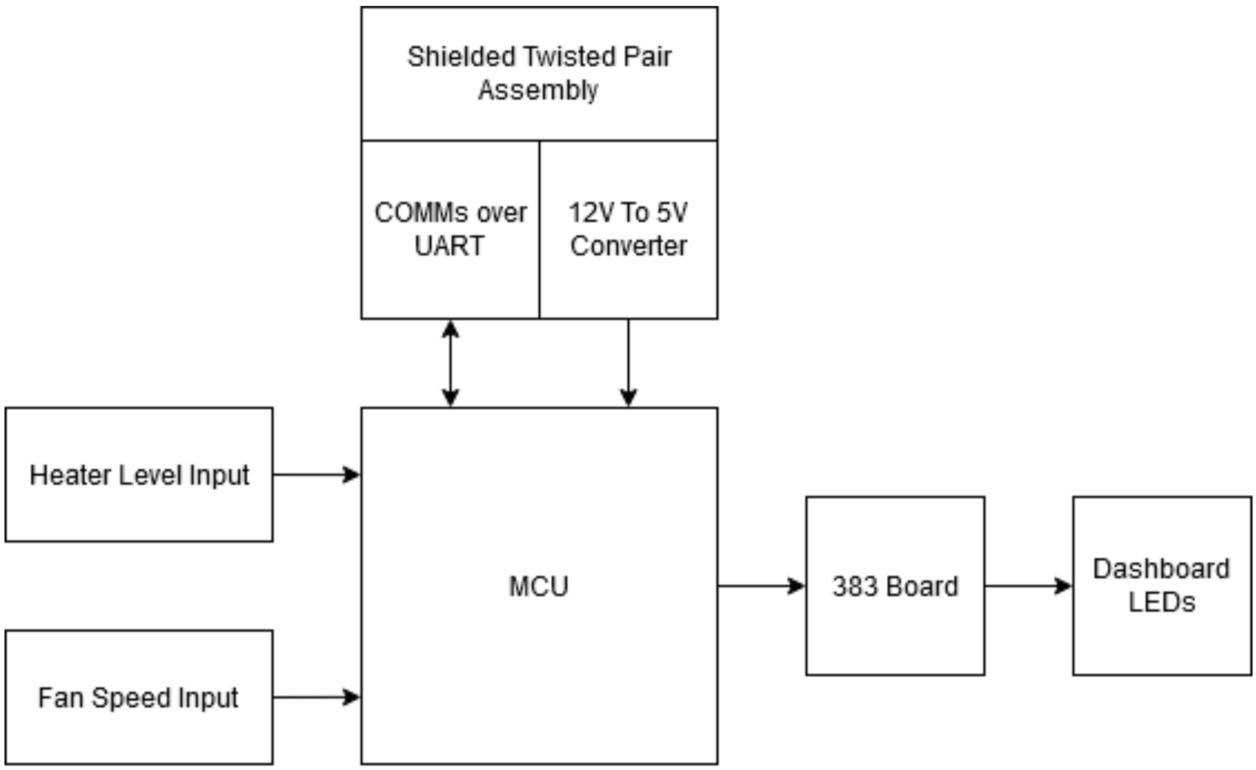



Figure 1: UI node block diagram

The node will have two inputs to handle, these are the heater temperature and heater fan speed. The heater temperature is controlled by a 4 position rotary switch. The possible positions of it are off, 1, 2, and 3 with 3 being full heat. This comes from the 3 taps that the heating element has that allow for only 3 possible temperatures. This switch state is read by just some basic pull down resistors, with pull down resistors being used to have the switch logic consistent with the designers preferences. The resistors used have a 10k$\Omega$ resistance, with a 5V supply this means each resistor will be dissipating only a few mW of power which is reasonable for this application. The fan speed is controlled by a rotary potentiometer with a linear resistance. The wiper of the potentiometer is just given to a channel of the MCU's built in ADC. It is a 12 bit ADC which gives far more resolution than is needed. That converted ADC value is then used to set the heater fan to one of 5 speeds. While this could be controlled by a 5 position switch with little trouble, a potentiometer was decided on as it allows for the other switch input on the board to be used for other functionalities as needed.

As previously stated, an additional device is used to control the dashboard display indicators. Currently it is planned to use an EENG383 development board for this. If that is not able to provide enough current, than a commercially available serially controlled LED driver will be used.

## 4.2 Parts Selection

The main part that had to be chosen for this node specifically is the 12 V to 5 V converter, U1 in the schematic. The converter chosen for this node is a Recom Power R-78E5.0-1.0.0, Digikey part number 945-2201-ND. This converter is capable of supplying up to 5 W at 5 V with 90% efficiency. The MCU and passive devices are expected to consume far less than 5 W total, giving plenty of room for higher power LEDs for the dashboard indicators.

## 4.3 Software

The software for this node is fairly basic. The main body of the standard infinite loop does the following functions:

- Check the UART receive buffer to see if any error messages have come in. If so, the appropriate indicator light is set and the loop continues.
- Check to see if the heater heat level switch has changed states. If so, the new state is recorded.
- Check to see if the heater level fan switch has changed states. If so, the new state is recorded.
- If the heater fan is above the minimum fan speed threshold (25% currently, subject to change), send the heater state to the node. If that transmission is not successful, try again 4 more times. If those are all not successful, turn on the respective indicator light.
- Start a timer that produces an interrupt in roughly 500 ms, and enter a low power mode. This is done to minimize power consumption. An update rate of 2 Hz was chosen as it allows for the system to be responsive to the user but avoids having the same things be done hundreds if not thousands of times a second.

# 5 Temperature Nodes

## 5.1 Schematic Design

As a reminder, the temperature node is responsible for monitoring 4 temperature sensors and controlling the cooling node based on those temperatures. The schematic for this node is the file **temp_node_rev_idr.pdf**, the bill of materials is **temp_node_bom.pdf**, and the PCB design (without the copper fills for clarity) is **temp_pcb_no_fill.pdf**. The figure below shows a block diagram of the node.

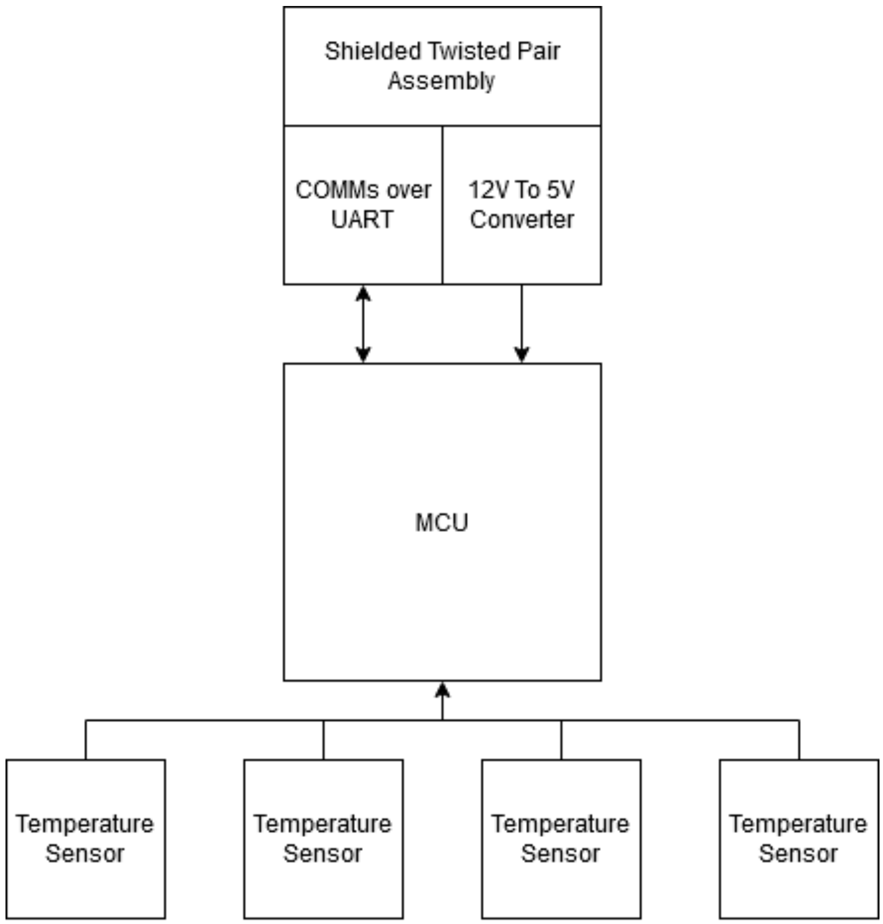



Figure 2: Temperature node block diagram

The node design has only the 4 inputs for the 4 temperature sensors. The sensors chosen are simple analog sensors, they will be detailed in a later section. The sensors just need power and ground, and output a simple analog voltage. That analog voltage is sent to the ADC built into the MCU, and have a very basic transfer function of 10 mV/°C. The sensors connect to the MCU via 4 3 pin terminal blocks, with the analog voltage just being routed to a channel on the MCU's built in ADC. Additionally, the MCU has a temperature sensor built in that can be used to monitor the boards temperature. While it may not be the most useful sensor for the cooling system, it does give one more possible indicator of a problem within the bus. The node has one output which is communication to the cooling node.

## 5.2 Parts Selection

This node needed 2 parts to be chosen, the temperature sensor and the 5 V converter.

The sensor chosen is an Analog Devices TMP36, Digikey part number TMP36GT9Z-ND. It was chosen due to its low cost, its ease of interfacing, and its footprint. It is a through hole sensor, this allows for it to be attached to a (short) wire assembly and attached to parts away from the actual PCB. The wire assemblies used have a 0.1 $\mu$F capacitor soldered between the power and ground leads at the sensor itself. That capacitor combined with another one between the power and ground connections on the board itself should ensure that the sensors have a stable power supply.

The converter chosen for this node is a Recom Power ROE-1205S, Digikey part number ROE-1205S-ND. This converter is capable of supplying up to 1 W at 5 V with 91% efficiency. This node design is expected to consume very low amounts of current. Each temperature sensor is expected to consume up to 25 $\mu$A at 5 V (from its datasheet), giving a total wattage for the sensors of 0.5 mW. The MCU is expected to consume a maximum of 13 mA at 5 V, giving it a wattage of 65 mW. A 1 W supply is more than overkill for this node, but one was chosen as it has an easy to use footprint and is relatively low cost.

## 5.3 Software

The software for the temperature node is very basic. Within the standard infinite loop, the following is done:

- Switch the ADC channel to the appropriate sensor and store the converted results in a buffer with 4 elements. Do this 4 times, once for each sensor.
- Take the average of each one of those buffers and store it. This effectively creates a moving average filter of 4 values and will help reduce any noise that the sensors pick up.
- If a single one of those average temperatures is above a predefined threshold, send a message to the cooling node. Note, the cooling node is also controlled by the battery management system.
- Start a timer that produces an interrupt in roughly 1 s, and enter a low power mode. This is done to minimize power consumption, and creates a roughly 1 Hz sample rate of each sensor. This sample rate was chosen as the temperature of a physical device is not expected to change that fast compared to how fast the node can react to that change.

It is not expected that the communication system will fail more than the 5 allotted times. This is due to the fact that the temperature and cooling system nodes will be very close to each other and will be in a noise resistant enclosure. However, if this does happen, it would mean that the motor controller is heating up. If that is occurring, it can be safely assumed that the batteries are heating up as well, and the battery management system will turn on the cooling system in that way. That will have the added effect of cooling the motor controller. This node in essence just adds a layer of redundancy to the cooling system.

# 6 Relay Node

## 6.1 Schematic Design

As a reminder, the relay node is used for both the cabin air heater and the battery cooling system. Each node is capable of doing the following:

1. Control up to 4 relays with coil currents of up to 500 mA at 12 V each.
2. Control up to 2 constant speed constant direction 12 Vdc motors at up to 10 A.
3. Control up to 2 variable speed variable direction 12 Vdc motors at up to 12 A.

A block diagram of the node can be seen below.

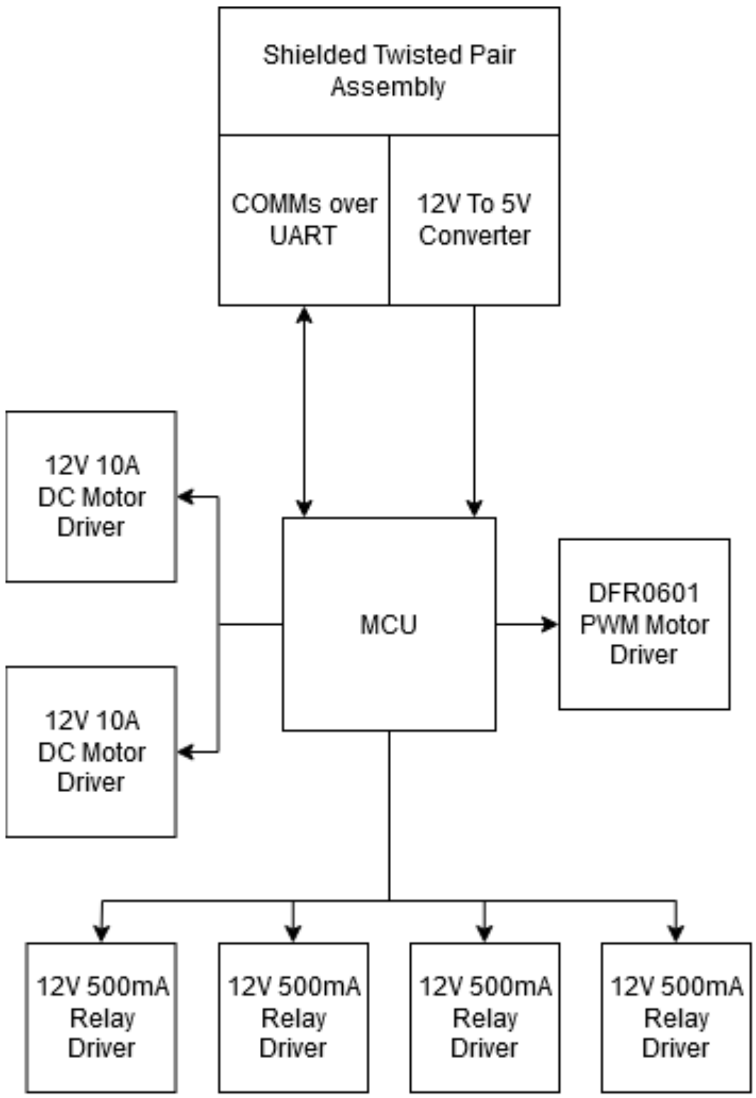



Figure 3: *Relay node block diagram*

The node has 8 outputs as stated above. As with the other circuits, these outputs will be connected with a number of terminal blocks. First, the relay control circuits will be examined.

The circuit used to control the relays can be seen in figure 4.

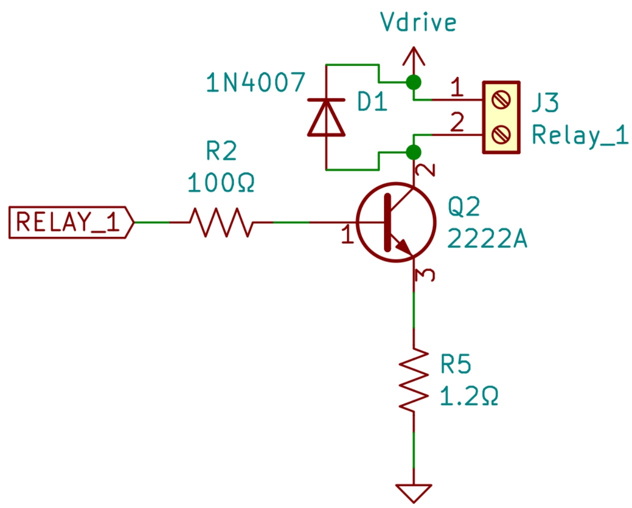



Figure 4: *Relay driving circuit*

It features a 2222A NPN type transistor, a 1N4007 diode, and the necessary passives to bias the transistor correctly. The specifics of why each non-passive part was chosen will be explained in a later section. This circuit is intended to (de)energize a relay's coil, controlled by an MCU. The diode is included as a flyback suppression technique to ensure that any voltage spikes from the coil's inducatance are handled safely. In the schematic above, the network **Vdrive** is connected to a high current 12 V supply. A 12V supply was chosen as the relays this is intended to drive use a 12 V powered coil. One item of note is the 1.2Ω resistor (R5 in the schematic). This resistor is expected to have over 500mA flowing through it, meaning it will dissipate up to 1/3W. As a result, the specific resistor chosen for this is rated up to 1W to help ensure that the power is dissipated safely and without drastically reducing the life of the component. The node design has 6 of these circuits on it, 4 for driving the externally connected relays and 2 for controlling the constant speed constant direction 12V DC motors.

The constant speed constant direction motors are controlled by just a simple relay circuit that can be seen in 5 below.

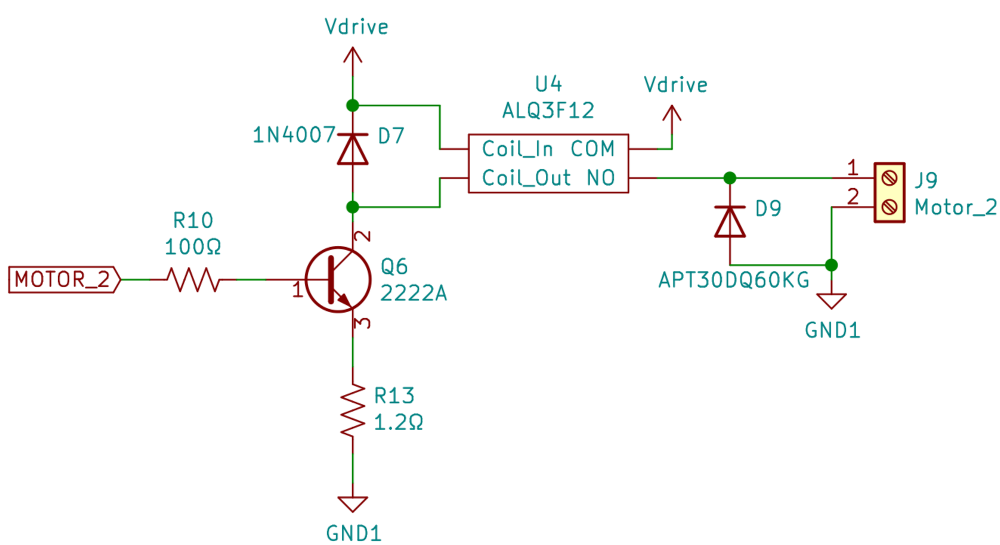



Figure 5: *Constant speed motor driving circuit*

The circuit that controls the relay (as previously stated) is the same circuit that drives the externally connected relays. The actual relay chosen for this circuit is a Panasonic ALQF12. It is capable of switching up to 10 A at voltages far higher than 12 V, and has an easy to use footprint. As with the relay driving circuit, this also features a flyback suppression diode, D9 in the figure. The specific diode used is a high current and high voltage capable one, detailed in a later section.

Lastly is the variable speed motor drive. The option of the team designing their own circuit was explored, and while possible the decision was made to go with an off the shelf solution due to time and safety concerns. The solution that was chosen is a DFRobot 0601 dual channel motor driver, Digikey part number 1738-DFR0601-ND. This driver is capable of supplying up to 12 A continuously on a voltage range that includes 12 V, and up to 80 A for short durations. It communicates with the MCU via 2 GPIO pins to indicate direction, and 1 PWM signal to indicate speed. The PWM signal has a wide range of acceptable frequencies that the MCU has no trouble generating. The main thing is that it is a tried and tested design that takes any concerns about safety and efficiency out of the teams hands. From the drivers documentation, connecting the input pins directly to a microcontroller is fine so that is what is done.

As previously stated, the cooling system node is controlled by both the temperature node as well as the battery management system. The control from the battery management system comes from one of its configurable output signals. Those signals are able to output a 12 Vdc signal and supply up to 500 mA. That 12 Vdc is fed to a voltage divider that reduces it to 5 V. That 5 V signal is then read by the cooling node to determine whether or not the batteries are warming up and need to be cooled down. Additionally, the pin that reads that voltage is setup to generate an interrupt when it changes.

## 6.2 Parts Selection

This node needed a number of parts to be chosen: the 2222A transistor, the 1N4007 diode, the motor flyback suppression diode, and the 5V converter.

The specific 2222A transistor chosen is a Nexperia USA PMBT2222A,215, Digikey part number 1727-2956-1-ND. A 2222A transistor was chosen due to its use in similar designs. This specific transistor was chosen due to the maximum collector current (600 mA), its footprint, and its price.

The specific 1N4007 diode chosen is a SMC Diode Solutions 1N4007FLTR, Digikey part number 1655-1N4007FLCT-ND. Similar to the 2222A transistor, this diode was chosen due to its use in similar designs. This diode was chosen due to its average rectified current (1 A), and its maximum reverse voltage (1000 V). It is expected to suppress at most 500 mA and at a far lower voltage, so it will be able to handle its task. Additionally, it is in an easy to use footprint and is at a reasonable price.

The diode used to suppress any flyback voltage from the DC motors was chosen to be a Microchip APT15DQ60KG, Digikey part number APT15DQ60KG-ND. It was chosen due to its average rectified current (10 A), and its maximum reverse voltage (600 V). It is expected to suppress at most 10A of current, and its maximum reverse voltage should be plenty for this application.

Lastly is the 5 V converter. Currently, the node design has all high current 12 V power (power for relays, motors) come to the board via a separate 2 pin jumper. As a result, the 5 V converter only needs to supply power to the MCU and the low power passives on the board. This means it has essentially the same power draw as the temperature node, so the same converter can be used. A maximum power of 1 W for the lower power circuitry for this node should be more than enough.

## 6.3 PCB Design

The PCB designed for this node is somewhat more complex than the ones designed for the other nodes. This complexity comes from splitting the top and bottom copper pours into 2 sections each. On the left side of the PCB, the copper pours are for the higher current 12 V supply. The right side of the PCB has copper pours for the 5 V supply. The two pours are separated by at least 5 mm. This design was done as there were a significant number of devices that needed 5 V power, and a significant number of devices needed 12 V power. This solution seemed to be the simplest, and had the added benefit of adding a bit of isolation between the lower power 5 V devices and the higher power 12 V devices.

The PCB was designed in KiCAD. As part of KiCADs design flow, the footprints for the devices are chosen after the schematic has been made. While this allows for more rapid prototyping than EAGLE (in the designers opinion that is), it allows for the possibility of choosing the wrong footprint for a given device. That occurred in this case, where the pins assigned to the collector and emitter of the BJTs that drive the relays were swapped. That is, the physical collector on the BJTs were connected to what was assigned to the emitter, and vice versa. This was solved by taking the BJTs, rotating them 180°, and soldering a short jumper from the base terminal to the pad that was assigned to the base. That was done for all BJTs, and when they were verified to work the assembly was coated in a layer of epoxy to make it permanent.

### 6.4 Software

The software for each node is very simple and relies on interrupts generated by a UART receive or an interrupt on the change of a pin state. The code overview is as follows:

- Check the UART receive buffer for the new message and if applicable check what state the interrupt on change pin is in.
- Process the new message and control the relay outputs as needed. If applicable, process the new state of the interrupt on change pin.
- Enter sleep mode, where the MCU is woken up on an interrupt from the UART receive or from the interrupt on change pin.

By using the devices sleep mode, power consumption is kept low and the device becomes a basic finite state machine with well defined transitions.

One item of note relates to the variable speed motor driver. For the fans used in this project, the motors have rather high inrush currents. If the motor driver attempts to set the motor from 0% to 100% power, its current limiting circuitry kicks in and ceases power delivery. Physically what this causes is the fan to try to run but is immediately stopped within a few milliseconds. So, this is rectified by the following method:

- The current speed of the fan is stored
- If the new requested speed is above that, the difference of those two speeds is computed.
- The duty cycle is then increased by one tenth of that difference every 100 ms until the full new speed has been reached. That timing is done by a timer that has a 100 ms period.
- If the new requested speed is below the current speed, then that appropriate duty cycle is set. Stepping down the speed is no issue, and the motor driver has the appropriate flyback suppression circuitry it needs.

The above method allows for the motor controller to set any speed that the motors need and it does so safely and effectively.

# 7 Connection Node

In the previous design review, a node that was used as a common connection point for the CANBus network was specified. Due to the changes in the communication system this board is not needed. Thankfully, little time was spent on it due to its simplicity so nothing of value was lost.

# 8 Next Steps

All that is left for the embedded systems is the code to be fully finalized and tested. The code for each node is 90% complete, with only the fine details left. The team is confident that this will be done with enough time for them to be installed and their functionality verified in the bus.

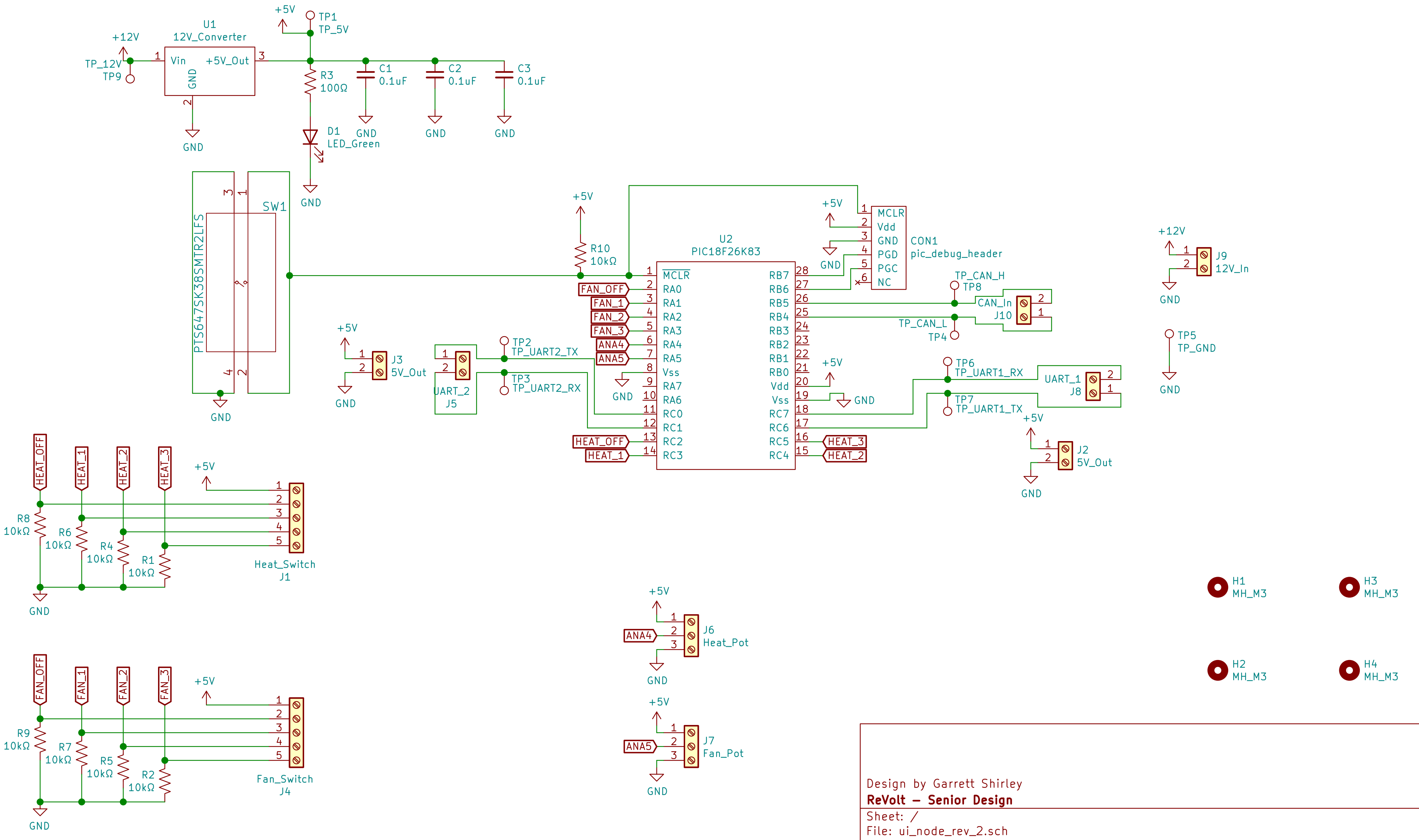
# 9 Lessons Learned

This part of the ReVolt project has been full of lessons learned. The main ones are:

- Keep designs flexible when possible so that changes to the project can be dealt with efficiently
- Make as few assumptions as possible, work based off of things that are known for certain
- Double check the footprints assigned to parts as necessary, in this case it was an easy fix for the BJTs but it could have been much harder if say, the base and emitter were swapped.

# Appendix E: User Interface Node, PCB, and Bill of Materials

| Description | MFR | MFR P/N | Digikey P/N | Footprint | Unit Cost | # UI | # Temp | # Relay | # Conn | # Extra | Total Quantity | Total Cost |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MCU | Microchip | PIC18F26K83-I/S | PIC18F26K83-I/S | 28 pin SSOP | 2.08 | 1 | 5 | 2 | 0 | 3 | 11 | 22.88 |
| Temperature Ser | Analog Devices | TMP36 | TMP36GT9Z-ND | TO-92-3 | 1.48 | 0 | 20 | 0 | 0 | 3 | 23 | 34.04 |
| green led | Wurth Elektronik | 150120GS75000 | 732-4990-1-ND | 1206 SMD | 0.21 | 1 | 5 | 2 | 0 | 2 | 10 | 2.1 |
| diode 1n4007 | Comchip Techno | 1N4007-G | 641-1312-1-ND | Through Hole | 0.1 | 0 | 0 | 12 | 0 | 2 | 14 | 1.4 |
| diode high currer | Microchip | APT15DQ60KG | APT15DQ60KG- | Through Hole | 0.54 | 0 | 0 | 8 | 0 | 1 | 9 | 4.86 |
| 2222A | Nexperia | PMBT2222A,215 | 1727-2956-1-ND | TO-236AB SMD | 0.12 | 0 | 0 | 12 | 0 | 4 | 16 | 1.92 |
| | | | | | | | | | | | 0 | |
| 5V Converter | Recom Power | R-78E5.0-1.0 | 945-2201-ND | 3 SIP Module | 3.26 | 1 | 0 | 0 | 0 | 1 | 2 | 6.52 |
| 5V Converter | Recom Power | ROE-1205S | ROE-1205S-ND | 4 SIP Module | 2.94 | 0 | 5 | 2 | 0 | 1 | 8 | 23.52 |
| | | | | | | | | | | | 0 | |
| 1.2Ω res | Stackpole | RMCF2512JT1R | RMCF2512JT1R | 2512 SMD | 0.28 | 0 | 0 | 12 | 0 | 4 | 16 | 4.48 |
| 100Ω res | Stackpole | RMCF1206JT10 | RMCF1206JT10 | 1206 SMD | 0.1 | 1 | 5 | 14 | 0 | 2 | 22 | 2.2 |
| 120Ω res | TE Connectivity I | CRGCQ1206F12 | A129799CT-ND | 1206 SMD | 0.1 | 0 | 0 | 0 | 2 | 2 | 4 | 0.4 |
| 10kΩ | Stackpole | RMCF1206FT10 | RMCF1206FT10 | 1206 SMD | 0.1 | 9 | 5 | 2 | 0 | 4 | 20 | 2 |
| 0.1uF cap | Samsung | CL31B104KBP5I | 1276-7034-1-ND | 1206 SMD | 0.26 | 3 | 25 | 6 | 0 | 4 | 38 | 9.88 |
| | | | | | | | | | | | 0 | |
| debug header | Amphenol | 10129379-90600 | 10129379-90600 | Through Hole | 0.19 | 1 | 5 | 2 | 0 | 2 | 10 | 1.9 |
| testpoint | Keystone Electro | 5272 | 36-5272-ND | Through Hole | 0.4 | 9 | 25 | 14 | 4 | 8 | 60 | 24 |
| 2 pin terminal | Phoenix Contact | 1935161 | 277-1667-ND | Through Hole | 0.43 | 6 | 10 | 20 | 1 | 2 | 39 | 16.77 |
| 3 pin terminal | Phoenix Contact | 1935174 | 277-1578-ND | Through Hole | 0.6 | 2 | 20 | 0 | 0 | 2 | 24 | 14.4 |
| 4 pin terminal | Phoenix Contact | 1935187 | 277-1579-ND | Through Hole | 0.84 | 0 | 0 | 0 | 10 | 2 | 12 | 10.08 |
| 5 pin terminal | Phoenix Contact | 1935190 | 277-1580-ND | Through Hole | 1.01 | 2 | 0 | 4 | 0 | 2 | 8 | 8.08 |
| | | | | | | | | | | | 0 | |
| Motor relay | Panasonic | ALQ3F12 | 255-5407-ND | Through Hole | 1.01 | 0 | 0 | 4 | 0 | 2 | 6 | 6.06 |
| Motor Driver | DFRobot | DFR0601 | 1738-DFR0601-N | Discrete | 29.67 | 0 | 0 | 2 | 0 | 0 | 2 | 59.34 |
| pushbutton | C&K | PTS 647 SK38 S | PTS647SK38SM | SMD | 0.07 | 1 | 0 | 2 | 0 | 2 | 5 | 0.35 |
| | | | | | | | | | | | | |
| **# UI Nodes** | 1 | | | | | | | | | | **Total Cost** | 257.18 |
| **# Temp Nodes** | 5 | | | | | | | | | | | |
| **# Relay Nodes** | 2 | | | | | | | | | | | |
| **# Conn Nodes** | 1 | | | | | | | | | | | |




Design by Garrett Shirley

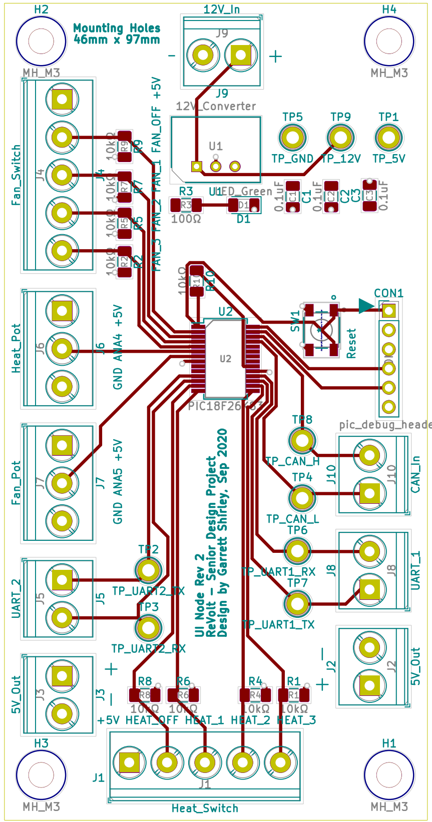
**ReVolt – Senior Design**

Sheet: /

File: ui_node_rev_2.sch

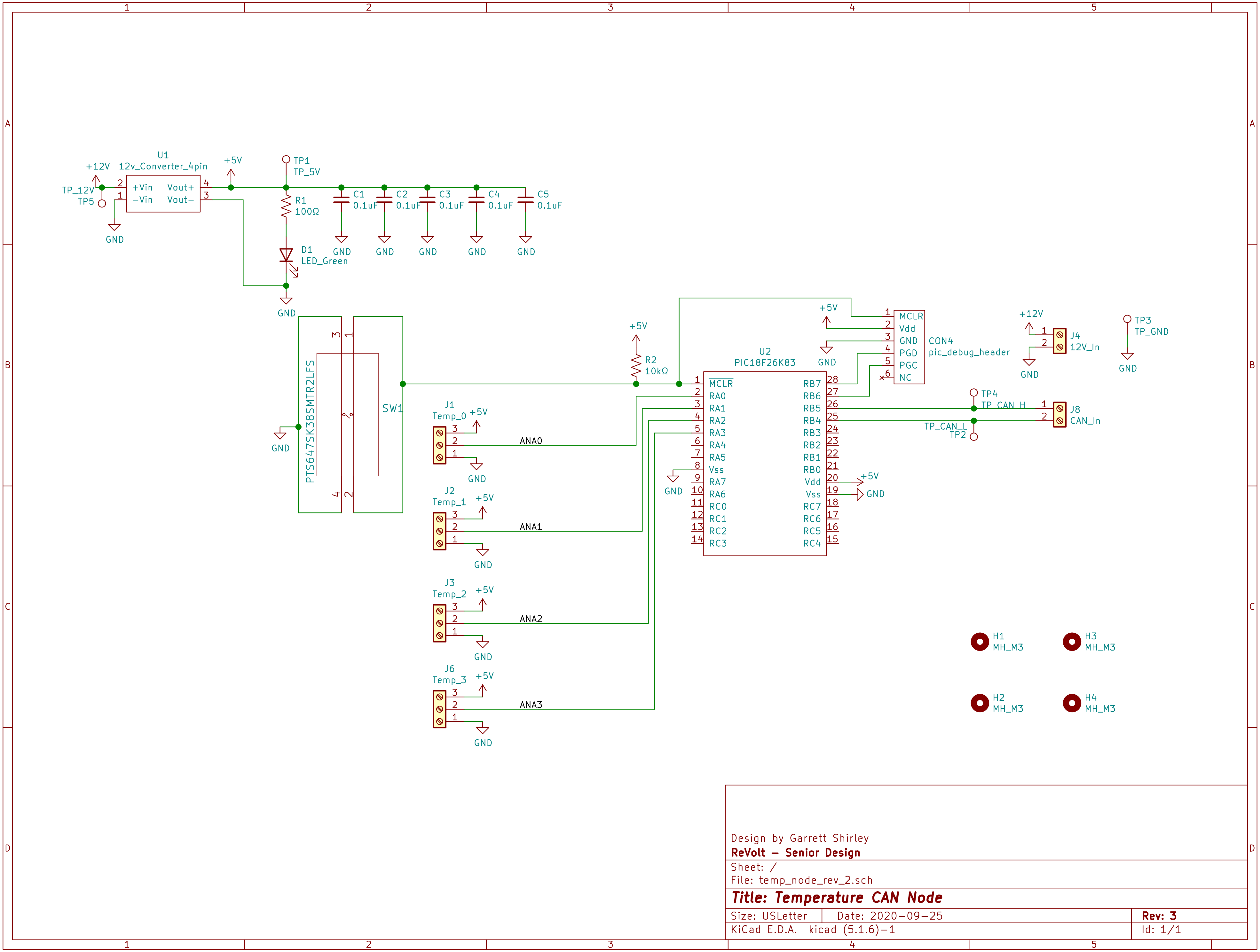
***Title: User Interface CAN Node***

| | | |
|---|---|---|
| Size: A4 | Date: 2020-09-25 | **Rev: 3** |
| KiCad E.D.A. kicad (5.1.6)-1 | | Id: 1/1 |

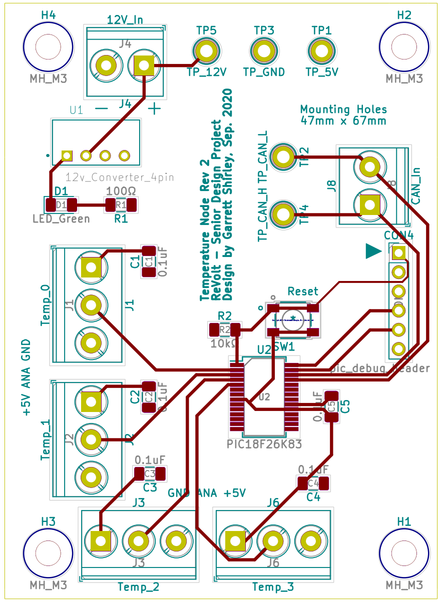

Mounting Holes
46mm x 97mm
H2
H4
H3
H1
MH_M3
12V_In
J9
12V_Converter
U1
TP5
TP9
TP1
TP_GND
TP_12V
TP_5V
R3
100Ω
LED_Green
D1
C1
C2
C3
0.1uF
Fan_Switch
J4
FAN_3 FAN_2 FAN_1 FAN_OFF +5V
10kΩ
R10
U2
PIC18F26K83
SW1
Reset
CON1
pic_debug_header
Heat_Pot
J6
GND ANA4 +5V
Fan_Pot
J7
GND ANA5 +5V
TP8
TP_CAN_H
TP4
TP_CAN_L
J10
CAN_In
TP6
TP_UART1_RX
TP7
TP_UART1_TX
J8
UART_1
UART_2
J5
TP2
TP3
TP_UART2_RX
UI Node Rev 2
ReVolt - Senior Design Project
Design by Garrett Shirley, Sep 2020
J2
5V_Out
J3
R8
R6
R4
R1
+5V HEAT_OFF HEAT_1 HEAT_2 HEAT_3
J1
Heat_Switch

# Appendix F: Temperature Node, PCB, and Bill of Materials

| Description | MFR | MFR P/N | Digikey P/N | Footprint | Unit Cost | Quantity | Total Cost |
|---|---|---|---|---|---|---|---|
| MCU | Microchip | PIC18F26K83-I/S | PIC18F26K83-I/S | 28 pin SSOP | 2.08 | 1 | 2.08 |
| 5V Converter | Recom Power | R-78E5.0-1.0 | 945-2201-ND | 3 SIP Module | 3.26 | 1 | 3.26 |
| 100Ω res | Stackpole | RMCF1206JT10( | RMCF1206JT10( | 1206 SMD | 0.1 | 1 | 0.1 |
| 10kΩ | Stackpole | RMCF1206FT10 | RMCF1206FT10 | 1206 SMD | 0.1 | 9 | 0.9 |
| 0.1uF cap | Samsung | CL31B104KBP5I | 1276-7034-1-ND | 1206 SMD | 0.26 | 3 | 0.78 |
| 3 pin terminal | Phoenix Contact | 1935174 | 277-1578-ND | Through Hole | 0.6 | 2 | 1.2 |
| 2 pin terminal | Phoenix Contact | 1935161 | 277-1667-ND | Through Hole | 0.43 | 6 | 2.58 |
| testpoint | Keystone Electro | 5002 | 36-5002-ND | Through Hole | 0.4 | 9 | 3.6 |
| debug header | Amphenol | 10129379-90600 | 10129379-90600 | Through Hole | 0.19 | 1 | 0.19 |
| green led | Wurth Elektronik | 150120GS75000 | 732-4990-1-ND | 1206 SMD | 0.21 | 1 | 0.21 |
| 5 pin terminal | Phoenix Contact | 1935190 | 277-1580-ND | Through Hole | 1.01 | 2 | 2.02 |
| pushbutton | C&K | PTS526 SMG15 | CKN12222-1-ND | SMD | 0.13 | 1 | 0.13 |
| | | | | | | | |
| | | | | | | **Total Cost:** | 17.05 |



U1
12v_Converter_4pin
+Vin
-Vin
Vout+
Vout-
+12V
TP_12V
TP5
GND
+5V
TP1
TP_5V
R1
100Ω
D1
LED_Green
C1
0.1uF
C2
0.1uF
C3
0.1uF
C4
0.1uF
C5
0.1uF
PTS647SK38SMTR2LFS
SW1
R2
10kΩ
U2
PIC18F26K83
MCLR
RA0
RA1
RA2
RA3
RA4
RA5
Vss
RA7
RA6
RC0
RC1
RC2
RC3
RB7
RB6
RB5
RB4
RB3
RB2
RB1
RB0
Vdd
Vss
RC7
RC6
RC5
RC4
CON4
pic_debug_header
MCLR
Vdd
GND
PGD
PGC
NC
J4
12V_In
TP3
TP_GND
TP4
TP_CAN_H
TP_CAN_L
TP2
J8
CAN_In
J1
Temp_0
ANA0
J2
Temp_1
ANA1
J3
Temp_2
ANA2
J6
Temp_3
ANA3
H1
MH_M3
H3
MH_M3
H2
MH_M3
H4
MH_M3
Design by Garrett Shirley
ReVolt - Senior Design
Sheet: /
File: temp_node_rev_2.sch
Title: Temperature CAN Node
Size: USLetter
Date: 2020-09-25
Rev: 3
KiCad E.D.A. kicad (5.1.6)-1
Id: 1/1

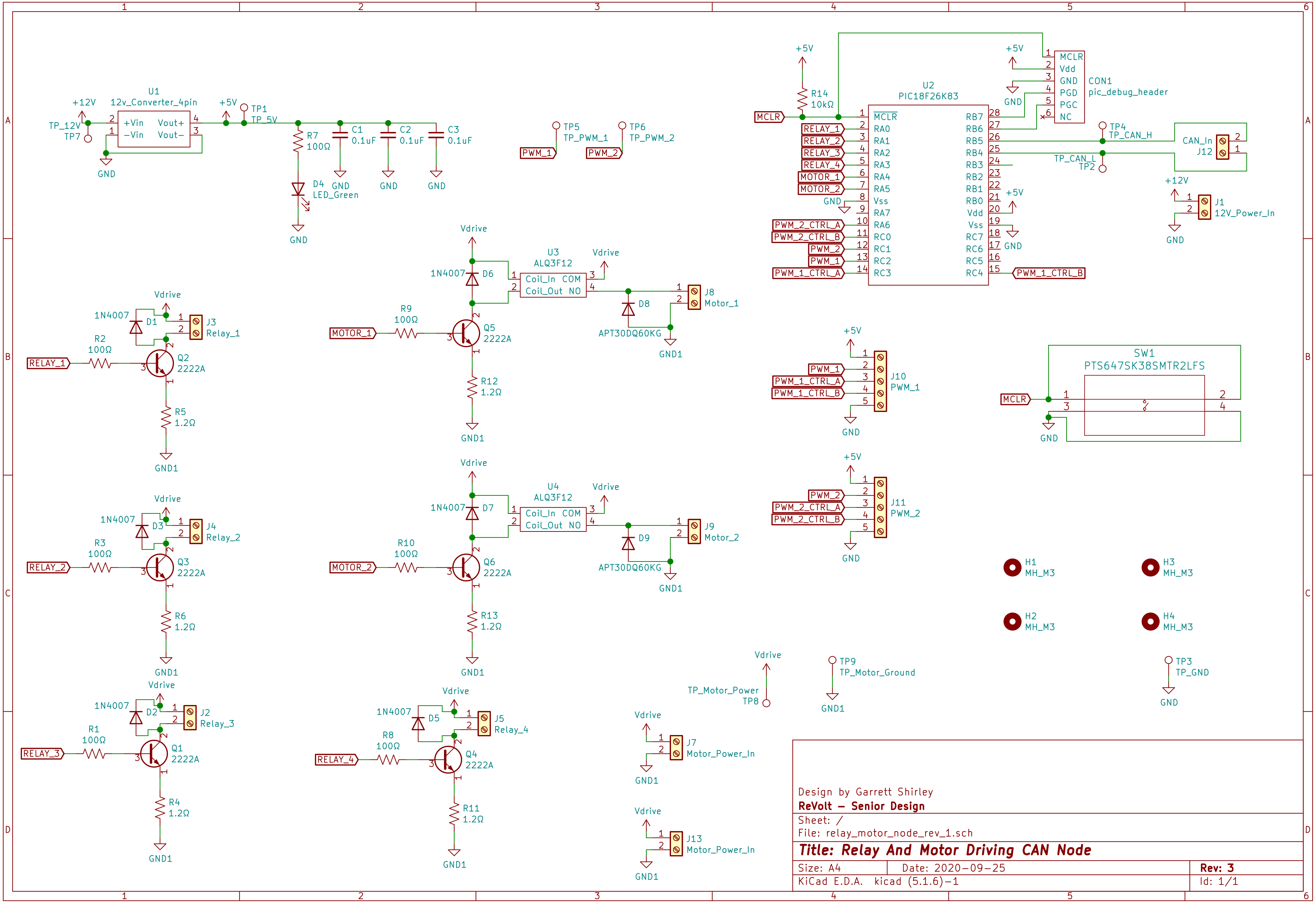


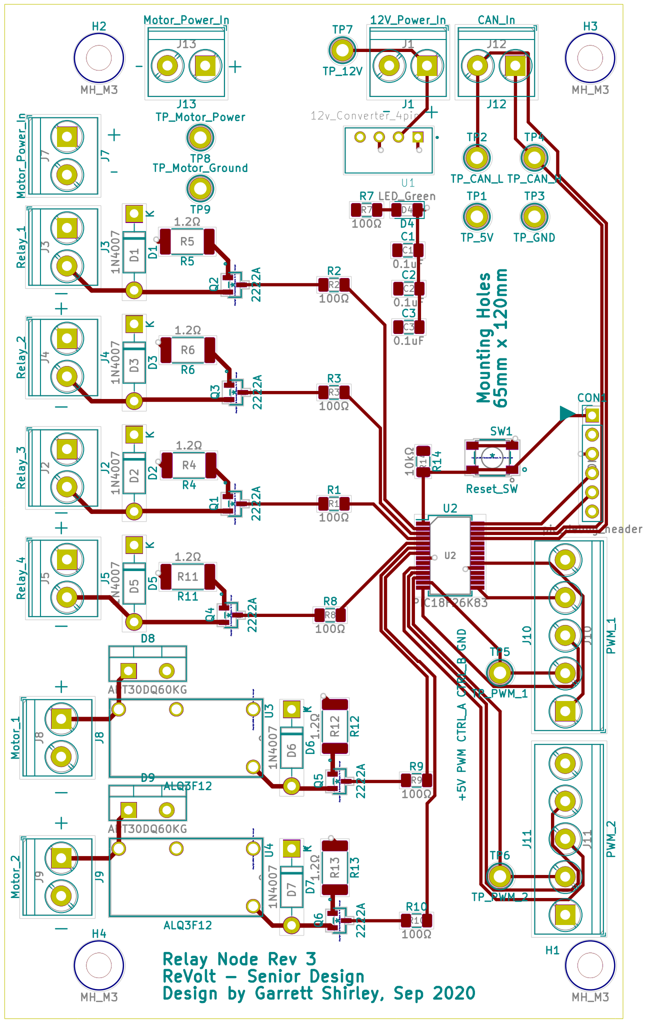
H4
12V_In
TP5
TP3
TP1
H2
MH_M3
TP_12V
TP_GND
TP_5V
MH_M3
J4
U1
Mounting Holes
47mm x 67mm
12v_Converter_4pin
D1
100Ω
LED_Green
R1
Temperature Node Rev 2
ReVolt - Senior Design Project
Design by Garrett Shirley, Sep. 2020
TP_CAN_H TP_CAN_L
J8
CAN_In
CON4
C1
0.1uF
Temp_0
J1
Reset
R2
10kΩ
U2
SW1
pic_debug_header
+5V ANA GND
C2
C5
Temp_1
J2
PIC18F26K83
0.1uF
C3
GND ANA +5V
C4
J3
J6
H3
H1
MH_M3
MH_M3
Temp_2
Temp_3

# Appendix G: Relay Node, PCB, and Bill of Materials

| Description | MFR | MFR P/N | Digikey P/N | Footprint | Unit Cost | Quantity | Total Cost | Total Quantity |
|---|---|---|---|---|---|---|---|---|
| MCU | Microchip | PIC18F26K83-I/S | PIC18F26K83-I/S | 28 pin SSOP | 2.08 | 1 | 2.08 | 2 |
| 5V Converter | Recom Power | ROE-1205S | ROE-1205S-ND | 3 SIP Module | 2.94 | 1 | 2.94 | 2 |
| 1.2Ω res | Stackpole | RMCF2512JT1R | RMCF2512JT1R | 2512 SMD | 0.28 | 6 | 1.68 | 12 |
| 100Ω res | Stackpole | RMCF1206JT10 | RMCF1206JT10 | 1206 SMD | 0.1 | 7 | 0.7 | 14 |
| 10kΩ res | Stackpole | RMCF1206FT10 | RMCF1206FT10 | 1206 SMD | 0.1 | 1 | 0.1 | 2 |
| 0.1uF cap | Samsung | CL31B104KBP5 | 1276-7034-1-ND | 1206 SMD | 0.26 | 3 | 0.78 | 6 |
| testpoint | Keystone Electro | 5002 | 36-5002-ND | Through Hole | 0.4 | 7 | 2.8 | 14 |
| debug header | Amphenol | 10129379-90600 | 10129379-90600 | Through Hole | 0.19 | 1 | 0.19 | 2 |
| green led | Wurth Elektronik | 150120GS75000 | 732-4990-1-ND | 1206 SMD | 0.21 | 1 | 0.21 | 2 |
| 5 pin terminal | Phoenix Contact | 1935190 | 277-1580-ND | Through Hole | 1.01 | 2 | 2.02 | 4 |
| 2 pin terminal | Phoenix Contact | 1935161 | 277-1667-ND | Through Hole | 0.43 | 10 | 4.3 | 20 |
| diode 1n4007 | SMC Diodes | 1N4007FLTR | 1655-1N4007FL | SOD123FL SMD | 0.1 | 6 | 0.6 | 12 |
| diode high curren | Microchip | APT15DQ60KG | APT15DQ60KG- | Through Hole | 0.54 | 2 | 1.08 | 4 |
| 2222A | Nexperia | PMBT2222A,215 | 1727-2956-1-ND | TO-236AB SMD | 0.12 | 6 | 0.72 | 12 |
| Motor relay | Panasonic | ALQ3F12 | 255-5407-ND | Through Hole | 1.01 | 2 | 2.02 | 4 |
| Motor Driver | DFRobot | DFR0601 | 1738-DFR0601-N | Discrete | 29.67 | 1 | 29.67 | 2 |
| push button | C&K | PTS526 SMG15 | CKN12222-1-ND | SMD | 0.13 | 1 | 0.13 | 2 |
| | | | | | | | | |
| | | | | | | **Total Cost Per Node:** | 52.02 | |
| | | | | | | **Number of Nodes** | 2 | |
| | | | | | | **Total Cost Per Node:** | 104.04 | |

| Description | MFR | MFR P/N | Digikey P/N | Footprint | Unit Cost | Quantity | Total Cost | Total Quantity |
|---|---|---|---|---|---|---|---|---|
| MCU | Microchip | PIC18F26K83-I/S | PIC18F26K83-I/S | 28 pin SSOP | 2.08 | 1 | 2.08 | 5 |
| Temperature Sensor | Analog Devices | TMP36 | TMP36GT9Z-ND | TO-92-3 | 1.48 | 4 | 5.92 | 20 |
| 5V Converter | Recom Power | ROE-1205S | ROE-1205S-ND | 3 SIP Module | 2.94 | 1 | 2.94 | 5 |
| 100Ω res | Stackpole | RMCF1206JT10 | RMCF1206JT10 | 1206 SMD | 0.1 | 1 | 0.1 | 5 |
| 10kΩ | Stackpole | RMCF1206FT10 | RMCF1206FT10 | 1206 SMD | 0.1 | 1 | 0.1 | 5 |
| 0.1uF cap | Samsung | CL31B104KBP5I | 1276-7034-1-ND | 1206 SMD | 0.26 | 5 | 1.3 | 25 |
| 3 pin terminal | Phoenix Contact | 1935174 | 277-1578-ND | Through Hole | 0.6 | 4 | 2.4 | 20 |
| 2 pin terminal | Phoenix Contact | 1935161 | 277-1667-ND | Through Hole | 0.43 | 2 | 0.86 | 10 |
| testpoint | Keystone Electro | 5002 | 36-5002-ND | Through Hole | 0.4 | 5 | 2 | 25 |
| debug header | Amphenol | 10129379-90600 | 10129379-90600 | Through Hole | 0.19 | 1 | 0.19 | 5 |
| green led | Wurth Elektronik | 150120GS75000 | 732-4990-1-ND | 1206 SMD | 0.21 | 1 | 0.21 | 5 |
| pushbutton | C&K | PTS526 SMG15 | CKN12222-1-ND | SMD | 0.13 | 1 | 0.13 | 5 |
| | | | | | | | | |
| | | | | | | **Total Cost Per Node:** | 18.23 | |
| | | | | | | **Number of Nodes:** | 5 | |
| | | | | | | **Total Cost:** | 91.15 | |


U1
12v_Converter_4pin
+Vin Vout+
-Vin Vout-
+12V
+5V
TP_12V
TP7
TP1
TP_5V
R7
100Ω
C1
0.1uF
C2
0.1uF
C3
0.1uF
D4
LED_Green
GND
TP5
TP_PWM_1
TP6
TP_PWM_2
PWM_1
PWM_2
U2
PIC18F26K83
MCLR
RA0
RA1
RA2
RA3
RA4
RA5
Vss
RA7
RA6
RC0
RC1
RC2
RC3
RB7
RB6
RB5
RB4
RB3
RB2
RB1
RB0
Vdd
Vss
RC7
RC6
RC5
RC4
R14
10kΩ
RELAY_1
RELAY_2
RELAY_3
RELAY_4
MOTOR_1
MOTOR_2
PWM_2_CTRL_A
PWM_2_CTRL_B
PWM_1_CTRL_A
PWM_1_CTRL_B
CON1
pic_debug_header
MCLR
Vdd
GND
PGD
PGC
NC
TP4
TP_CAN_H
TP_CAN_L
TP2
CAN_In
J12
J1
12V_Power_In
Vdrive
U3
ALQ3F12
Coil_In COM
Coil_Out NO
1N4007
D6
D8
APT30DQ60KG
J8
Motor_1
R9
100Ω
Q5
2222A
R12
1.2Ω
GND1
J10
PWM_1
SW1
PTS647SK38SMTR2LFS
J3
Relay_1
D1
R2
100Ω
Q2
2222A
R5
1.2Ω
U4
ALQ3F12
D7
D9
J9
Motor_2
R10
100Ω
Q6
2222A
R13
1.2Ω
J11
PWM_2
H1
MH_M3
H3
MH_M3
H2
MH_M3
H4
MH_M3
J4
Relay_2
D3
R3
100Ω
Q3
2222A
R6
1.2Ω
J2
Relay_3
D2
R1
100Ω
Q1
2222A
R4
1.2Ω
J5
Relay_4
D5
R8
100Ω
Q4
2222A
R11
1.2Ω
TP_Motor_Power
TP8
TP9
TP_Motor_Ground
TP3
TP_GND
J7
Motor_Power_In
J13
Motor_Power_In
Design by Garrett Shirley
ReVolt - Senior Design
Sheet: /
File: relay_motor_node_rev_1.sch
Title: Relay And Motor Driving CAN Node
Size: A4
Date: 2020-09-25
Rev: 3
KiCad E.D.A. kicad (5.1.6)-1
Id: 1/1


Relay Node Rev 3
ReVolt - Senior Design
Design by Garrett Shirley, Sep 2020
Mounting Holes
65mm x 120mm

# Appendix H: Re-Volt Project Bill of Materials

## BILL OF MATERIALS

| Item Description | Quantity | Price Each | Estimated Shipping | Total Cost | Actual Cost |
|---|---|---|---|---|---|
| NetGain HyPer9 HV motor | 1 | $3,969.00 | | $4,184.00 | $4,300.00 |
| AC-X144 motor controller | 1 | -- | | | |
| HyPer9 motor Chill Plate | 1 | $155.00 | $215.00 | $155.00 | $147.25 |
| LED Headlight Conversion Kit | 1 | $114.99 | Free | $114.99 (+tax) | $101.99 |
| Embedded Parts | 1 | <$250 | $15.00 | <$275 | $260.99 |
| Vaccum Pump for Power Brakes | 1 | $115.00 | $0.00 | $115.00 | $167.88 |
| Vaccum Switch for Power Brakes | 1 | $29.99 | $0.00 | $29.99 | |
| Door panel clips | 1 | $12.99 | $0.00 | $12.99 | |
| Heater Element | 1 | $22.99 | $0.00 | $22.99 | $36.85 |
| Thermal Fuse | 1 | $7.99 | $0.00 | $7.99 | $8.43 |
| Heater Fan | 1 | $26.99 | $0.00 | $26.99 | $813.47 |
| Radiator | 1 | $548.99 | $0.00 | $548.99 | |
| Coolant Pump | 1 | $193.99 | $0.00 | $193.99 | |
| Hose adapter AN | 4 | $19.48 | $11.99 | $89.95 | $96.70 |
| Heater Reducer/Adapter | 1 | $7.53 | $0.00 | $7.53 | $14.28 |
| Front door interior pull handles | 1 | $9.84 | $0.00 | $9.84 | $10.40 |
| Cable-accuated TPS sensor unit | 1 | $172.08 | $10.95 | $183.93 | $183.03 |
| Tesla Model S Battery Modules | 12 | $1,100.00 | $400.00 | $13,600.00 | $14,008.00 |
| Tesla Model S Battery Modules | 6 | $1,100.00 | $350.00 | $6,950.00 | $7,158.50 |
| VW Custom Radio w/ Bluetooth | 1 | $358.95 | $0.00 | $358.95 | $478.90 |
| VW Front Rubber Floor Mat | 1 | $119.95 | $0.00 | $119.95 | |
| Re-Volt Custom Stickers | 300 | | $12.00 | $250.00 | $269.25 |
| Re-Volt Business Cards | 200 | | $0.00 | $70.00 | $70.00 |
| Yeti Mugs | 15 | $24.99 | | $374.85 | $448.85 |
| Hex Head Bolts (for Transaxle connection) | 4 | $1.38 | $0.00 | $5.52 | $5.52 |
| High Voltage Connectors<br>Transaxle Adapter nuts & washers | 8<br>4/ea | | | | $43.60 |
| Coolant Manifold | 4 | $17.95 | $3.95 | $75.75 | $75.75 |
| PPE & Auto Cleaning Supplies | | $40.45 | | $43.81 | $43.81 |
| Key Stock 1 (for Shaft Adapter) part # 98830A200 | 1 | $1.48 | $8.55 | For all 4 before shipping $9.57 | $8.55 |
| Key Stock 2 part # 98510A136 | 1 | $1.62 | | | |
| Key Stock 3 part # 98491A136 | 1 | $1.55 | | | |
| Key Stock 4 part # 98535A150 | 1 | $4.62 | | | |
| Dilithium BMSC | 1 | $450.00 | $0.00 | $450.00 | $725.00 |
| BMSS | 1 | $275.00 | $0.00 | $275.00 | |
| OnBoard Charger- Elcon UHF 6.6kW | 1 | $1,747.00 | $0.00 | $1,747.00 | $3,030.57 |
| High Voltage Contactors | 4 | $84.00 | | $336.00 | |
| High voltage disconnect switch | 1 | $105.00 | | $105.00 | |
| High voltage to 13.8V converter | 1 | $467.00 | | $467.00 | |
| J1772 inlet (charge port) | 1 | $84.00 | | $84.00 | |
| 12V battery charger | 1 | $213.00 | $13.03 | $226.03 | $226.03 |
| Level 1 Charger | 1 | $199.00 | $9.00 | $208.99 | $208.99 |
| Level 2 Charger | 1 | $699.00 | $0.00 | $699.00 | $719.27 |
| Transaxle Adapter Stock Material/Billet | 1 | $230.00 | | $230.00 | $230.00 |
| Coolant Hose - chongus | 1 | | In Store | | $66.39 |
| Vent Control Levers - red | 2 | $11.95 | free | $13.90 | $25.25 |
| HV Wires | 50 | $2.75 | free | $137.50 | $68.75 |
| Orange Split Loom | 1 | $29.99 | ship to store | $29.99 | $36.52 |
| Orange electrical tape | 1 | $3.98 | ship to store | $3.98 | |
| HV sticker | 2 | $5.93 | ship to store | $11.86 | $12.75 |
| Digikey order 2 | 1 | $143.69 | $21.59 | $165.28 | $165.28 |
| Rubber liner for battery box | 1 | $157.50 | free | $157.50 | $182.00 |
| Aux. 12V Sockets | 1 | $9.99 | free | $9.99 | $73.08 |
| HV Gloves | 1 | $45.20 | free | $45.20 | |
| USB port | 1 | $13.99 | free | $13.99 | |
| 12V Battery | 1 | $36.17 | $0.00 | $36.17 | $37.80 |
| Engine bay lock | 1 | $27.95 | unknown | $27.95 | $106.85 |
| Plastic Glove Box | 1 | $39.95 | $0.00 | $39.95 | |
| Cup Holder - Plug n chug | 1 | $38.95 | $0.00 | $38.95 | |
| Door handle clips | 1 | | | | |
| 5/16-18 1.5in Hex bolts - QTY-50 | 1 | $11.25 | store pickup | $11.25 | $81.33 |
| 5/16 flat washers - QTY-25 | 3 | $3.08 | store pickup | $9.24 | |
| 5/16 -18 lock nuts QTY-15 | 4 | $1.87 | store pickup | $7.48 | |
| 5/16-18 1in Hex bolts - QTY-1 | 20 | $0.21 | store pickup | $4.20 | |
| 10-24 3/4in flathead bolts QTY- 8 | 3 | $1.18 | store pickup | $3.54 | |
| #10 flat washer QTY - 100 | 1 | $4.87 | store pickup | $4.87 | |
| #10 lock washer QTY - 30 | 1 | $1.18 | store pickup | $1.18 | |
| #10 36in All thread | 2 | $2.48 | store pickup | $4.96 | |
| 4in Corner brackets QTY-4* | 3 | $7.82 | store pickup | $23.46 | |
| Crimping tool for BMS connections | 1 | $22.59 | Free | $22.59 | $169.01 |
| 2/0 wire lugs | 3 | $33.59 | Prime | $100.77 | |
| 12V wiring | 1 | $23.95 | Prime | $23.95 | |
| WeatherPak Connector for TPS sensor | 1 | $13.99 | Free | $13.99 | |
| Battery Display + Shunt | 1 | $303.00 | Unknown | $370.94 | $421.94 |
| 1:10 Prescaler | 1 | $56.00 | Pick up on location | $56.00 | $56.00 |
| Mouser order: 12V high current fuse holder parts, heater/regen brake input switches, heater input pot, thermistor connectors, spare thermistors, knobs for controls | 1 | $81.80 | $7.99 | $97.27 | $97.27 |
| Anderson power connector for charger + crimp tool for it | 1 | $18.33 | N/A | $18.33 | $18.33 |
| Electrical conduit, couplings, crimps, battery box hardware | | | | $40.11 | $40.11 |
| 2/0 wire crimper | 1 | $46.19 | N/A | $46.19 | $46.19 |
| 5/16-18 x 2.5 inches hex head | 2 | | | | $3.50 |
| ¼-20 x .5 | 4 | | | | $2.00 |
| ¼-20 x .75 socket head cap screw | 4 | | | | $3.00 |
| U-Channel Edge Trim | 5 feet | $8.99 | | $8.99 | $9.66 |
| Steel panels and tubing | | | | $115.00 | $115.00 |
| Bronze bushing for shaft adapter | 1 | $18.27 | | $18.27 | $18.27 |
| Small Vinyl Coolant Hose (will need lots more!) | 10 | $1.10 | | | $12.17 |
| | | | | **PROJECT TOTAL** | **$35,760.31** |

| Categorical Breakdown | |
|---|---|
| Optional Add-ons | $1,887.81 |
| Batteries | $21,166.50 |
| Cooling System | $1,141.24 |
| Mechanical Integration | $377.14 |
| Electrical Integration | $6,177.01 |
| Fabrication | $653.31 |
| Motor + Controller | $4,300.00 |
| **PROJECT TOTAL** | **$35,760.31** |

# Appendix I: Test Plans and Results

Name or title of test: Motor Spinup and Compatibility

Date: 10/15/2020

Location of test: BBW 180

Why we are doing this test: To ensure the compatibility of key components and to ensure they are functional before installation in the Bus.

Hypothesis: The motor will spin slowly and accelerate at a constant throttle input.

Materials or equipment:

- Main contactor
- Laptop + requisite software
- Motor controller
- Motor controller to laptop cable (supplied with motor controller)
- Motor
- 6 charged Tesla battery modules
- Small wiring [This test does not involve high current]
- 12 V power supply to close the contactor and act as a 12 V battery
    - The 12 V battery had not arrived yet
- Low voltage power supply
    - This simulates the accelerator pedal which provides voltages between 1 and 5 volts.

Numbered list test procedure to conduct test:

1. Wire motor to controller
2. Wire Tesla battery modules in series and through the main contactor
3. Wire the contactor to the 12 V power supply and the motor controller
4. Connect the motor controller to to the contactor
5. Connect the laptop to the motor controller and ensure that there are no errors
6. Once errors are cleared, ensure that the main contactor closes. It will audibly click.
7. The motor will spin as the throttle voltage is increased. The motor should accelerate with constant throttle input as there is no load.
   **Turn off the throttle before the motor reaches the redline. Throttle should only be applied in short durations without load.**

Results:

There were more error codes than anticipated but ultimately the motor spun and is ready for installation.

Implications including supporting or disproving the hypothesis, and what this all means for the design and what needs to be done next:

The motor and associated key components are ready for installation.

Name or title of test: Unpowered drivetrain rotation

Date: 11/25/2020

Location of test: BBW 180

Why we are doing this test: To ensure that the motor has been installed correctly and components won't be damaged when power is applied.

Hypothesis: The motor will spin slowly and accelerate at a constant throttle input.

Materials or equipment:

- Motor
- Bellhousing adapter
- Stock clutch and transmission
- Hydraulic floor jack
- Two jack stands
- Two people

Numbered list test procedure to conduct test:

1. Jack the bus's rear wheels off the ground and place it on jack stands for safety
2. Place the bus in neutral and spin both tires by hand
3. Listen for any noise or vibration
   Because the bus is in neutral, the motor will not be spinning
4. Repeat the test in each of the bus's forward gears and reverse
   There should be more resistance on the tires as the motor is now being spun
   The bus transaxle is capable of spinning backwards so the direction of the wheels and the gear chosen does not matter.

Results:

The drivetrain spun at low speed in every gear and neutral. Resistance increased in gear as expected and there were no noises or vibrations

Implications including supporting or disproving the hypothesis, and what this all means for the design and what needs to be done next:

The motor and key components are ready for a powered test.

Name or title of test: Low-speed powered drivetrain rotation

Date: 12/8/2020

Location of test: Flat roads on Colorado School of Mines campus

Why we are doing this test: To ensure that the motor has been installed correctly and components won't be damaged at higher speed.

Hypothesis: The motor will spin slowly and accelerate at a constant throttle input.

Materials or equipment:

- Bus with motor installed
- Driver
- 2 Passengers to look/listen/smell

Numbered list test procedure to conduct test:

1. Power on bus
2. Drive slowly under 10 miles per hour
3. Have passengers view the drivetrain through the trunk panel
4. Have passengers listen for metal on metal sounds
5. Have passengers smell for anything unusual

    Unusual smells to keep in mind: Clutch smell, rubbing brakes, and gear oil from the transmission.

Results:

All components operated smoothly and as expected.

Implications including supporting or disproving the hypothesis, and what this all means for the design and what needs to be done next:

The bus is ready to test driving at higher speeds.

Name or title of test: Mid-speed powered drivetrain rotation

Date: 12/8/2020

Location of test: Highway 93

Why we are doing this test: To ensure that the motor has been installed correctly and components won't be damaged at higher speed.

Hypothesis: The motor will spin slowly and accelerate at a constant throttle input.

Materials or equipment:

- Bus with motor installed
- Driver
- 2 Passengers to look/listen/smell

Numbered list test procedure to conduct test:

6. Power on bus
7. Drive under 45 miles per hour
8. Have passengers view the drivetrain through the trunk panel
9. Have passengers listen for metal on metal sounds
10. Have passengers smell for anything unusual

    Unusual smells to keep in mind: Clutch smell, rubbing brakes, and gear oil from the transmission.

Results:

All components operated smoothly and as expected.

Implications including supporting or disproving the hypothesis, and what this all means for the design and what needs to be done next:

The bus is ready to test driving at higher speeds.

Name or title of test: High-speed powered drivetrain rotation

Date: TBD

Location of test: The open highway

Why we are doing this test: To ensure that the motor has been installed correctly and components won't be damaged at higher speed.

Hypothesis: The motor will spin slowly and accelerate at a constant throttle input.

Materials or equipment:

- Bus with motor installed
- Driver
- 2 Passengers to look/listen/smell

Numbered list test procedure to conduct test:

11. Power on bus
12. Drive between 55 and 75 miles per hour
13. Have passengers view the drivetrain through the trunk panel
14. Have passengers listen for metal on metal sounds
15. Have passengers smell for anything unusual

    Unusual smells to keep in mind: Clutch smell, rubbing brakes, and gear oil from the transmission.

Results:

Has not happened yet.

Implications including supporting or disproving the hypothesis, and what this all means for the design and what needs to be done next:

The bus is ready for 0-60 mph testing

Name or title of test: High-speed powered drivetrain rotation

Date: TBD

Location of test: The open highway

Why we are doing this test: To ensure that the motor has been installed correctly and components won't be damaged at higher speed.

Hypothesis: The motor will spin slowly and accelerate at a constant throttle input.

Materials or equipment:

- Bus with motor installed
- Driver
- 1 passenger to look/listen/smell
- 1 timer
- 1 person to operate timer

Numbered list test procedure to conduct test:

16. Power on bus
17. Accelerate from 0-60 miles per hour as fast as possible and time it
18. Have passengers view the drivetrain through the trunk panel
19. Have passengers listen for metal on metal sounds
20. Have passengers smell for anything unusual

    Unusual smells to keep in mind: Clutch smell, rubbing brakes, and gear oil from the transmission.

    This is the most likely test that will generate clutch slippage and clutch smell

Results:

Hasn't happened yet

Implications including supporting or disproving the hypothesis, and what this all means for the design and what needs to be done next:

If all goes well, the drivetrain is ready for The Client

All tests detailed in this document rely on information presented in the FDRt Embedded Systems Supplementary Report. Questions about tests should be answered in there; if not, direct questions to Garrett Shirley.

Name or title of test: **UI node unit test**

Date: **2020-11-14**

Location of test: Brown 304/305 labs

Why we are doing this test: Ensure that the UI node is able to respond to new inputs within 100ms of the input being changed. Response must be properly formatted communication message with the expected contents

Hypothesis: **UI node sends a properly formatted communication message over its UART when the fan speed and heater intensity inputs are changed**

Materials or equipment:

- UI node
- Oscilloscope
- Computer with serial to USB adapter
- DC power supply

Numbered list test procedure to conduct test:

1. Power on the node
2. Connect an oscope probe to the UART TX test point
3. Setup the oscope's serial decoder function
4. Connect the serial adapter to the UART lines via the terminal block on the node
5. Open a serial terminal on the computer
6. Change the inputs of the heater and observe the messages that are sent out (both on the serial terminal and the oscope), if the messages have the expected content the UI node behaves correctly for that input
7. Repeat step 6 with as many combinations of inputs as possible, if a single one fails the test has failed

Results: The messages the node sent out contained the correct values for the heater node. Messages were only sent when the inputs were changed

Implications including supporting or disproving the hypothesis, and what this all means for the design and what needs to be done next: The code developed for the node functions as expected and the node is ready for the broader system integration.

Name or title of test: **Cooling node unit test**

Date: **2020-12-12**

Location of test: Brown 304/305 labs

Why we are doing this test: Ensure that the cooling node can respond correctly to either messages from the temperature node or from the signal from the BMS

Hypothesis: **The cooling node will respond correctly to messages from the temperature node and the BMS and control the cooling system mock components correctly**

Materials or equipment:

- Cooling node
- Oscilloscope
- Computer with serial to USB adapter
- 2 DC power supplies
- 12V DC motor
- Relay or contactor with a 12V coil

Numbered list test procedure to conduct test:

1. Power on the node
2. Connect the relay and DC motor to the node
3. Connect an oscope probe to the UART TX test point
4. Setup the oscope's serial decoder function
5. Connect the serial adapter to the UART lines via the terminal block on the node
6. Open a serial terminal on the computer
7. Using Python with the pyserial backend, develop a script that sends messages to the cooling node when run. Make sure the messages are the same that the temperature node is expected to output
8. Use the Python script to tell the cooling node to turn on the cooling components.
9. If the relay switches on and the fan is brought to full speed, the test may continue. If they don't, then the test has failed
10. Use the Python script to tell the cooling node to switch off all cooling components.
11. If the relay switches off and the fan turns off, the test may continue. If they don't, then the test has failed
12. Use the second DC power supply to output a 12V signal limited to 500mA that goes through a voltage divider which brings it down to ~5V. Do not switch on the output yet
13. Connect the voltage dividers output to the input pin of the cooling node
14. Switch on the power supply's output
15. If the relay switches on and the fan turns on, the test may continue. If they don't, then the test has failed
16. After a minute or so, switch the power supply's output off.

17. If the relay switches off and the fan turns off, the test has been a success. If not then the test has failed.

Results: The cooling node response to the messages sent to it as expected, and reacts to the signal from the voltage divider as well

Implications including supporting or disproving the hypothesis, and what this all means for the design and what needs to be done next: The code developed for the node functions as expected and the node is ready for the broader system integration.

Name or title of test: **Temperature node unit test**

Date: **2020-12-12**

Location of test: Brown 304/305 labs

Why we are doing this test: Ensure that the temperature node is able to sense temperatures up to and over the threshold of 95 degrees F and send the appropriate message over its UART

Hypothesis: **When a single temperature sensor rises above the threshold temperature the node will output the appropriate message. When the sensor goes below that threshold it will output the appropriate message**

Materials or equipment:

- Temperature node
- Oscilloscope
- Computer with serial to USB adapter
- DC power supply
- Small heat gun

Numbered list test procedure to conduct test:

1. Power on the node
2. Connect an oscope probe to the UART TX test point
3. Setup the oscope's serial decoder function
4. Connect the serial adapter to the UART lines via the terminal block on the node
5. Open a serial terminal on the computer
6. Heat up a temperature sensor with the heat gun until it is guaranteed it is above 95 F.
7. Observe the message that the node sends out over UART on both the oscope and the serial terminal
8. If the message is formatted as expected, repeat steps 6-8 with each sensor
9. If all 4 sensors behave as expected, the test has been a success. If not the test has failed

Results: The temperature node is able to accurately read its temperature sensors and act correctly to their readings.

Implications including supporting or disproving the hypothesis, and what this all means for the design and what needs to be done next: The code developed for the node functions as expected and the node is ready for the broader system integration.

Name or title of test: **Heater node unit test**

Date: **2020-12-12**

Location of test: Brown 304/305 labs

Why we are doing this test: Ensure that the heater node is able to control its fan and relay outputs based on messages sent to it over UART

Hypothesis: **The heater node is able to correctly respond to messages sent to it over UART**

Materials or equipment:

- Heating node
- Oscilloscope
- Computer with serial to USB adapter
- DC power supply
- 12V DC motor
- 3 relays or contactors each with a 12V coil

Numbered list test procedure to conduct test:

1. Power on the node
2. Connect an oscope probe to the UART TX test point
3. Setup the oscope's serial decoder function
4. Connect the serial adapter to the UART lines via the terminal block on the node
5. Open a serial terminal on the computer
6. Using Python with the pyserial backend, develop a script that sends messages to the heating node when run. Make sure the messages are the same that the UI node is expected to output. Make sure all possible messages are written, this can and should be done in a way that avoids having to have a person write out each of the possible 20 messages
7. Have the Python script send each possible message to the heater node. Ensure that the fan and correct number of relays are switched on.
8. If a single message does not produce the expected behavior in the node, the test has failed. Otherwise the test has succeeded

Results: The heater node is able to respond correctly to the messages sent to it.

Implications including supporting or disproving the hypothesis, and what this all means for the design and what needs to be done next: The code developed for the node functions as expected and the node is ready for the broader system integration.

Name or title of test: **UI node and heater node integration test**

Date: **2020-12-12**

Location of test: Bay

Why we are doing this test: Ensure that the UI node and heater node, having passed their unit tests, are able to be integrated with each other successfully

Hypothesis: **The UI and heater nodes are able to be integrated successfully**

Materials or equipment:

- UI node
- Heater node
- Oscilloscope
- Computer with serial to USB adapter
- DC power supply
- 12V DC motor
- 3 relays or contactors each with a 12V coil

Numbered list test procedure to conduct test:

1. Power on the nodes
2. Connect an oscope probe to the UART TX test point on the UI node
3. Setup the oscope's serial decoder function
4. Connect the serial adapter to the UART lines via the terminal block on the node
5. Open a serial terminal on the computer
6. Connect the TX line from the UI node to the RX line of the heater node
7. With both nodes powered, switch the inputs and observe the behavior of the heater node
8. If all input combinations tested create the expected behavior, the test has succeeded. If not the test has failed

Results: The UI and heater nodes are able to be successfully integrated and work as designed.

Implications including supporting or disproving the hypothesis, and what this all means for the design and what needs to be done next: The code developed for the node functions as expected and the node is ready for the broader system integration.

Name or title of test: **Temperature node and cooling node integration test**

Date: **Date test is/was completed**

Location of test: Bay

Why we are doing this test: Ensure nodes and components work seamlessly together

Hypothesis: **Expected result**

Materials or equipment:

- Temperature node
- Oscilloscope
- Computer with serial to USB adapter
- Small heat gun
- Cooling node
- 2 DC power supplies
- 12V DC motor
- Relay or contactor with a 12V coil

Numbered list test procedure to conduct test:

1. Power on the nodes
2. Connect an oscope probe to the UART TX test point on the temperature node
3. Setup the oscope's serial decoder function
4. Connect the serial adapter to the UART lines via the terminal block on the node
5. Open a serial terminal on the computer
6. Connect the TX line of the temperature node to the RX line of the cooling node
7. Heat up a temperature sensor with the heat gun until it is guaranteed it is above 95 F.
8. Observe the behavior of the cooling node. If the motor switches on and the relay switches on the, the test can be continued. Otherwise the test has failed
9. Remove heat from the temperature sensor.
10. Observe the behavior of the cooling node. If the motor switches off and the relay switches off, the test has been a success. Otherwise the test has failed

Results: The temperature and cooling nodes are able to integrate and work as designed.

Implications including supporting or disproving the hypothesis, and what this all means for the design and what needs to be done next: The code developed for the node functions as expected and the node is ready for the broader system integration

All tests have been completed successfully, the system is ready for final installation

Name or title of test: **Cooling system thermal test**

Date: TBD

Location of test: TBD

Why we are doing this test: To determine if the temperature control of the cooling system will communicate to the cooling system. This will ensure the cooling system properly keeps the components cool.

Hypothesis: **The cooling system will engage and keep the batteries below 130F**

Materials or equipment:

- Infrared thermometer
- Laptop (for tuning the embedded nodes)

Numbered list test procedure to conduct test:

1. Program setpoint and thermal management behavior in cooling node
2. Drive bus aggressively in order to generate heat in the motor controller and the batteries.
3. Check that the cooling system begins operating when the temperature threshold has been met.
4. Check module temperatures with a thermometer to verify that all modules are being properly cooled.

Results: *Test has not been completed.*

Implications including supporting or disproving the hypothesis, and what this all means for the design and what needs to be done next:

Upon completion of the test, the clients will be able to drive the Bus with increased load (from carried weight and terrain demands) without concern for batteries overheating.

Name or title of test: **Cooling system leak test**

Date: TBD

Location of test: TBD

Why we are doing this test: To make sure the coolant loop does not leak

Hypothesis: **The coolant will not leak**

Materials or equipment:

- flashlight
- bicycle pump

Numbered list test procedure to conduct test:

1. Attach bike pump to cooling system through the coolant manifold
2. Gently pressurize the cooling system to less than 5 PSI
3. Check for leaks at all coolant connections, and well as decreased pressure on the pump gauge

Results: *Test has not been completed*

Implications including supporting or disproving the hypothesis, and what this all means for the design and what needs to be done next:
By ensuring system integrity, the cooling system is ready to fill with ethylene glycol coolant.

Name or title of test: **Onboard Charger Test**

Date: TBD

Location of test: BBW 180

Why we are doing this test: To ensure proper system communication with batteries, BMS, and charger.

Hypothesis: The charger will perform as stated by the manufacturer. BMS will control charging distribution and fully charge all 18 batteries.

Materials or equipment:

- Multimeter
- Charger connected in work bay

Numbered list test procedure to conduct test:

1. Ensure all wiring is properly connected
2. Connect outboard charger to wall and charge port.
3. Monitor battery voltages to see if they are increasing equally

Results: Test has not yet been completed

Implications including supporting or disproving the hypothesis, and what this all means for the design and what needs to be done next:

When charging capabilities are proven effective and functioning nominally, the Bus is ready for additional driving tests.

Name or title of test: **DC-DC converter test**

Date: **12/13/2020**

Location of test: BBW 180

Why we are doing this test: To ensure that the DC step-down is functioning properly, in order to use the 12 V functions of the bus.

Hypothesis: Functioning equipment, power to 12 V systems

Materials or equipment:

- multimeter

Numbered list test procedure to conduct test:

1. Make sure that all wires are connected
2. Use multimeter to test voltage above and below the step down to confirm correct values

Results: Test not yet completed

Implications including supporting or disproving the hypothesis, and what this all means for the design and what needs to be done next:

Upon completion of this test, the clients may operate 12 V functions without draining the 12 V battery.

Name or title of test: Fabrication Components Test Plan

Date: Ongoing, iterative

Location of test: Inside/Outside the bay (BBW180)

Why we are doing this test: To ensure all components function without interference

Hypothesis: As extensive planning and iterative design was performed, all components were expected to function properly

Materials or equipment:

- The components themselves (functional go-or-no-go gauges)
- Human ears and eyes

Numbered list test procedure to conduct test:

1. Secure bus on jackstands with rear wheels off the ground
2. Rotate components by hand (where possible) and observe for any mechanical interference
3. Make adjustments if necessary
4. Rotate components slowly under motor power and repeat procedure from steps 1 and 2
5. Slowly increase omega until a desired top rotational velocity is reached
6. Repeat observational procedure from steps 1 and 2

Results:

She chooched

Implications including supporting or disproving the hypothesis, and what this all means for the design and what needs to be done next:

Everything worked exceptionally well during testing. Next steps would involve continuing to monitor the conditions of the mechanical components both audibly and visibly.

Name or title of test: **General method for testing the viability of electrical connections for User Interface functions**
Date: Ongoing and iterative

Location of test: Re-Volt garage bay space (BBW 180), or in the adjacent cement courtyard.

Why we are doing this test: The reason for this test is to verify that the physical connections to make electrical connections were correct before being finalized and energized.

Hypothesis: With the proper wiring and connections, the result of this test will allow the tester to know with certainty that the physical connections of user interface components are correct before energizing the system to avoid potential fire hazards and prevent component damage. Sometimes when using this method, mistakes in wiring will be found. Once the problem is fixed, then the entire system is safer and more reliable overall and the user will be able to navigate the function of the user interface components

Materials or equipment:

- Schematic or circuit diagram
- A basic understanding of the function of the circuit
- Proper safety equipment for personal protection
- A digital multimeter (DMM)

Numbered list test procedure to conduct test:

1. Begin by referencing the circuit diagram for the connection currently being tested.
2. Make a quick check to determine if the physical connection that has been made is also the correct electrical connection for the circuit.
3. Inspect each connection and use the DMM to check for continuity on any connection made, or when the wire is out of sight from one end to another.
4. Double check that the connection being made is the correct electrical connection, and check that if the connection is to transfer power, that the correct gauge of wire is being used, and a fuse is properly connected in the circuit before powering on.
5. (When All Connections Ready) Power the connection when the circuit's connections have all been tested using this method.
6. (When All Connections Ready) Use the DMM to confirm and record the voltages of all nets in the system, and always check for voltage of the chassis ground just in case of an unseen electrical short or malfunction.
7. Check that the energized system performs functions as intended

Results:
All readings of the DMM should be expected. If otherwise, revisit the expected values and determine the reason behind the discrepancy.
Mistakes should be found with zero consequences. Instead of just powering components on, it is always worthwhile to double check the connections between everything, especially when working with high voltages.

# Appendix J: Technical Advisor Approvals

Technical Advisor Approval Form
Re-Volt VW Bus Conversion
S20-25, Fall 2020

Technical Advisor Name: _Dr. Christopher Coulston________________________________

Technical Advisor Email: _coulston@mines.edu________________________________

Student Subsystem Lead Name: ___Garrett Shirley______________________________

Subsystem: __Embedded Systems_______________________________

Description of project analyses reviewed by Technical Advisor:

1. The overall design and execution plan of the embedded systems subsystem for the project
2. The specific technical schematics of each component of the embedded system
3. The designs of the printed circuit boards for each component of the embedded system
4. The parts selected for each component of the embedded system

Design approval of above project facets:

| | | |
|---|---|---|
| ______________________________ | ______________________________ | ____________ |
| Technical Advisor Signature | Technical Advisor Name | Date |

Technical Advisor Approval Form
Re-Volt VW Bus Conversion
S20-25, Fall 2020

Technical Advisor Name: _Chuck Stone_

Technical Advisor Email: _cstone@mines.edu_

Student Subsystem Lead Name: _Max Porter_

Subsystem: _Drivetrain_

Description of project analyses reviewed by Technical Advisor: _Professor Chuck Stone reviewed the calculations and free body diagrams on the stock VW motor mount to ensure that we are not applying more load to the motor mount than it was originally designed to handle.

Design approval of above project facets:

| Chuck Stone | Chuck Stone | 30Nov2020 |
|---|---|---|
| Technical Advisor Signature | Technical Advisor Name | Date |

# 7.0 Work Cited


[1] M. Barber, “Before Tesla: Why everyone wanted an electric car in 1905,” Curbed, 22-Sep-2017. [Online]. Available: https://www.curbed.com/2017/9/22/16346892/electric-car-history-fritchle.

[2] “Lithium-Ion Battery Inventor Introduces New Technology for Fast-Charging, Noncombustible Batteries,” UT News, 08-Nov-2018. [Online]. Available: https://news.utexas.edu/2017/02/28/goodenough-introduces-new-battery-technology/.

[3] TheSamba.com :: Performance/Engines/Transmissions - View topic - Official WTF Transmission do I have/should I get thread. [Online]. Available: https://www.thesamba.com/vw/forum/viewtopic.php?t=658674. [Accessed: 10-Apr-2020].

[4] VW transporter 1700/1800/2000 owners workshop manual. Haynes Publishing Group, 2014.

[5] “NetGain HyPer 9 AC Motor X1 Controller Kit 120 Volt, EV West - Electric Vehicle Parts, Components, EVSE Charging Stations, Electric Car Conversion Kits,” [Online]. Available: https://www.evwest.com/catalog/product_info.php?products_id=469. [Accessed: 27-Mar-2020].

[6] “Curtis 1239e-8521 HPEVS AC-51 Brushless AC Motor Kit - 144 Volt, EV West - Electric Vehicle Parts, Components, EVSE Charging Stations, Electric Car Conversion Kits,” [Online]. Available: https://www.evwest.com/catalog/product_info.php?cPath=8&products_id=172&osCsid=rko3mftcbg9rm1o8pv6s8tv5s7. [Accessed: 06-Apr-2020]

[7] TheSamba.com :: Performance/Engines/Transmissions - View topic - Official WTF Transmission do I have/should I get thread. [Online]. Available: https://www.thesamba.com/vw/forum/viewtopic.php?t=658674. [Accessed: 10-Apr-2020].

[8] NetGain HyPer9 HV AC Motor X144 Controller Kit 144 Volt, EV West - Electric Vehicle Parts, Components, EVSE Charging Stations, Electric Car Conversion Kits. [Online]. Available: https://www.evwest.com/catalog/product_info.php?cPath=8&products_id=482.

[9] “Customers who bought this product also purchased,” EV West VW Air Cooled Billet Aluminum Transmission Adapter, EV West - Electric Vehicle Parts, Components, EVSE Charging Stations, Electric Car Conversion Kits. [Online]. Available: https://www.evwest.com/catalog/product_info.php?cPath=36&products_id=228.

[10] “Cable Operated TPS,” HGM Automotive Electronics. [Online]. Available: https://www.hgmelectronics.com/cable-operated-tps/#product-description

[11] “TBS E-Xpert Pro,” *EVolve Electrics*. [Online]. Available: https://evolveelectrics.com/products/tbs-e-xpert-pro?_pos=7&_sid=896203493&_ss=r.

[12] “Battery Management System v2.2,” Dilithium Design. [PDF] Available:https://evwest.com/support/BMSv2.2.pdf [Accessed: Nov-2020]

[13] 14] EV West, “Volkswagen Bus 21 Window EV Build | EV Show,” Youtube, 27-Aug-2020. [Online]. Available: https://www.youtube.com/watch?v=Lu98V-8aTmQ. [Accessed: Sep-2020].

[14] Orders of magnitude (energy),” *Wikipedia*, 18-Nov-2020. [Online]. Available: https://en.wikipedia.org/wiki/Orders_of_magnitude_(energy)

[15] R. M. Fish and L. A. Geddes, “Conduction of electrical current to and through the human body: a review,” *Eplasty*, 12-Oct-2009. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2763825/.

[16] “Electrical Gloves: 5 Things You Should Know,” *Grainger KnowHow*. [Online]. Available: https://www.grainger.com/know-how/safety/ppe-in-the-workplace/hand-protection/kh-electrical-gloves-5-things-to-know.

[17] Matthew.lynberg.ctr@dot.gov, “Automated Vehicles for Safety,” NHTSA, 15-Jun-2020. [Online]. Available: https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety

[18] “Specifying, Ordering & Installation Guidelines,” Strike First USA, 01-May-2020. [Online]. Available: https://www.strikefirstusa.com/resources/ordering-installation-guidelines/.

[19] “Customers who bought this product also purchased,” *Gigavac Maintenance Switch HBD41AA 1000V 400A Continuous Hermetically Sealed, EV West - Electric Vehicle Parts, Components, EVSE Charging Stations, Electric Car Conversion Kits*. [Online]. Available: https://www.evwest.com/catalog/product_info.php?cPath=2_42&products_id=267.