REVO Electric Racing, Olin College of Engineering

Electrical System Form FSAE-E 2016
Car E212

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List of Abbreviations

- MSD- Manual Service Disconnect
- CONN- Main accumulator connector
- NDA - Non Disclosure Agreement

Any other abbreviations used in this document are those used in the 2016 Formula SAE Rules and those used in the FSAE ESF template document.

1 System Overview

The system will support all requirements for vehicular movement while guaranteeing driver and maintenance safety. There will be two primary electrical systems, galvanically isolated from each other: a 100V high power tractive system and a 12V low power sense and communication system.

The low power system will include a shutdown circuit, a series of sensors and switches that ensures the vehicle is safe to drive before engaging the tractive system. There is a low voltage battery and DC-DC converter, because the 12V battery will start up the car and the DC-DC converter will take over and continue powering the system. The shutdown circuit will also monitor the vehicle for dangerous conditions, such as a collision or ground fault in the tractive system, and will disengage the tractive system in case of emergency. Finally, the low power system will power a CAN communication network using atmega16M1 microcontrollers that will be used to operate several rules required functions, such as the ready to drive noise, but will also serve as a debugging tool for both electrical systems.

The tractive system consists of a custom accumulator container, two Sevcon motor controllers, two Zero Motorcycles brushless DC motors, and a junction box to split the high voltage line to the two controllers. The accumulator comprises 12 Nissan Leaf battery modules. The motors are configured for rear wheel drive with independent control over the left and right wheels. Communication to the motor controllers is completed using a galvanically isolated CAN connection.

See Figure 1 for an electrical block diagram.

Maximum Tractive system voltage	99.6V VDC
Nominal Tractive system voltage	90 VDC
Control-system voltage	13.5VDC & 12VDC
Accumulator configuration	2s2p in 12s
Total Accumulator capacity	NDA
Motor type	Brushless DC Motor
Number of motors	Total: 2
Maximum combined motor power in kW	NDA

Table 1: General parameters

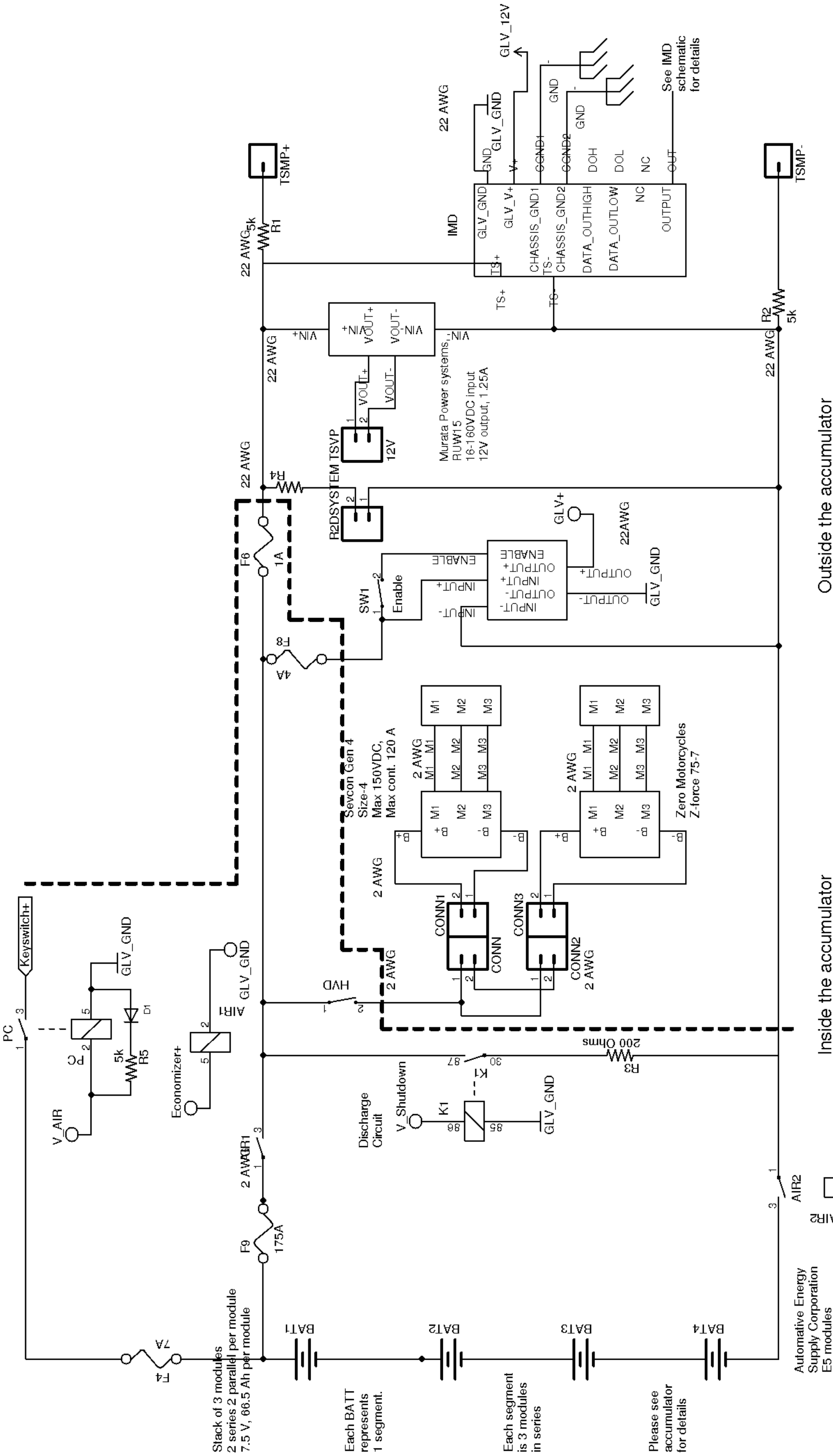

Figure 1: Tractive system block diagram

2 Electrical Systems

2.1 Shutdown Circuit

2.1.1 Description/Concept

The shutdown circuit is the primary method for maintaining driver and maintenance electrical safety at all times. The shutdown circuit prevents high voltage from being present outside of the accumulator container before the vehicle is safe to drive and will shut down the tractive system during driving if it detects an unsafe or emergency condition. The shutdown circuitry is based entirely upon analog logic and when operational is in a closed configuration. Triggering the shutdown circuit opens the circuit and causes the AIRs to open. Each component of the shutdown circuit is connected to a CAN node to inform the driver and crew what system triggered the shut down for debugging purposes. To power the system, we have both a DC-DC converter and a 12V battery. The battery jump-starts the car, and allows the GLV system to power up the TS system. Then, the DC-DC converter powers the car for the rest of the functional time. The battery is left there for backup purposes.

The shutdown circuit consists of 10 major components

- The GLVMS controls all power to the GLV system. As a result, high voltage cannot be present when the low voltage system is not active.
- The TSMS is the last component in the shutdown circuit before the AIRs. This allows full testing of the GLV system without engaging the TS and only intentional use of the TS.
- The BOTS is used to detect a mechanical failure in the brake system. If the brake fails, the TS is disabled to allow the vehicle to roll to a stop and ensure the safety of the driver.
- The SDBs are used for emergency shutdown of the TS. The cockpit SDB allows the driver to quickly shutdown the vehicle from the driver's seat. The left and right SDBs are intended for emergency shutdown in a crash or rollover scenario by first responders.
- The IMD is used to detect if the TS short circuits to the GLVS. Because the chassis is used to ground the GLVS, a short circuit presents a dangerous driver and maintenance scenario so the IMD disables the TS.
- The AMS monitors the health of the accumulator and triggers a TS shutdown if the modules enter a dangerous temperature or electrical condition.
- The inertia switch triggers a TS shutdown if it experiences an acceleration indicative of a collision. This ensures the vehicle is electrically safe in an emergency situation.
- Interlocks close the shutdown circuit when all high voltage connections are properly made. This ensures that high voltage is only present within the TS and disabled if connections are left open.
- The BSPD detects if the motor controllers are drawing significant current from the accumulator while the brakes are engaged. To protect the driver and the vehicle, this scenario triggers a TS shutdown.
- Finally, the shutdown circuit contains a CAN Watchdog to shut down the TS in the event of a CAN error. The primary intent of this additional component is to monitor the health of the motor controllers and shutdown TS if necessary to protect them.

Part	Function
Main Switch (GLVMS and TSMS)	Normally open
Brake over travel switch (BOTS)	Push-pull button
Shutdown buttons (SDB) (Left, right, cockpit)	Normally closed
Insulation Monitoring Device (IMD)	Normally open
Battery Management System (AMS) x4	Normally open
Inertia switch	Normally closed
Interlocks	Closed when circuits are connected
Brake System Plausibility Device (BSPD)	Normally Open
CAN Watchdog	Normally closed

Table 2: List of switches in the shutdown circuit

2.1.2 Wiring/Additional Circuitry

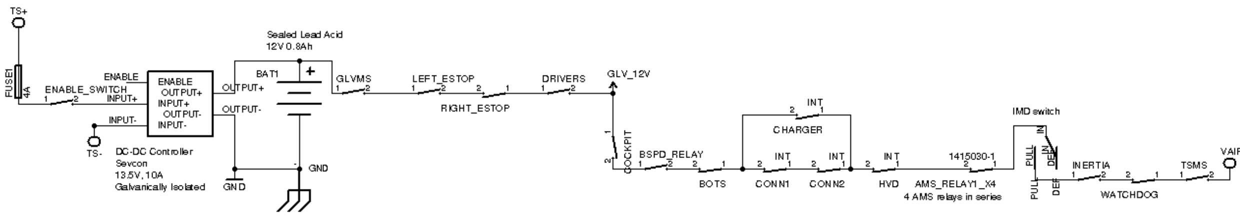

Figure 2: Shutdown Circuit Switches

Figure 2 shows only the switches in the shutdown circuit, and does not include the AIRs or the precharge and discharge systems. The tractive system can only be enabled when all switches are closed, allowing the AIRS to be closed. The point after the TSMS splits into power for the AIRs, which are in parallel, and the keyswitch (trigger for the internal precharge system of the motor controller). This schematic has been simplified to not include the circuitry around the coils that close these switches, but those schematics can be found in their respective sections.

Total Number of AIRs:	2
Current per AIR	3.8A until 150 ms passes, then 0.4 A
Additional parts consumption within the shutdown circuit:	0.5 A
Total current:	4.3 A until 150 ms passes, then 1A
Cross sectional area of the wiring used:	0.000506 in^2 (22 AWG)

Table 3: Wiring–Shutdown Circuit

The GLV system also has 12V and 5V supply lines in parallel to the shutdown circuit. It supplies the 555 timers, CAN nodes, coils and lights, which are all in parallel with the AIRs, increasing the total current to 1A.

2.1.3 Position in Car

With the exception of the emergency shutdown buttons and tractive system interlocks, the components comprising the shutdown circuit are housed within a waterproof enclosure, located at the rear of the chassis, behind the main hoop, on the driver's right as shown in Figure 3. This enclosure consists of a carbon fiber panel, where accessible switches, buttons, and measuring points will be mounted, and a 3D printed rear housing with integrated 18-pin Deutsch DT panel mount connector as shown in Figure 4. Actual components are not shown due to lack of CAD files at this point in time. Tractive system interlocks are located at each individual high voltage connection including the main two-way accumulator bus, HVD, & three MSD's (manual service disconnects/maintenance plugs). The emergency shutdown buttons are located on the driver's dashboard (1) and on the right (2) & left (3) sides of the car at driver's head level, attached to the main hoop with welded steel brackets.

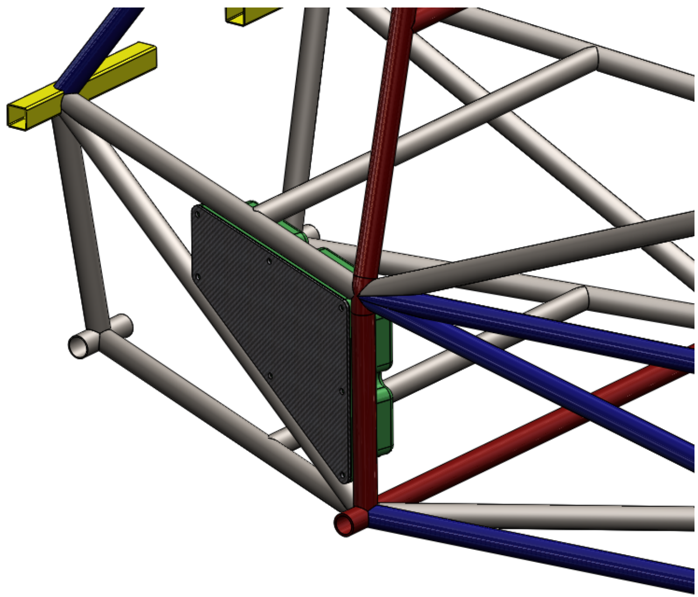

Figure 3: Shutdown Circuit Enclosure Vehicle Location

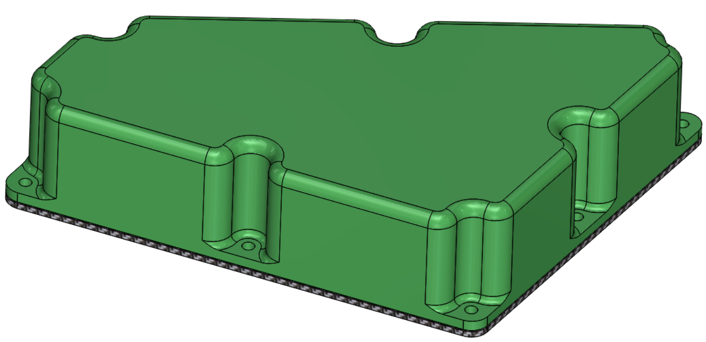

Figure 4: Waterproof Enclosure for TS MS, GLV MS, TSMP, GLVMP, & Shutdown Circuit

2.2 IMD

2.2.1 Description (Type, Operation Parameters)

The IMD used will be a Bender A-ISOMETER IR155-3204. The output is normally low and only high if it does not detect a ground fault. The output is then used in a 4PDT relay to power both the indicator light and closes the switch in the shutdown circuit.

Supply voltage range:	10...36VDC
Supply voltage	12VDC
Environmental temperature range:	Unknown
Selftest interval:	Every 5 minutes
High voltage range:	0-1000 VDC
Set response value:	100 kΩ
Max. operation current:	150 mA
Approximate time to shut down at 50% of the response value:	$\leq$ 40 sec

Table 4: Parameters of the IMD

2.2.2 Wiring/Cables/Connectors

To fit the connectors and the low current draw of the IMD, the wires used for the IMD will be 22 AWG and 18 AWG. There is a fuse protecting the low current, high voltage wiring of the IMD and other components, and it is fused to 1A (details of the fuse are in the appendix, section ??).

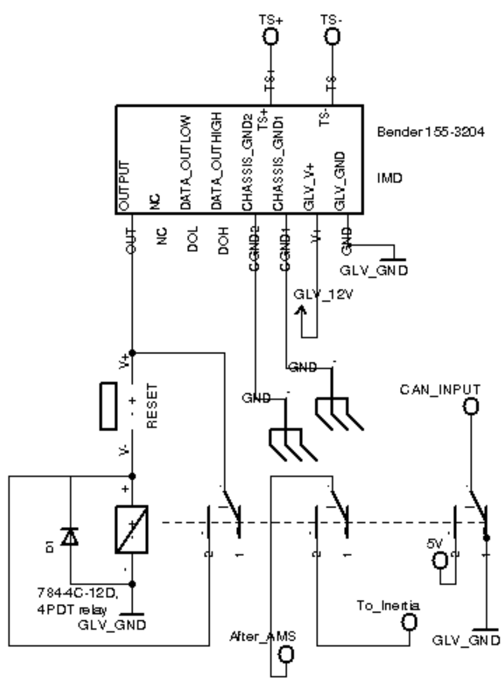

Figure 5: Schematic of the IMD and its connections

The IMD output powers a four pole double throw relay. However, for the relay to become powered, at the start of each driving/operable session (not when there is a fault in the shutdown system), a person must press the IMD reset button, which closes the circuit and allows the coil to power itself through the first pole. The other two poles close the shutdown circuit and the input pin to the CAN node. The fourth pole is not connected. The can input will inform the CAN system about the status of the IMD (pull up resistor is

controlled with software on the input pin). The Atmega controls the IMD light in the cockpit through CAN software. With the coil powered from the IMD's positive output, the shutdown circuit will close.
The connectors used for the IMD are the TYCO-MICRO MATE-N-LOK 1 x 2-1445088-8 and its mate.

2.2.3 Position in Car

As part of the shutdown circuit, the IMD will be located inside the enclosure shown in Figure 4. This is a convenient location for the IMD as high voltage sensing lines must already be present here for the TSMP's.

2.3 Inertia Switch

2.3.1 Description (Type, Operation Parameters)

The Sensata Resettable crash sensor (6-11g version) will trigger due to an impact that decelerates the vehicle at between 6-11g. The normally closed switch will then open to protect both the driver and any operator from a short that was caused by the accident.

Inertia switch type	Sensata 6-11g crash sensor
Supply voltage range	12 VDC
Supply voltage	12VDC
Environmental temperature range	-10-120 °C
Maximum operational current	20A for max. duration 30sec, 10A max. continuous
Trigger charactersitics	Operate above 11g peak, 60ms duration Not operate below 6g peak, 60ms duration

Table 5: Parameters of the Inertia Switch

2.3.2 Wiring/Cables/Connectors

The Inertia switch will be wired to be normally closed and open the shutdown circuit in the case that there is a crash.

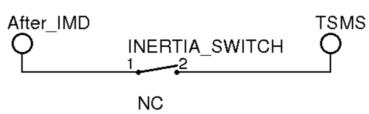

Figure 6: Schematic of the inertia switch and references to where it is in the shutdown circuit

2.3.3 Position in Car

The inertia switch will also be located in the enclosure shown in Figure 4 to keep wire paths short and provide an easy access point to reset the switch if triggered.

2.4 Brake Plausibility Device (BSPD)

2.4.1 Description/Additional Circuitry

The BSPD will constantly check if there is a substantial amount of current across the motor controllers and if the brakes are being pressed hard. If both are true, after 0.5 second of continuity, the relay will open the switch in the shutdown circuit. The circuitry consists of an AND gate with two hall effect sensors and the brake sensor as inputs and a 555 timer to check if the states of both the brakes and the motor controllers are continuous. Two hall effect sensors had to be used, as not once outside of the accumulator does the TS wiring all go through one wire.

Brake sensor used:	Pegasus Brake Light switch, part 3601
Torque encoder used:	Active Sensors MHR5621
Supply voltages:	5V
Maximum supply currents:	15 mA
Operating temperature:	-55 to 150 °C
Output used to control AIRs:	TE Connectivity Relay, part PB766-ND

Table 6: Torque Encoder Data

2.4.2 Wiring

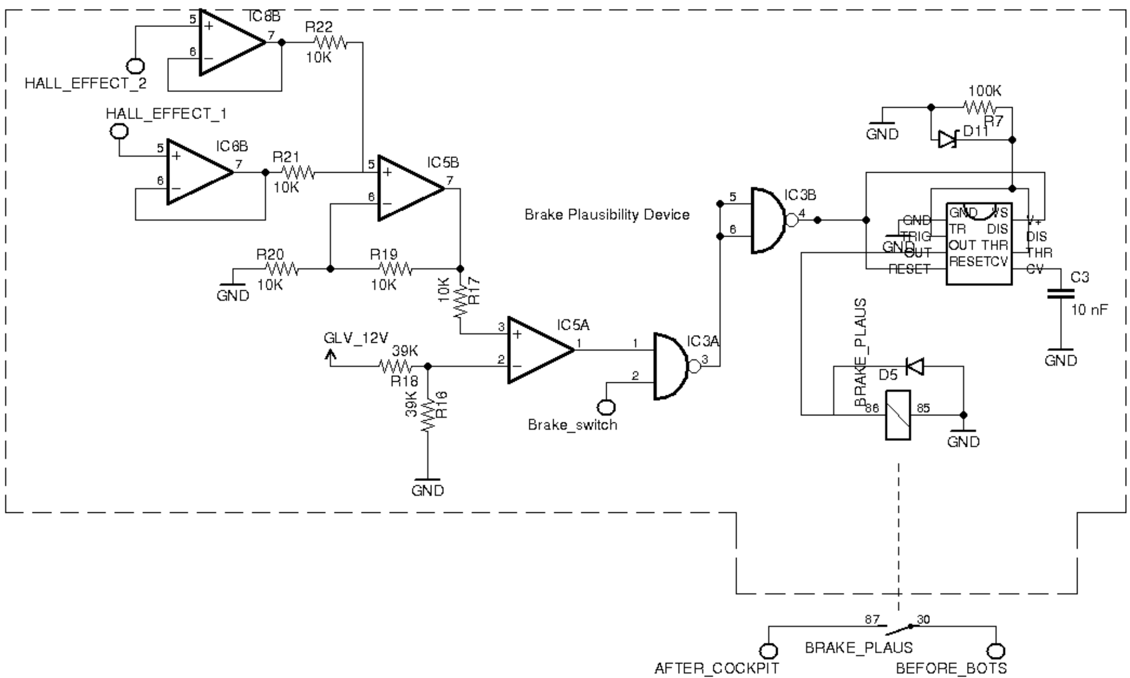

Figure 7: Schematic of the BSPD

A Hall effect current sensor, wired before the current splits to the motor controllers, will send a proportional signal to a comparator. If the current is above 50 Amps, the output will be positive, and a positive signal will be sent to the AND gate. If the brakes are actuated, a positive signal will come from the brake pressure switch, causing the AND gate to return positive. These signals will go to two 555 timers, causing a time delay of .5 seconds. If the signal is maintained over this time period, current will flow through the normally-closed relay, opening it and shutting down the current to the AIRs.

2.4.3 Position in Car/Mechanical Fastening/Mechanical Connection

The brake sensor is Pegasus Racing P/N 3601 pressure switch that activates between 60 and 120psi. It is attached to the brake line using a -3 AN T-fitting. The brake system is composed of a combination of hard and flexible brake line and will use a combination of SAE flare connections and AN fittings.

The circuit board controlling the BSPD is located in the enclosure shown in Figure 4, and receives inputs from the brake pressure switch and hall effect sensor discussed in the previous section. The board will be positively retained in the enclosure using standard hardware and stand-offs, and all internal enclosure connections will be made using Molex PCB connectors. The pressure sensor will be mounted as discussed in the previous section.

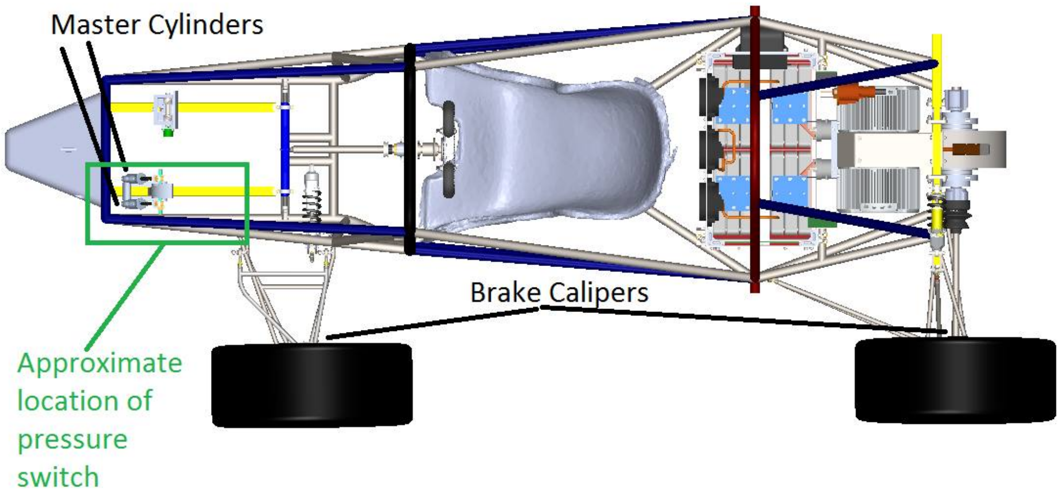

Figure 8: View of BSPD Pressure Switch and T-Fitting

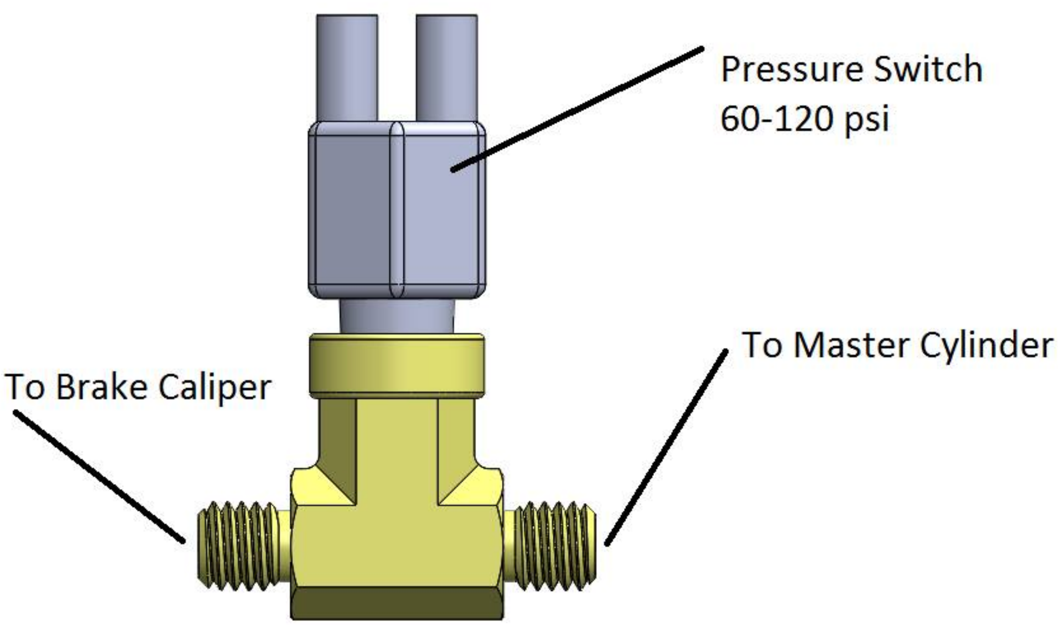

Figure 9: Approximate Location of BSPD Pressure Switch in Vehicle

2.5 Reset/Latching for IMD and BMS

2.5.1 Description/Circuitry

If the AMS detects a fault. It opens the shutdown circuit, and latches into that state. When the AMS reset switch is pressed, the nearby CAN node passes a "Reset" CAN message to the AMS boards. If the accumulator is within safe electrical and temperature operating limits the AMS closes the shutdown circuit.

To reset the IMD an operator other than the driver must push the IMD reset button located on the outside of the car on a panel next to the TSMPs, master switches and E-stops. If the output of the IMD is high because there is no ground fault, the reset button will activate the coil and close the shutdown circuit.

2.5.2 Wiring/Cables/Connectors

The IMD's output, as seen in figure 5, continuously closes the shutdown circuit as long as its output is high. The reset button closes the circuit to the coil to then allow the coil to power itself for as long as the output is high. Once low, the coil will open its four poles, thereby not allowing power to the CAN node input or the switch in the shutdown circuit. The 4PDT relay is specified for 15A, while the GLV system it controls is fused for 4A. The wire gauge to the IMD relay is 22AWG.

The BMS reset button is a button that connects 5V to a CAN input pin on the IMD/Ready to Drive/Watchdog node later mentioned in section 8.3. When the CAN node receives a high signal it sends a message to the rest of the system, including the AMS nodes, and if the AMS detects the accumulator is safe, the AMS relay will close the shutdown circuit and allow normal operation. All wire gauges will be 22 AWG except for PCB traces. Because CAN communication requires very little current, the lines will not be fused.

The connectors used for the IMD will be Molex, LLC 0022013037 and its pair, Molex, LLC 0022232031, or other Molex products of the same series but with a different number of headers on each side of the connector.

2.5.3 Position in Car

The IMD and BMS reset buttons will be panel mounted to the enclosure shown in Figure 4. The AMS will be within the accumulator container.

2.6 Shutdown System Interlocks

2.6.1 Description/Circuitry

Interlocks are low voltage mechanically activated switches that close when a high voltage connection is made or a system is closed. In the shutdown circuit, the main accumulator connection, HVD, and the three manual service disconnects all have interlocks. The shutdown circuit will be open when any of these TS connections are opened.

2.6.2 Wiring/Cables/Connectors

Interlock wires are mechanically integrated with HV connectors such that they are simultaneously disconnected with the removal of a connector. The removal of a connector therefore breaks shutdown circuit continuity.

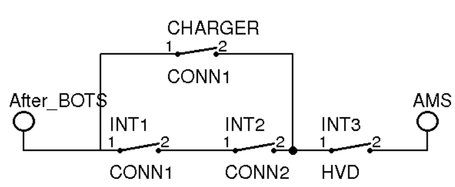

Figure 10: Interlocks contained in the shutdown circuit

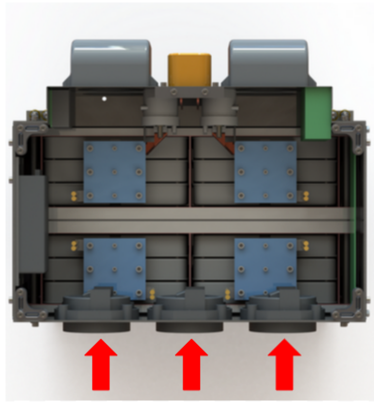

Figure 11: MSDs in the accumulator, indicated by the red arros

2.6.3 Position in Car

Interlocks are contained within the main accumulator two-pole HV connector (labeled CONN) and the HVD. Both connections are out of the accumulator, and located in the back of the car. Please see section 2.11 for details.
There is a charger interlock that overrides (in parallel with) the main connection interlocks. This interlock is only used during charging.

2.7 Tractive system Active Light

2.7.1 Description/Circuitry

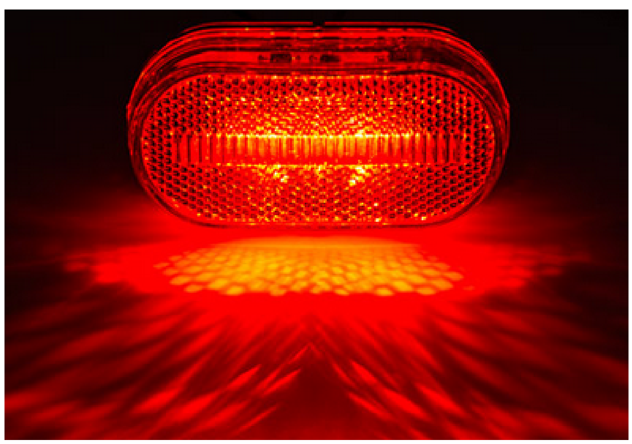

Figure 12: Product picture of the TSAL, from Super Bright LEDs part no. M9-R4

The TSAL illuminates when the tractive system is active, which is defined as the tractive system voltage being over 60V or the AIRs being closed.

Supply voltage:	12V
Max. operational current:	0.04A
Lamp type	LEDs
Power consumption:	0.48 W
Brightness	Unknown
Frequency:	Manual with 555 timer, 2.4 Hz
Size (length x height x width):	103x27x51 mm

Table 7: Parameters of the TSAL

2.7.2 Wiring/Cables/Connectors

There is a DC-DC (isolated) converter that converts TS 100V to 12V for the light. The DC-DC converter accepts 16-166VDC as input voltage. This will power a 555 timer astable circuit. When the TS is over 60V, zener diodes with a breakdown voltage of 56V and 3.6V respectably power one side of an optocoupler when the TS voltage is over 60V. The optocoupler closes the circuit on the other side for the timer's output to go to the light through an OR gate. The OR gate also accepts the GLV 12V as an input, which is only live when both AIRs are closed. In this way, the light will be powered when the tractive system is over 60V or the AIRs are closed. The light will blink at 2.4 Hz.

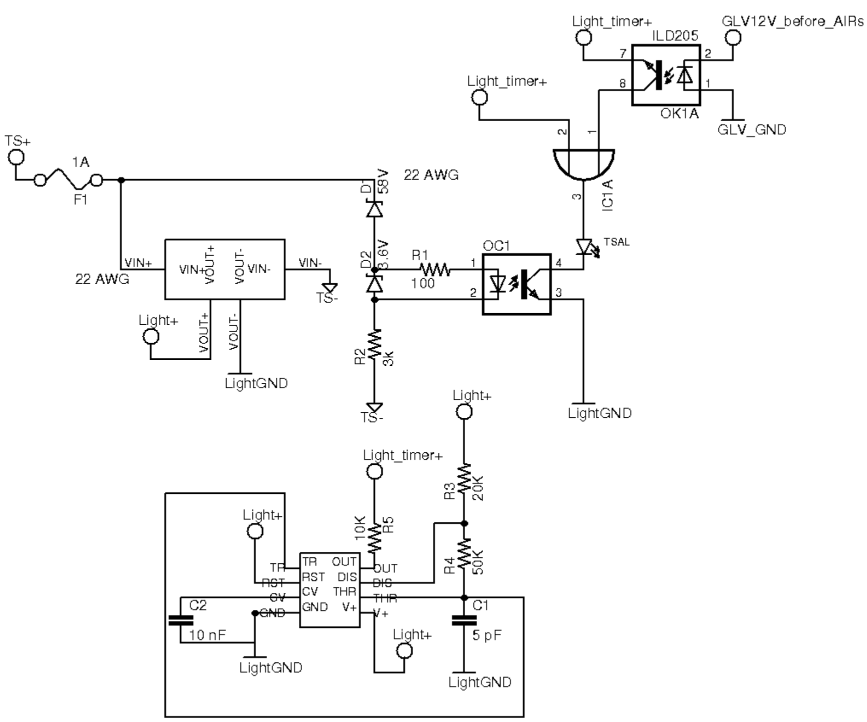

Figure 13: Schematic for the TSAL

As shown in Figure 13, there is a 1A fuse protecting both the DC-DC converter and the light's optocoupler. There is a fuse not shown that is in the GLV system, which protects the GLV 12V shown before the AND gate. All connections made by wires will be 22 AWG rated for 600V, 125 °C and 7A, while all PCB traces will be a minimum of 10 mil, but nominally 20 mil in width.

2.7.3 Position in Car

The TSAL will be mounted to the underside of the highest point of the main roll hoop, per EV 4.12.4 using a robust 3D printed bracket integrating the light and necessary wiring. This enclosure has not been designed

yet.
The PCB will be located in the side panel enclosure, also known as the TSMP housing.

2.8 Measurement Points

2.8.1 Description

The TSMPs and GLVS ground measuring points are housed in a non-conductive, well-marked housing that can be opened without tools. It will be protected from people touching it by shrouded banana jack connectors. The measuring points allow for safe measurement of the tractive system voltage and for manual detection of ground faults.

2.8.2 Wiring, Connectors, Cables

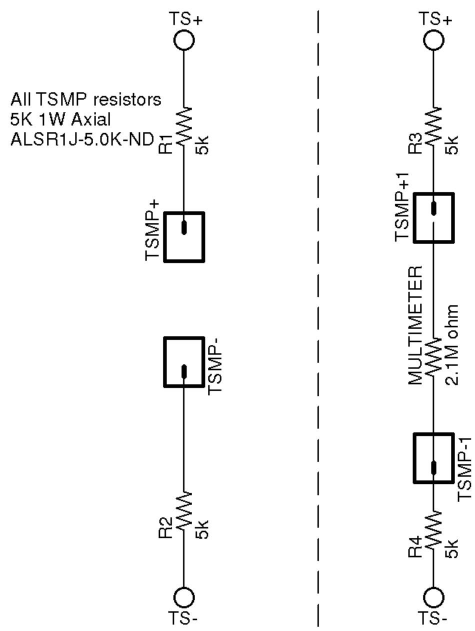

Figure 14: Tractive System Measuring Points

Figure 14 shows the TSMP schematic. Left shows the schematic including the banana jacks. Right shows the multimeter measuring the tractive system, with the multimeter's expected resistance and the same resistors as before the TSMP's on the left side.

There will be four measuring points: TS+, TS-, GLV+, and GLV-. The TSMP connections will be secured with 5 kΩcurrent limiting resistors. There will not be a fuse. The worst case scenario for the TSMPs occurs when there is a short between the TS+ and TS- banana jacks. This could occur as a result of operator error when measuring the TS voltage and create a voltage over a human operator's hands. The current limiting resistors ensure that the current draw in this scenario will not harm a human.

$$V = I * R \tag{1}$$
$$100V = I * 10,000\Omega \tag{2}$$
$$I = 0.01A \tag{3}$$

$$P = I * V \tag{4}$$
$$P = 0.01I * 100VV \tag{5}$$
$$P = 1W \tag{6}$$

Therefore, a 1W, 5kΩresistor will be placed before each TSMP banana jack. The resistor will be on a small, separate PCB or break out board that only contains the resistors to the TSMPs. This PCB does not have a finished design yet, but will be housed such that it is insulated from all adjacent conductive materials.

Another worst case scenario that could occur at the measuring points is a short between the TS and GLV systems over the banana jacks, again by operator error. In this scenario, the IMD will open the shutdown circuit.
The TSMP banana jacks are 72930-2 and 72930-0 Pomona Electronics 4 mm banana jacks (red and black, respectively). The TSMP resistors are Vishay Dale, ALSR035K000FE12 (manufacturer's part number), rated for V and part of the ALSR/ALVR series. The datasheets for both the banana jacks and the resistors can be found in section 11.

2.8.3 Position in Car

The TSMP's will be located in the enclosure shown in Figure 4. Body panel removal will not be required for access, and any protective covers for the TSMP's will be removable without the use of tools. The enclosure itself is bolted together using 1/4" hardware, but we intend to provide additional banana jack measuring points to measure the TSMP resistors without removal of any vehicle components.

2.9 Pre-Charge Circuitry

2.9.1 Description

In order to prevent damage to the motor controllers, AIRs, and ultimately the driver, it is important to ramp the tractive system up to full operating voltage rather than instantaneously jump from 0V to 100V. One consequence of an immediate transition to high voltage can be arcing across the AIRs. This can cause pitting in the relay contacts over time and ultimately cause the system to fail. Pre-charging reduces the difference in potential on each side of the relay to prevent arcing and ensure the integrity of the electrical system over many uses.

2.9.2 Wiring, Cables, Current Calculations, Connectors

Once the shutdown circuit is closed, it will immediately power the coils of the normally closed discharge relay, the normally open precharge relay, and the normally open TS- AIR. This opens the discharge relay, and closes the precharge relay and TS- AIR. Instead of connecting Batt+ to TS+ through a current limiting resistor, the precharge relay connects B+ to the key switch terminal on each of the Sevcon motor controllers. When powered by their key switch terminals, the motor controllers charge their internal capacitors up to around 50V for 0.5 seconds, then up to 90V (or another specified voltage) for 0.1 seconds before signaling though the CAN system that the precharge is complete. This CAN message causes a node in the battery to allow the shutdown circuit to close the TS+ AIR.
Please note the schematic in figure 15.

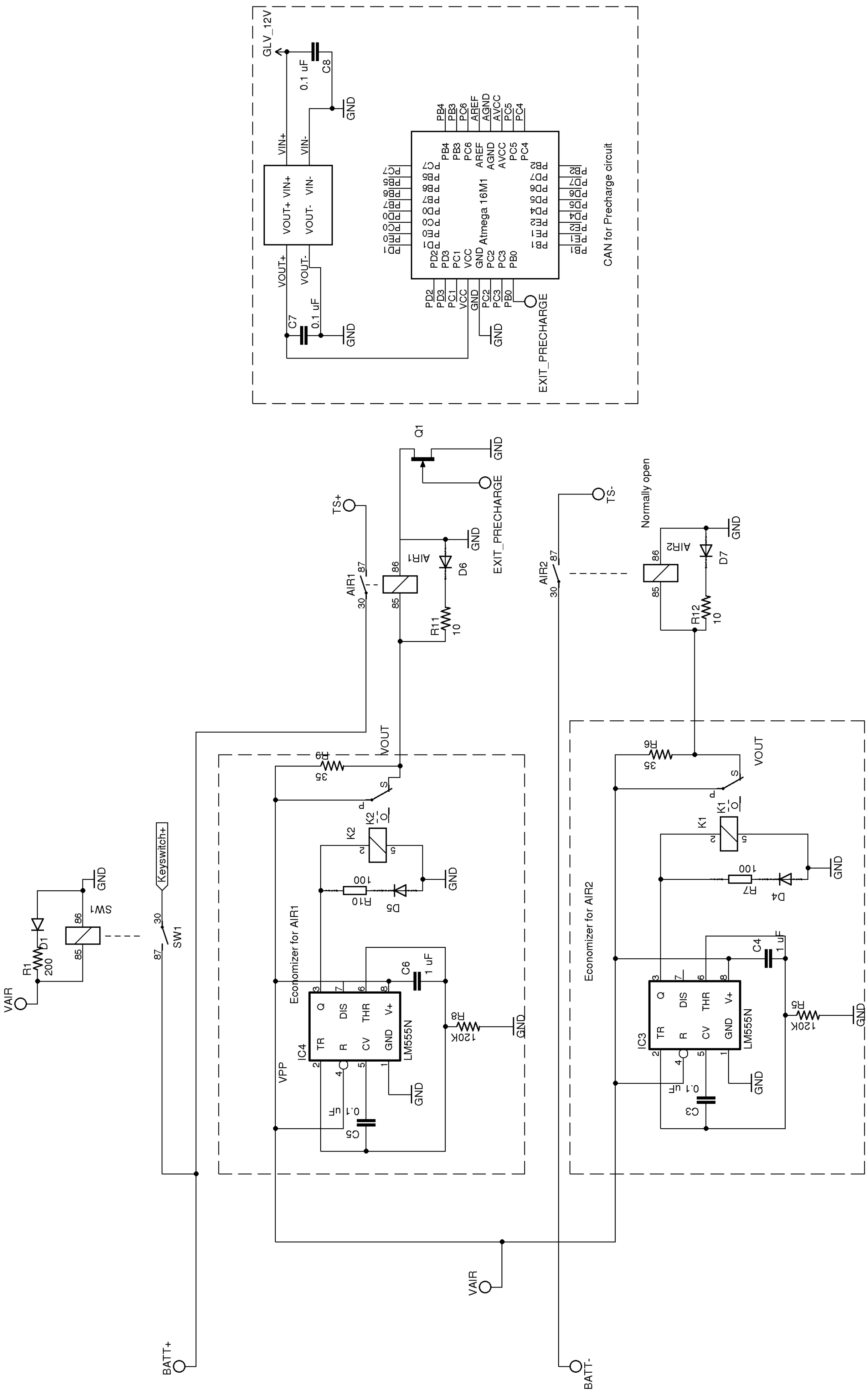

Figure 15: Precharge system schematic, including the AIR economizers

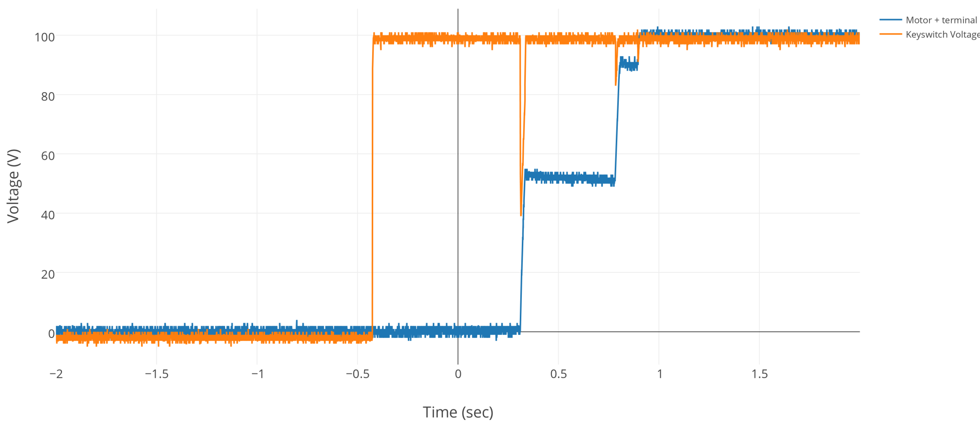

Figure 16: Voltage vs time, measured in a test setup.

In figure 16, the voltage of a test setup of the pre-charge system internal to the motor controller was measured. Because there is no resistor other than the motor controller, the current could not be calculated and/or graphed. This was discussed in rules clarification ticket 4487. As discussed above, the function describing the pre-charge is stepwise.

Resistor type	N/A
Resistance	N/A
Continous power rating	Same as motor controller, 14.4 kW
Overload power rating	Same as motor controller, 54kW
Voltage rating	150VDC
Cross-sectional area of wire used	0.001275 inˆ2 (18 AWG)

Table 8: General data of pre-charge resistor

Relay type	Omron Electronics, G5CA series, G5LE-14-DC12 part no.
Contact arrangement	SPDT
Continous DC current	10A
Voltage rating	125VDC
Cross-sectional area of wire used	0.001275 in^2 (18 AWG)

Table 9: General data of the pre-charge relay

2.9.3 Position in Car

The pre-charge circuit is located internal to the Sevcon motor controllers. The position of the controllers in the vehicle is discussed at length in section 5.1.3 and first shown in figure 47.

2.10 Discharge Circuitry

2.10.1 Description

When the car shuts down, there are still reserves of energy in the tractive system that can be harmful to the driver or team members conducting maintenance. The discharge circuit dissipates the capacitance found in the vehicle after TS shutdown. When the shutdown circuit is opened, the normally open discharge relay will close a switch and discharge the tractive system with a 220 Ωpower resistor.

2.10.2 Wiring, Cables, Current Calculations, Connectors

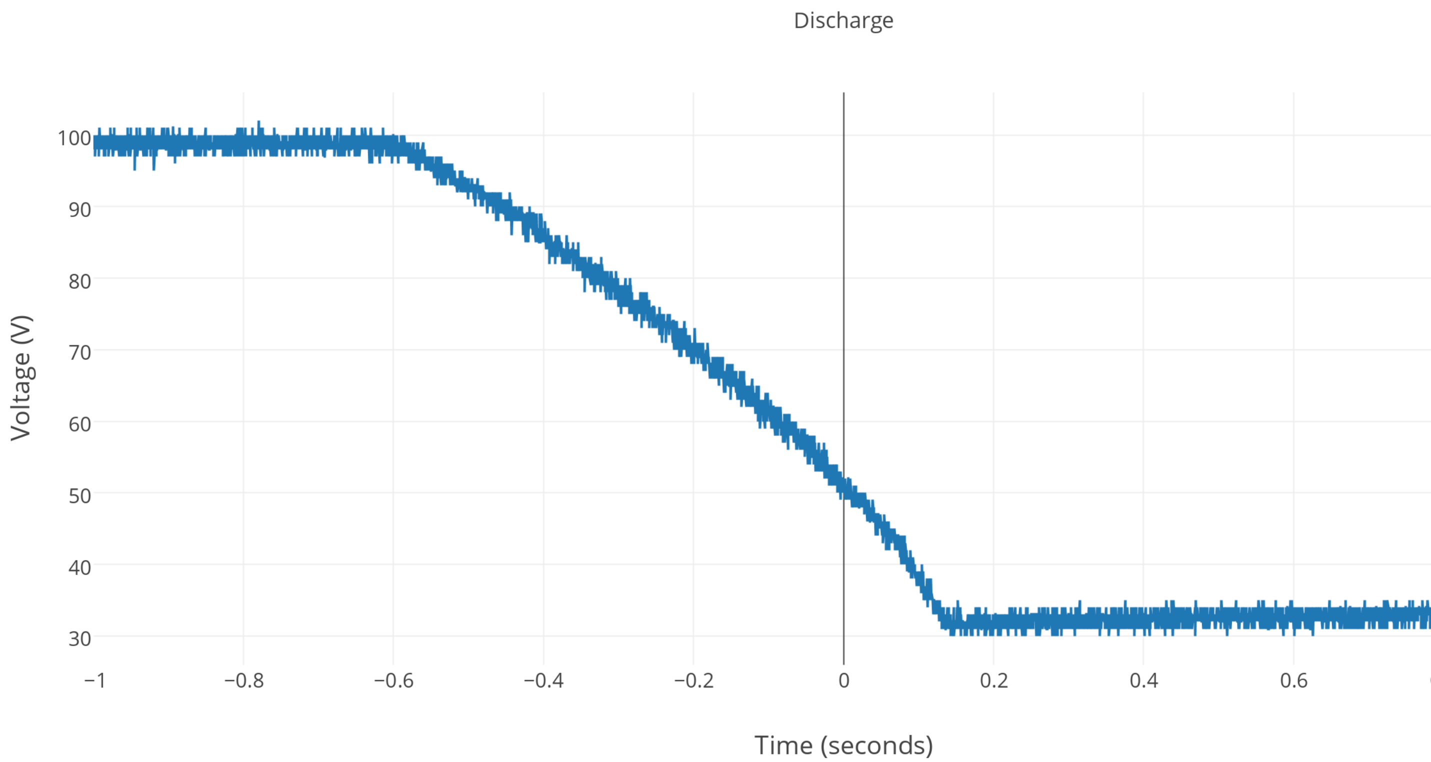

Figure 17: Schematic of the discharge system

Since the capacitance of our motor controllers was unknown, it was determined by the team experimentally.

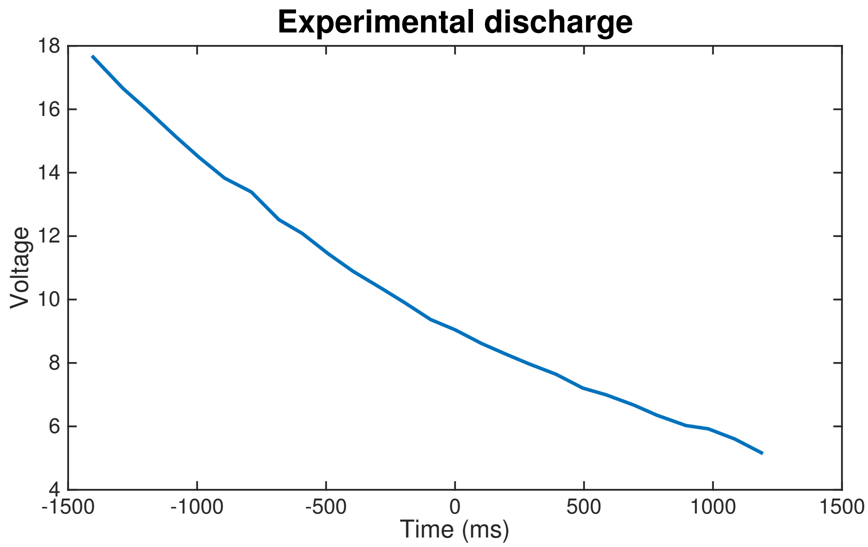

Figure 18: A single motor controller being discharged across a known resistor.

That experimental discharge in figure 18 starts at 17.65 volts at a time of -1403 milliseconds. Given that this is an RC parallel circuit, we expect to loose 63% of the charge in the first RC time constant. The graph hits $17.56V * 0.37 = 6.53V$ at 773.5 milliseconds, or in 2.1765 seconds. Given that we know we were discharging with an 846Ω resistor, we can calculate the internal capacitance of the motor controller.

$$RC = 2.1765s \tag{7}$$

$$C = \frac{2.1765s}{846\Omega} \tag{8}$$

$$C = 2.57mF \tag{9}$$

With that calculation, we can estimate that our two motor controllers will have a combined capacitance of $5.14mF$ that the discharge circuit needs to handle.
With a 220Ω discharge resistor, we can calculate how the discharge will progress over time using the natural response of an RC circuit,

$$V(t) = V_0 * e^{-t/RC} \tag{10}$$

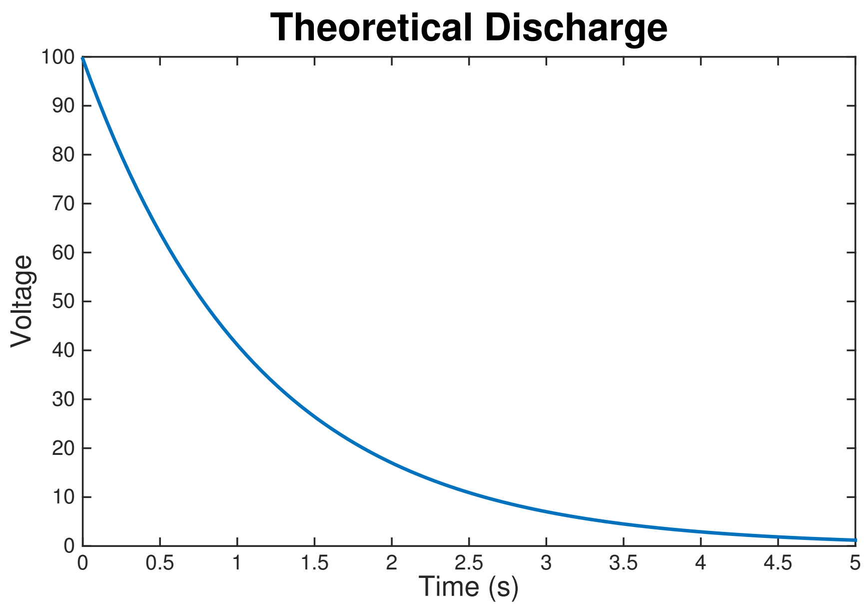

Figure 19: The theoretical discharge of both motor controllers across the resistor specified in table 10. This calculation shows that we should able to discharge to well under 60V DC in 5 seconds.

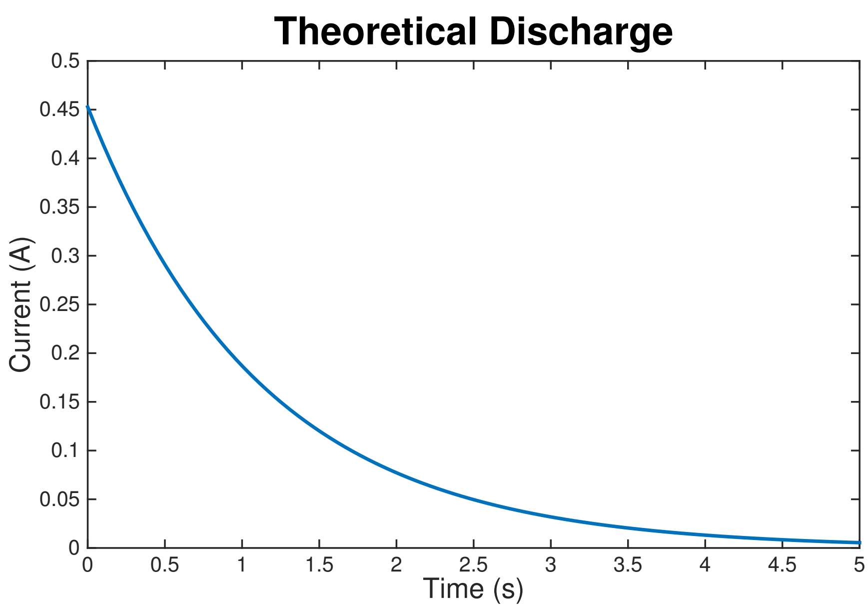

Figure 20: The current of the theoretical discharge.

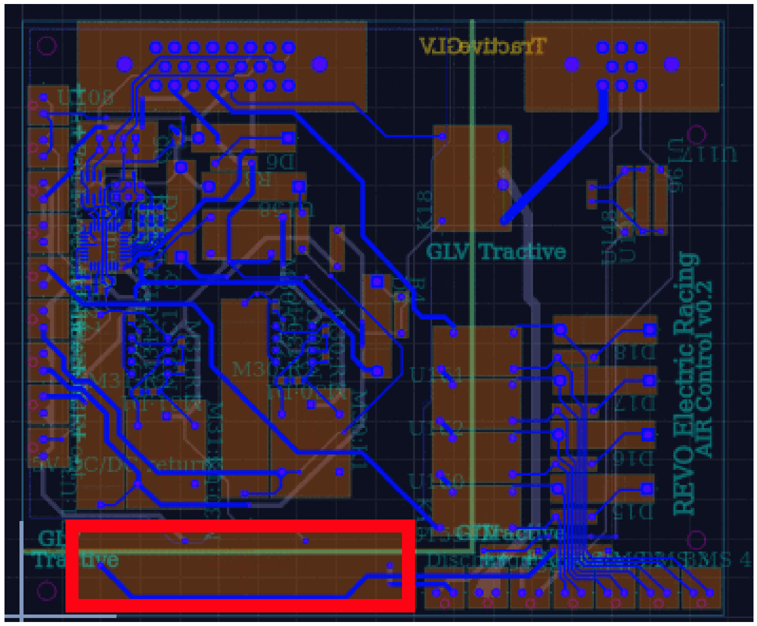

Figure 21: The discharge relay is pointed out in the red box, on the PCB containing most of the accumulator wiring (called AIR control board). The resistor will be located right next to the PCB, at the same height of the accumulator.

Resistor type	WH Series, part no. WH50-220RJI
Resistance	220 Ω
Continuous power rating	50W
Overload power rating	See figure in appendix
Maximum expected current	0.45 A
Average current	0.1 A
Cross-sectional area of the wire used	0.001275 in^2 (18 AWG)

Table 10: General data of the discharge circuit

At peak power, the discharge resistor should be dissipating 44.82 W. The power rating of the resistor is higher than the peak power it will see. Further resistor and relay information can be found in section 11.

2.10.3 Position in Car

The circuit board containing the discharge circuit will be housed inside the accumulator, above and isolated from the battery cells.

2.11 HV Disconnect (HVD)

2.11.1 Description

We will be using an Anderson Power Products SB Smart VEH-G12 HVD (P/N 115158G12 Vehicle Side and P/N 115158G11 Outboard Side) as our high voltage disconnect, provided by Zero Motorcycles. The part we have in-hand also has a rubber grip on the outboard side of the HVD, which gives the user a greater purchase on the HVD, as shown in Figure 22.

2.11.2 Wiring, Cables, Current Calculations, Connectors

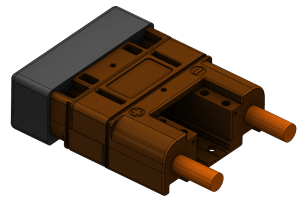

Figure 22: Anderson Power Products SB Smart VEH-G12 HVD

The connector is rated for 600V and 230.0A on the primary contacts. Because the HVD has an interlock connection with the shutdown circuit, when it is opened it shuts down the TS system by opening the shutdown circuit.

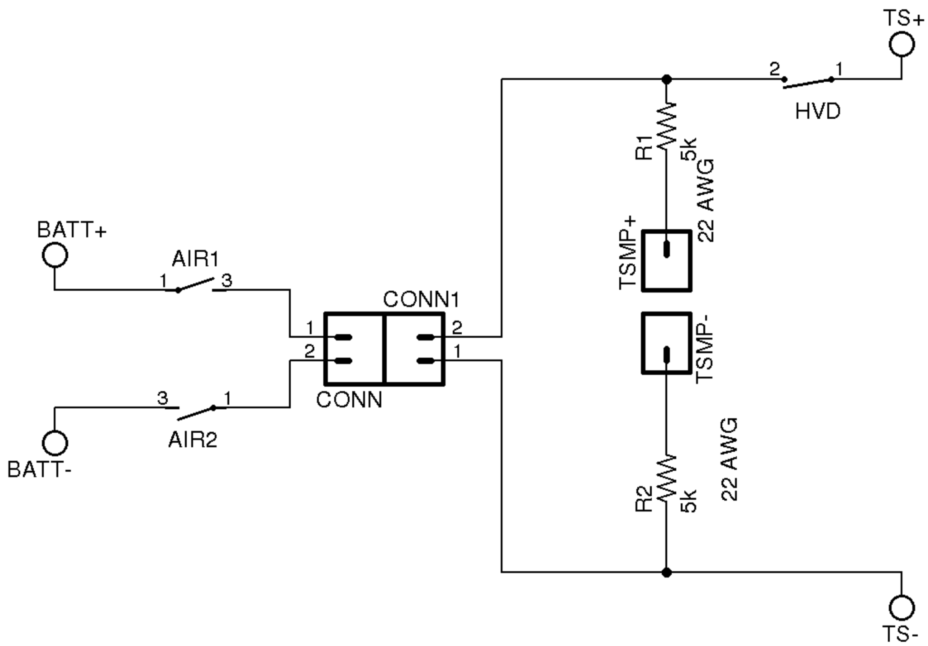

Figure 23: Schematic of primary tractive system connections

2.11.3 Position in Car

The HVD comes out of the accumulator, as it is in-line with the tractive system high side wire. In figure 24, it is the only non-shaded part, with the view being from the back right of the vehicle. The HVD will be clearly indicated and located higher than 350mm from the ground, as per EV 4.7.1.

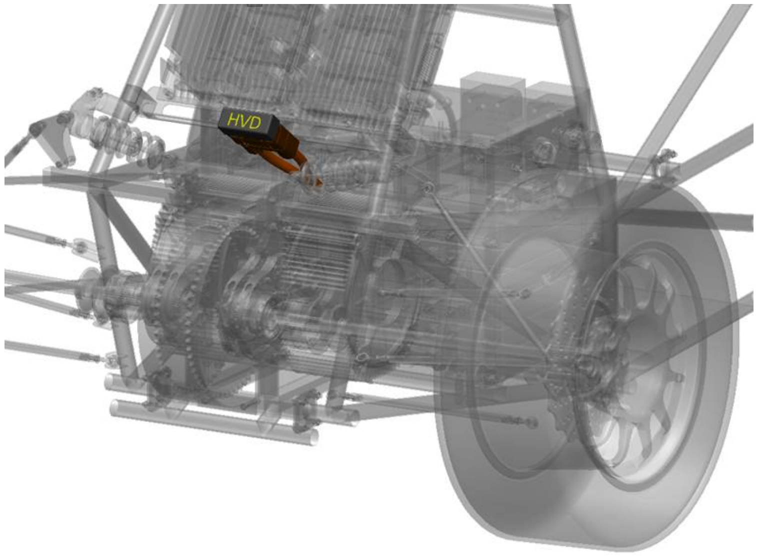

Figure 24: Position of the HVD in the vehicle. It is located in line with TS+, and is attached to the accumulator in the back of the vehicle.

2.12 Ready To Drive Sound (RTDS)

2.12.1 Description

The Ready to Drive sound includes a buzzer (Link: Mallory Sonalert Products Inc. SC648ANR), a CAN node, and a relay. The buzzer automatically makes a noise when given power, with the loudness proportional to the voltage. The last step in the startup up sequence will notify the CAN system it is time for the ready to drive sound. Then the corresponding node on the buzzer will close a relay between TS+, after a 2.6 kOhm resistor (5 Watts), and the buzzer for two seconds. The resistor limits the voltage over the buzzer to 48V and the current to 20 mA. The SC648ANR is rated to be 95 dB(A) at 2 ft.

2.12.2 Wiring, Cables, Current Calculations, Connectors

When the shutdown circuit closes and activates the AIRs and the start button has been pushed (while the driver's foot is on the brake), the car is in ready to drive mode. As soon as the car is in this mode, the CAN system will activate the ready to drive sound node to send a positive output that powers the relay for 2 seconds, thus letting the buzzer sound for 2 seconds. This node is also connected to the IMD, and the full schematic can be found in figure 5. The resistor will be current-limiting and act in the place of a fuse.

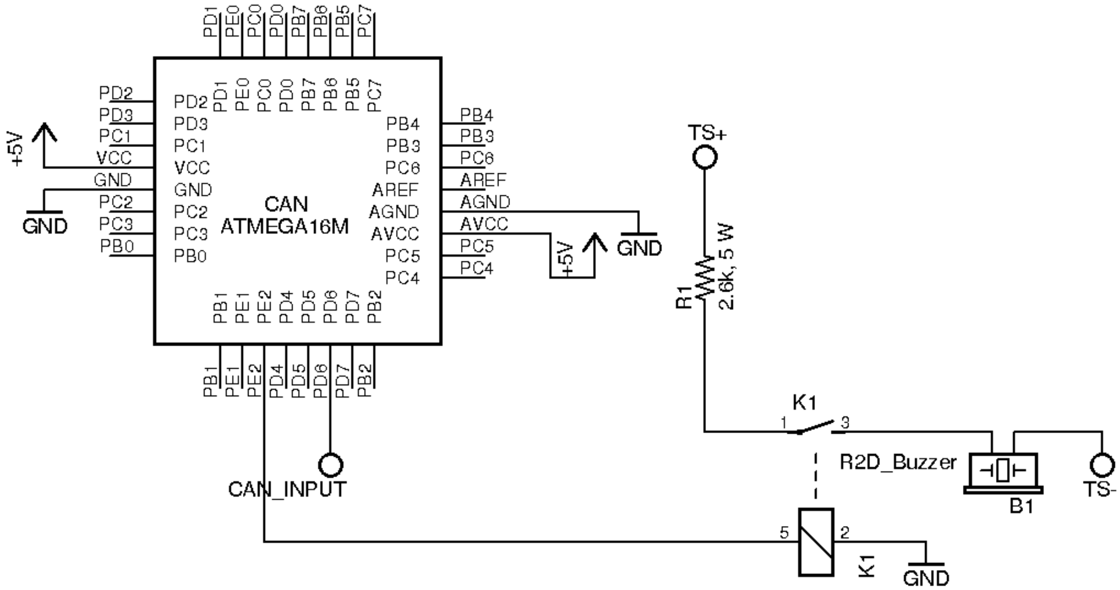

Figure 25: Schematic for the Ready to Drive Sound Buzzer

$$V = I * R \tag{11}$$
$$100 - 48V = 0.021A * R \tag{12}$$
$$R = 2285\Omega \tag{13}$$

$$P = I * V \tag{14}$$
$$P = 0.021A * 52V \tag{15}$$
$$P = 1.09W \tag{16}$$

According to these calculations, a 2.6kΩ 5W resistor will function as a current limiting resistor.

2.12.3 Position in Car

The ready to drive sound will be located in the enclosure shown in Figure 4. The buzzer will be mounted to the exterior and bottom of this enclosure. It must be contained outside of the box so that the buzzer is loud enough and underneath to assist with water proofing of the container.

3 Accumulator

3.1 Accumulator Pack 1

3.1.1 Overview/Description/Parameters

The accumulator comprises 12 Nissan Leaf battery modules, wired in series. Each module comprises four LiMnO2 pouch cells, in a 2S-2P configuration as shown in Figure 27. Each module has a shutdown separator in the middle of each string of cells in parallel (at points MIDPWR1 and MIDPWR2 in section 3.1.3). Each cell has a nominal voltage of 3.75V, resulting in 7.5V per module and 90V total. The modules have alternating positive and negative terminal locations to make bus bar routing more efficient.

Maximum Voltage	99.6 VDC
Nominal Voltage	90 VDC
Minimum Voltage	60 VDC
Maximum output current	Unknown
Maximum nominal current	NDA
Maximum charging current	17 A
Total number of cells	48
Cell configuration	12 2s2p in series
Total capacity	65 Ah at 2C rate, 25 °C
Number of cell stacks	4

Table 11: Main accumulator parameters

The maximum voltage is calculated from the maximum charging voltage, (4.15V per cell), and the maximum charging current is the maximum of the charger.

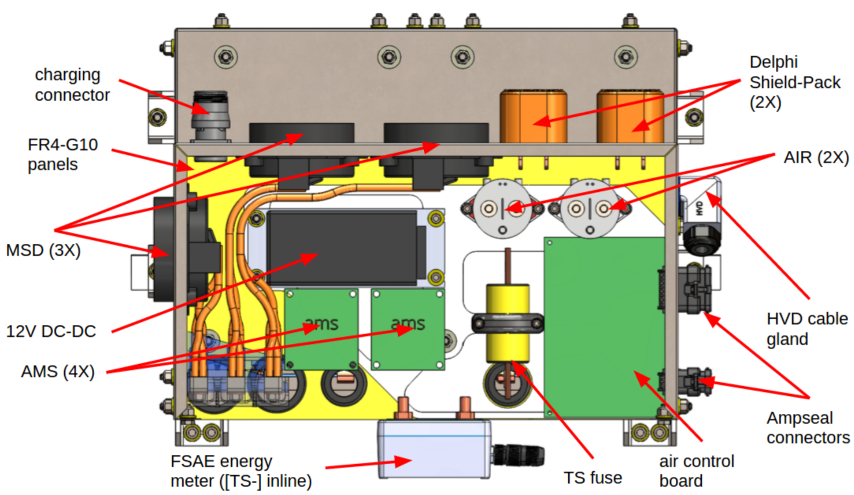

Figure 26: Locations of all major parts within the accumulator.

3.1.2 Cell Description

The cells are laminate type lithium ion cells (LiMnO2), packaged in modules for Nissan Leaf vehicles.

Cell Manufacturer and Type	Automotive Energy Supply Corporation Model E5
Cell nominal capacity	32.2 Ah
Maximum Voltage	4.15V
Nominal Voltage	3.75V
Minimum Voltage	2.5V
Maximum output current	Unknown
Maximum nominal output current	NDA
Maximum charging current	NDA
Maximum Cell Temperature (discharging)	NDA, see below
Maximum Cell Temperature (charging)	NDA, see below
Cell Chemistry	Lithium-ion - Laminate type Cathode/Anode Material: LIMn2O4 with LiNiO2/Graphite

Table 12: Main cell specification

‘ In software, we are restricting the maximum cell temperature (charging) to 50 °C, and the maximum cell temperature (discharging) to 60 °C.

3.1.3 Cell Configuration

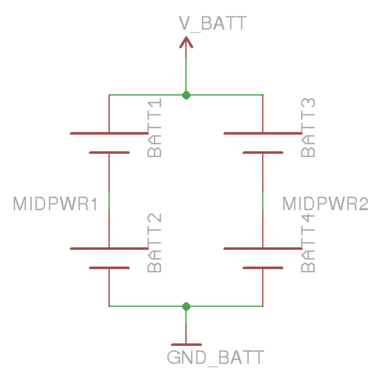

Figure 27: Schematic of a Nissan Leaf Battery Module

As stated in Section 3.1.1, there are 12 modules in series. Each module holds 4 cells which are in a 2s-2p configuration. There is a shutdown separator between parallel cells, which acts as a fuse in over-current conditions. The terminal marked in white in Figure 28 references the point between the two parallel cell strings. The white terminal is the cell interconnection point, as shown in figure 27.

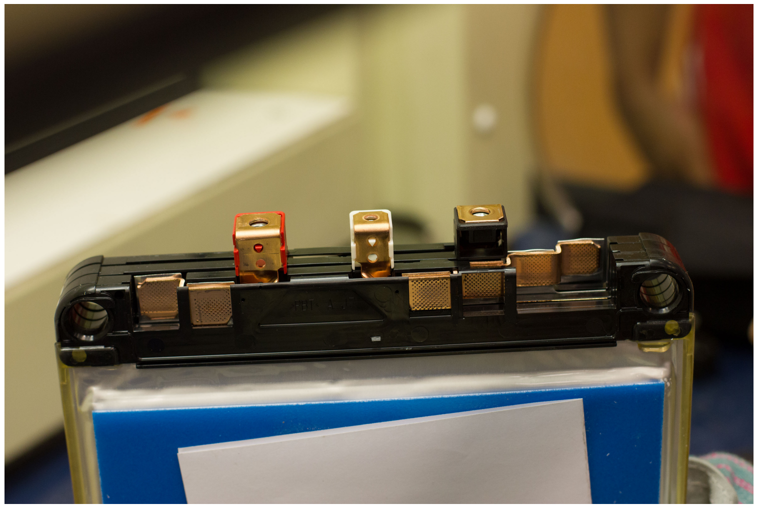

Figure 28: Inside view of a module

Busbars connect the modules in series, as shown in Figure 29. The busbars connecting module to module are copper with a cross-section of 60.5 mm^2, which exceeds the required wire gauge for tractive system lines (2 gauge).

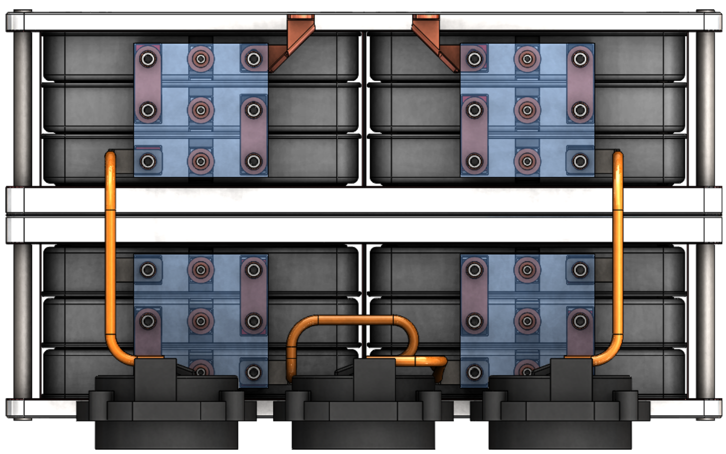

Figure 29: Busbar Routing with MSD Wire Leads

There are 3 maintenance plugs, separating the segments to be less than 6 MJ each. Figure 26 points out the maintenance plugs, shortened as MSD. The connectors are further described in section 3.1.7.

3.1.4 Cell Temperature Monitoring

The temperature of the cells is monitored using 10K thermistors attached to the negative terminals. The middle pole of each module is considered the ground of two cells. Each module's midpoint is measured and one out of three module grounds is measured per accumulator segment. The thermistors are used to form three voltage dividers. When the temperature of the cells increases, the resistance decreases, resulting in less voltage drop across the thermistor. Three analog to digital converters attached to each of the voltage dividers is then used by the Atmega 16M1 used in the CAN system to determine whether the temperature is too high or low. If the temperature is out of range, the shutdown system activates. There is a pull up resistor that pushes the output voltage to 5V if the ADC is a past a certain threshold and 0V otherwise.

Because we are monitoring the negative terminals of half of the cells in each module, we are monitoring 50% of the total cells.

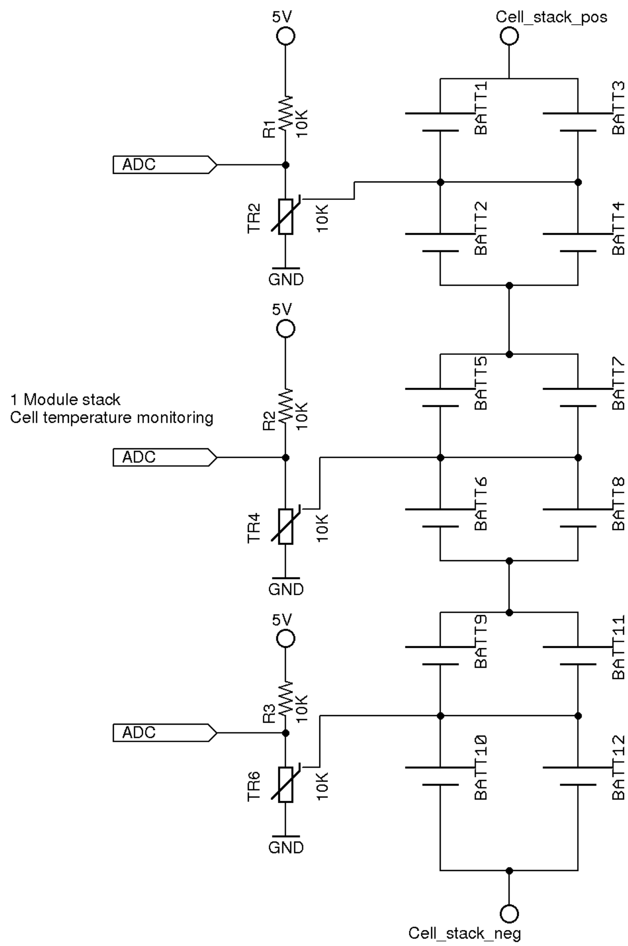

Figure 30: Schematic, (1) Module Cell Temperature Monitoring

3.1.5 Battery Management System

The AMS monitors 6 groups of cells in series. Each module contains 4 cells, 2 series x 2 parallel, so each AMS monitors 3 modules, or 12 cells (6 series x 2 parallel). There are 4 AMS boards. Each AMS board is coupled to a cell breakout board, which includes 3 thermistors and bolts to the power terminals of three modules, as shown in Figure 29 (blue circuit boards). The purpose of the cell breakout boards is to help manage wiring inside the accumulator. The cell breakout boards will have compression limiting copper pads at the terminal bolts and will be spaced above the bus bars using copper washers.

The AMS shunts 3 A when the cell gets above 4.0 V. The AMS opens a relay in line with the shutdown circuit if any cell drops below 2.5 V or above 4.15V. The AMS opens a relay in line with the shutdown circuit if any cell gets above 60 °C.

CAN communication from the board is isolated via a TI ISO1050DUBR (isolated CAN transceiver), with board cutouts to maintain proper clearance and creepage. Only CAN communication is used to have the information from each AMS relayed to the rest of the system, and the boards are otherwise independent of each other. On each cell-top board, there are 7 surface mount Bel C1Q 3 A fuses. (Lowest voltage reference, and top voltage of each of 6 cells.) The relays which allow the AMS to control the shutdown circuit provide isolation between the AMS and the GLV system, as well as the isolated CAN transceivers.

Please see Figure 69 on the following page for the schematic of one of the battery management system boards.

Figure 31 shows the CAD of one AMS PCB. The AMS boards only communicate through the CAN system. Close ups of this PCB in figure 32 show the protective distances between the components of the tractive system and low voltage. Figure 69 in the appendix is to refer to the schematic of the AMS.

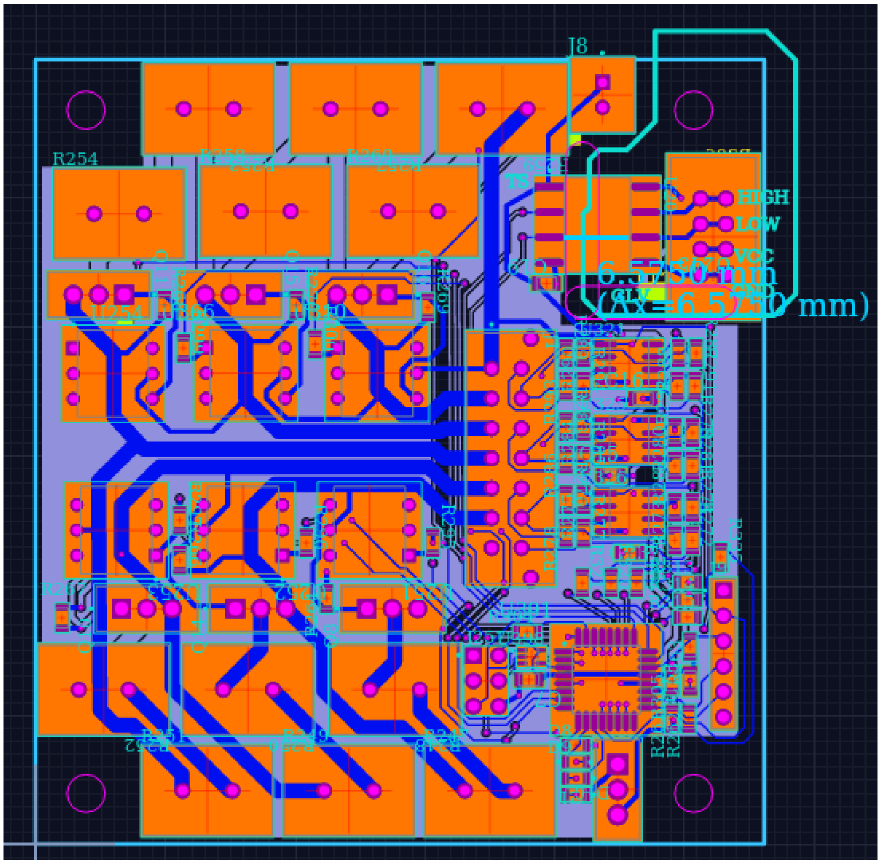

Figure 31: CAD of 1 AMS board (all identical). Cyan polygon indicates GLV voltage, and the δx measurement is the distance between TS and GLV.

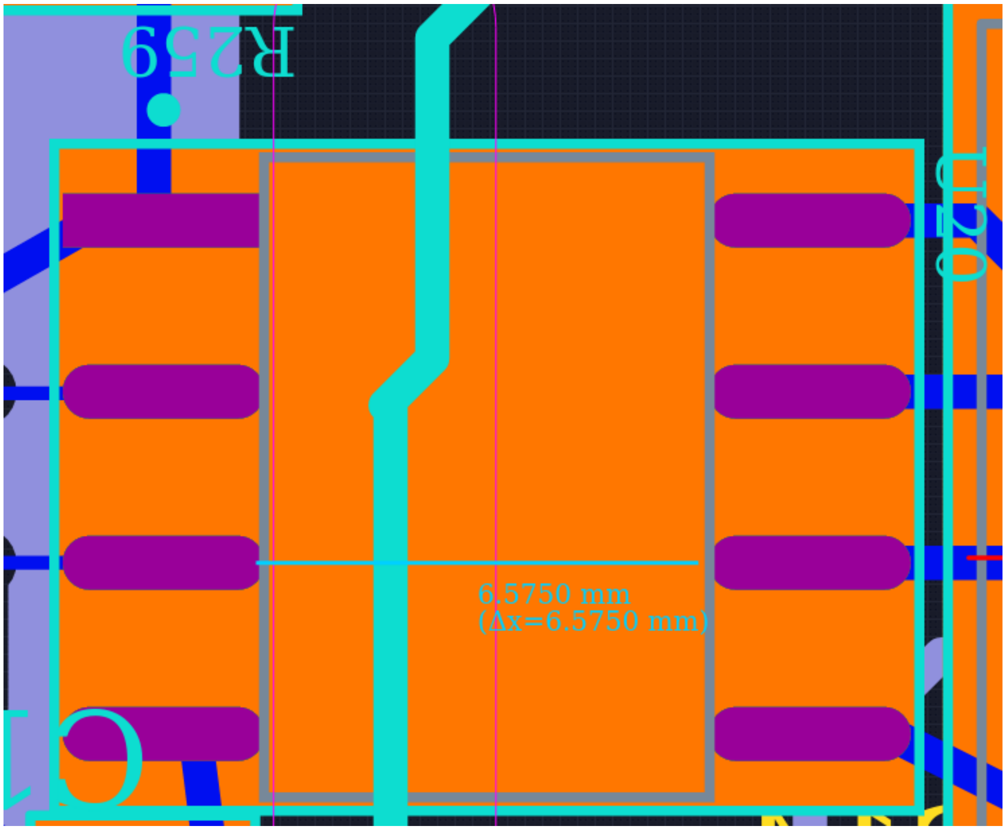

Figure 32: Detail of BMS PCB where the minimum over surface distance (6.4 mm) are met. Distance between TS and GLV is shown to be 6.57 mm (over surface)

Voltage and temperature data is relayed to the AMS by the cell breakout boards discussed earlier in this section. The cell top boards are electrically identical, but have two different layouts to accomodate which side of the accumulator they are on. There is a left hand side, figure 34 and right hand side, figure 35. The cell breakout board contains fuses on all sensing lines, detailed in Figures 33 - 34.

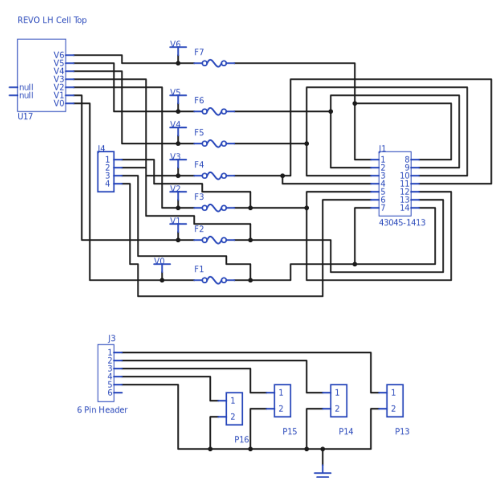

Figure 33: Schematic of Cell Breakout Board Connecting to the AMS

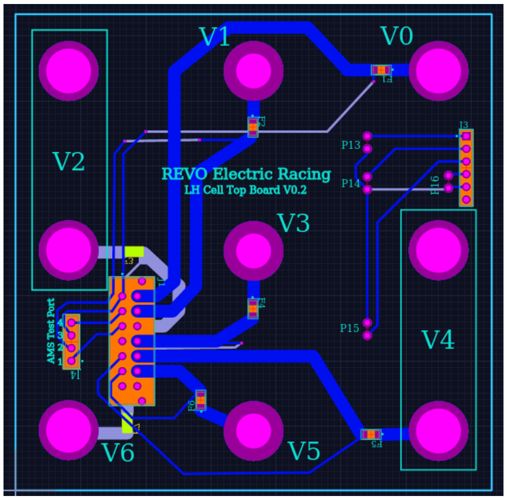

Figure 34: Cell Breakout Board PCB Layout for the left hand side Note the fuses labeled with "F" and then a number. There is only TS voltage on this PCB.

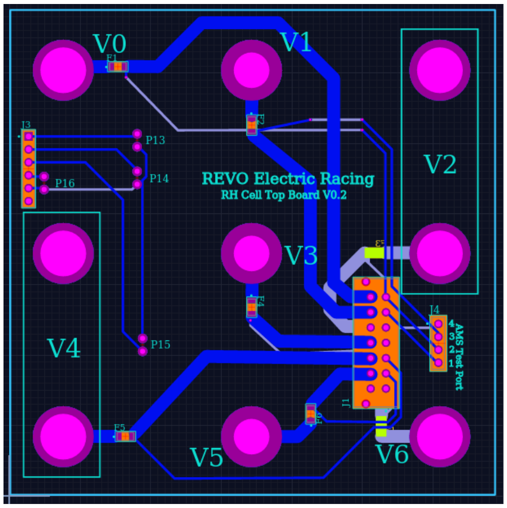

Figure 35: Cell Breakout Board PCB Layout for the right hand side Note the fuses labeled with "F" and then a number. There is only TS voltage on this PCB.

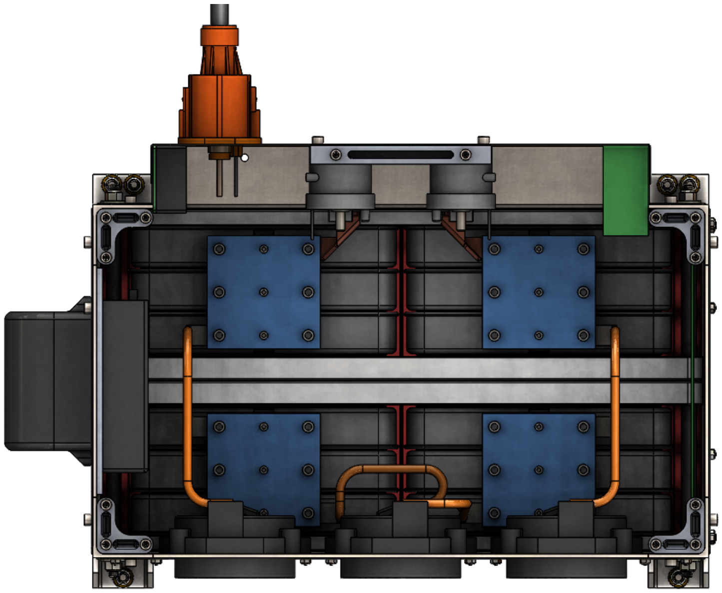

Figure 36: CAD of the location of the cell-top boards in the accumulator

3.1.6 Accumulator Indicator

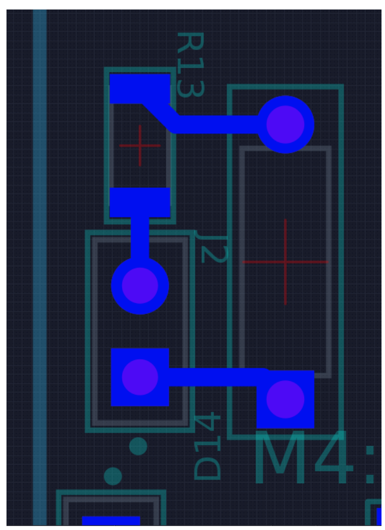

Figure 37: Detail of the Accumulator Indicator PCB

As shown in Figure 37, J2 connects the accumulator indicator, D14, to a DC-DC converter that runs off tractive system voltage and supplies the GLV 12V system. R13 is a 220 Ohm resistor to limit current. The DC-DC converter supplies 12V. The calculations are as follows, assuming a forward voltage drop of the LED to be 2V:

$$10V = I * 220\Omega \tag{17}$$

$$I = 45mA \tag{18}$$

A 22 gauge wire will be used to connect the PCB to the DC-DC converter.

3.1.7 Wiring, Cables, Current Calculations, Connectors

The high current (motor, motor controller) wires used for the tractive system will be as described in table 24. The low current (IMD, Lights DC-DC, GLV DC-DC and ready to drive sound) TS connections will be made with the wire described in table 13.

Wire type	CnC Tech, 22 AWG
Current rating	7A
Cross sectional area	0.326 mmˆ2
Maximum voltage	600V
Temperature rating	120 °C
Wire connects the following components:	TS V to GLV DC-DC converter, TS V to IMD HV input, TS V to ready to drive sound buzzer

Table 13: Wire data of the company: CnC Tech, 0.326 mm^2

We will use OEM maintenance plugs provided by General Motors. As shown in Figure 38, these maintenance plugs, known internally as Manual Service Disconnects (MSD's), comprise a panel-mounted plastic housing (black) and a plastic plug (orange). The plug must be twisted and then pulled in two distinct steps, which disengages the copper bus-bar, contained in the orange plug, from spring-loaded contacts contained in the black housing. There will not be any fuses in the MSDs. General Motors will also be crimping custom length leads onto these MSD's for our vehicle. The leads are 40 mm^2 in cross-section, not including insulation. Each MSD also contains a two-pin interlock, as described in Section 2.6. To the best of our knowledge, these MSD's comply with EV 3.3.3. Additionally, the spring-loaded contacts located in the black housing are encapsulated in plastic, providing protection from shorting and accidental contact.

Figure 38: Manual Service Disconnect (Maintenance Plug)

3.1.8 Accumulator Insulation Relays (AIR)

We will use Kilovac EV200 relays as accumulator insulation relays. They will be paired with economizer circuits to draw less current during normal usage. The relay requires a 12 V control signal, and is rated for 500 A. Figure 15 shows the schematic location of the economizers and the AIR's.

Relay Type:	Normally Open
Contact arrangement	SPST-NO-DM
Continuous DC current rating	500A
Overload DC current rating	2000A
Maximum operation voltage	900VDC
Nominal coil voltage	12VDC
Normal Load switching	See figure
Maximum Load switching	See figure

Table 14: Basic AIR Data

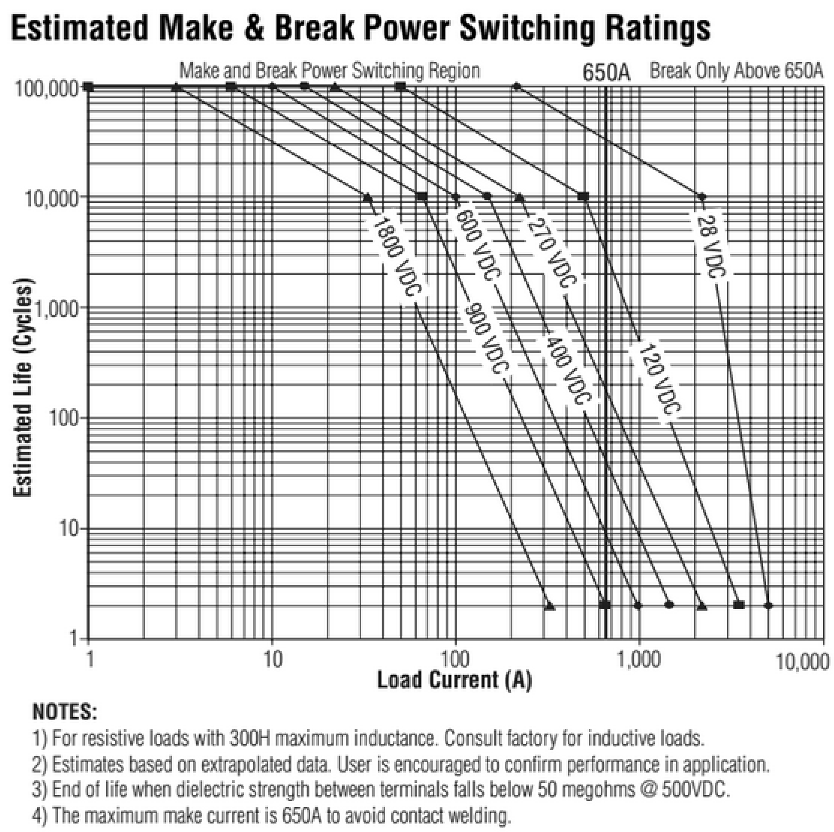

Figure 39: Load Switching detail from Accumulator Indicator Relay datasheet

3.1.9 Fusing

Fuse manufacturer and type:	Littledfuse, SPF Series (SPF-004)
Continuous current rating	4A
Maximum operating voltage	1000 V
Type of fuse	Fast acting
I2t rating	@10kA: 76.270, @20kA: 80.254
Interrupt Current (max. current at which the fuse can interrupt the circuit)	20 kA

Table 15: GLV fuse, type

Fuse manufacturer and type:	Littledfuse, MINI Series (MIN2BP)
Continuous current rating	2A
Maximum operating voltage	32 V
Type of fuse	Fast acting
I2t rating	2.8 A2s
Interrupt Current (max. current at which the fuse can interrupt the circuit)	1000A at 32 VDC

Table 16: GLV 12V fuse, MIN type

Fuse manufacturer and type:	Littelfuse, MINI Series (MIN2BP)
Continuous current rating	2A
Maximum operating voltage	32 V
Type of fuse	Fast acting
I2t rating	2.8 A2s
Interrupt Current (max. current at which the fuse can interrupt the circuit)	1000A at 32 VDC

Table 17: Shutdown system fuse, MIN type

Fuse manufacturer and type	Littelfuse, 251/253 Series
Continuous current rating	1 A
Maximum operating voltage	125V
Type of fuse	Fast acting
I2T rating	0.405 A2s
Interrupt Current (max.,current at which the fuse can interrupt the circuit)	300A at 125VDC

Table 18: Fuse to the IMD, TSMPs and light DC-DC converter, 251/253 Series

Fuse manufacturer and type	Ferraz Shawmut, Semiconductor AC series (A15QS)
Continuous current rating	7A
Maximum operating voltage	150VDC
Type of fuse	Fast acting
I2T rating	0.011 at 150 VDC and 10ms
Interrupt Current (max.,current at which the fuse can interrupt the circuit)	100kA

Table 19: Fuse to the keyswitch v+

Fuse manufacturer and type:	Bussmann, LPJ type
Continuous current rating	175A
Maximum operating voltage	600 V
Type of fuse	Time delay
I2t rating	None listed, see figure 40
Interrupt Current (max. current at which the fuse can interrupt the circuit)	300 kA

Table 20: Tractive system main fuse, LPJ type

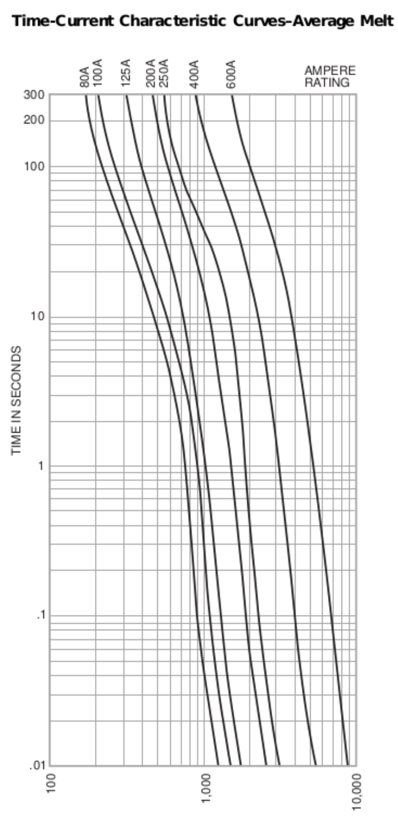

Figure 40: TS main fuse (175A) Time-Current information

All wire ampacity ratings are according to the Power Stream's Wire Gauge chart, located in the appendix, Figure 83.

Location	Wire Size	Wire Ampacity	Fuse type	Fuse rating
TS Main fuse (before HVD, on pos pole)	2 AWG	181A	LPJ type	175A
TS+ to GLV DC-DC converter	22 AWG	7A	SPF fuse	4A
GLV 12V+	22 AWG	7A	MIN fuse	2A
Shutdown pos pole	22 AWG	7A	MIN fuse	2A
TS+ to IMD, TSMPs TSAL's DC-DC converter	22 AWG	7A	ABC fuse	1A
GLV 12V to 5V regulator (CAN system)	22 AWG	7A	ABC fuse	1A
Keyswitch, in parallel with TS voltage	18 AWG	16A	AC fuse	7A
Cell to BMS x28	PCB trace	Trace ampacity: 7.6 A (open air)	CIQ Fuse x28	3A

Table 21: Fuse Protection Table

3.1.10 Charging

Charger Type:	Delta Q Technologies QioQ 1000 Series
Maximum charging power	70.55 W
Maximum charging voltage	4.15V
Maximum charging current	17.0A
Interface with accumulator	CAN-Bus
Input voltage	125VAC or 250VAC
Input current	13A@125VAC or 10A@250VAC

Table 22: General Charger data

This UL-listed charger supplies constant current at 17.0A until cell voltages reach 4.15V. Then, constant voltage is supplied at 4.15 V per cell, summing to 99.6V, until the current tapers to 2.0 A.

The charger will indicate complete on its LED display when the battery voltage reaches 4.15V per cell, however it will continue charging until it finishes both stages.

The accumulator will only be charged on the charging cart. This cart has not yet been specified or designed. It will be able to support the full weight of the accumulator and only move when a dead man's switch is activated.

The accumulator cart will contain a specialized shutdown circuit that allows the accumulator to be charged through the main pack connector. The AMS will be active during charging and have the ability to open the AIRs and stop charging in the event of dangerous battery conditions. This shut down circuit will contain a separate IMD, an emergency stop, and an interlocking connection between the charger and accumulator. The separate IMD used is also the IR155-3204 from Bender, the same IMD used on the car.

Figure 41: DeltaQ 96V QUIQ ICON charger

3.1.11 Mechanical Configuration/Materials

The accumulator mechanical configuration presented in this document was designed under the assumption that the Nissan module casings were not electrically isolated from the cells. However, after tearing down a module, we found that the casing is completely insulated from the cells and therefore, the design of the accumulator is likely to change.

As shown in Figure 42, the accumulator frame comprises a 1/8" thick welded angle iron frame with panels meeting the minimum material requirement given in EV 3.4.6. Figure 44 shows an exploded view of a half-pack: six cells bolted into 3/4" polycarbonate brackets with 5/16" bolts. Two half-packs slide into the accumulator frame and are bolted into the frame with 5/16" SAE Grade 8 threaded rod and locknuts. Figure 43 shows a cutaway of the bolt stackup for the two half-packs. 4130 steel sleeves limit the compression of the threaded rods bolting the entire pack together. Finite element analysis allowed us to prove structural integrity in 20G vertical and 40G lateral load conditions.

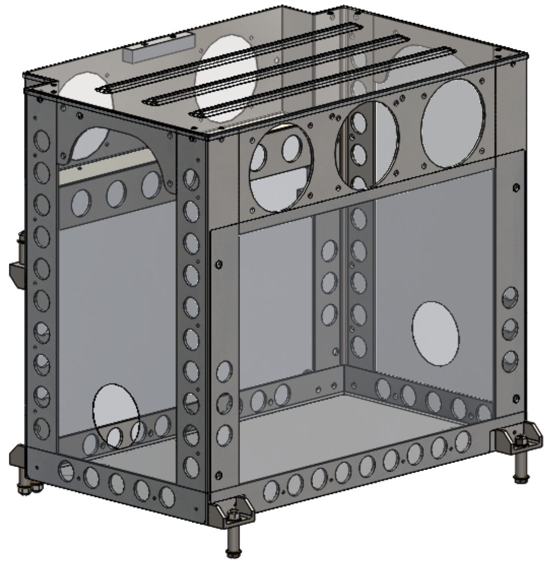

Figure 42: Accumulator Frame

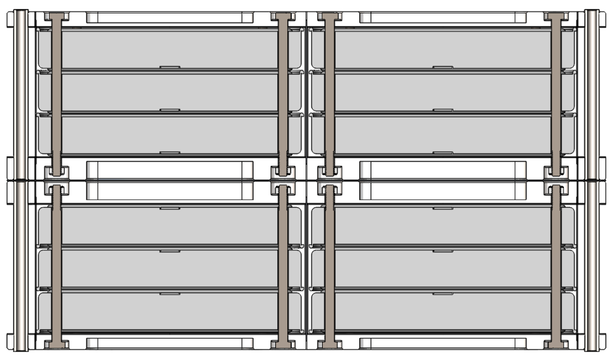

Figure 43: Cell Mounting Cutaway

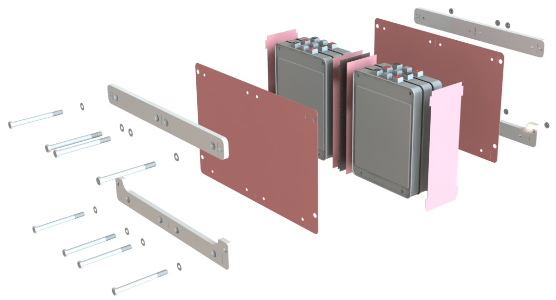

Figure 44: Cell Mounting Exploded

3.1.12 Position in Car

The accumulator is located behind the driver, under the main roll hoop, and is entirely encapsulated by the primary frame structure.

3.2 Accumulator Pack 2

There will only be one accumulator for the vehicle, as described in Section 3.1

4 Energy Meter Mounting

4.1 Description

The energy meter is a tool made by FSAE to calculate energy use during competition. The meter checks that the voltage is within the rule's ranges, the total power used is not over the maximum limit of 80 kW, and calculates the amount of energy used. The energy is calculated as the time integrated value of the measured voltage multiplied by the measured current logged by the Energy Meter, as per rule EV 4.9.

4.2 Wiring, Cables, Current Calculations, Connectors

The energy meter will measure current in the tractive system by being connected in series with the HV- line. It measures voltage in the system with a connection to HV+. The low power data collection systems inside of the Energy Meter are powered using the GLVS.

4.3 Position in Car

The energy meter will be integrated with the junction box described in Section 2.11. This is an ideal location for the energy meter because it can be securely mounted in a waterproof location and is proximal to all of the necessary connections.

5 Motor Controller

5.1 Motor Controller 1

5.1.1 Description, Type, Operation Parameters

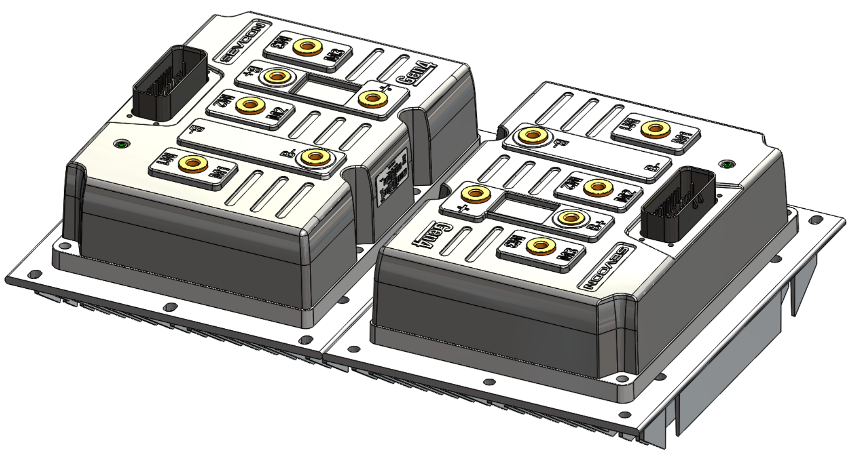

Figure 45: Sevcon Gen 4 Size 4 motor controllers

There are two of the same type (Sevcon Gen 4 Size 4, as described in Table 23) of motor controller that will control the speed of the vehicle. The motor controller, which is used commercially in the motorcycles of Zero Motorcycles, responds to a CAN connection for throttle information and then delegates the power to the motor. The motor controller comes with extra capabilities that will be used for other systems, like the precharge system. The motor controller does not provide isolation between its low and high voltage components, so all low voltage signals to the motor controller will be individually isolated.

Motor Controller type	Sevcon Gen 4 Size 4
Maximum continuous power	14.4 kW
Maximum peak power	54 kW
Maximum input voltage	150 VDC
Output voltage	Same as input voltage
Maximum continuous output current	120A
Maximum peak current	420A
Control method	messages through CAN system
Cooling method	Air
Auxiliary supply voltage	24VDC

Table 23: General Motor Controller data

5.1.2 Wiring, Cables, Current Calculations, Connectors

Wire type	Welding Cable 2 AWG
Current rating	181 A
Maximum operating voltage	600 V
Temperature rating	-49...105 °C

Table 24: Wire data of the company: Electric motor sport, 0.052 in^2

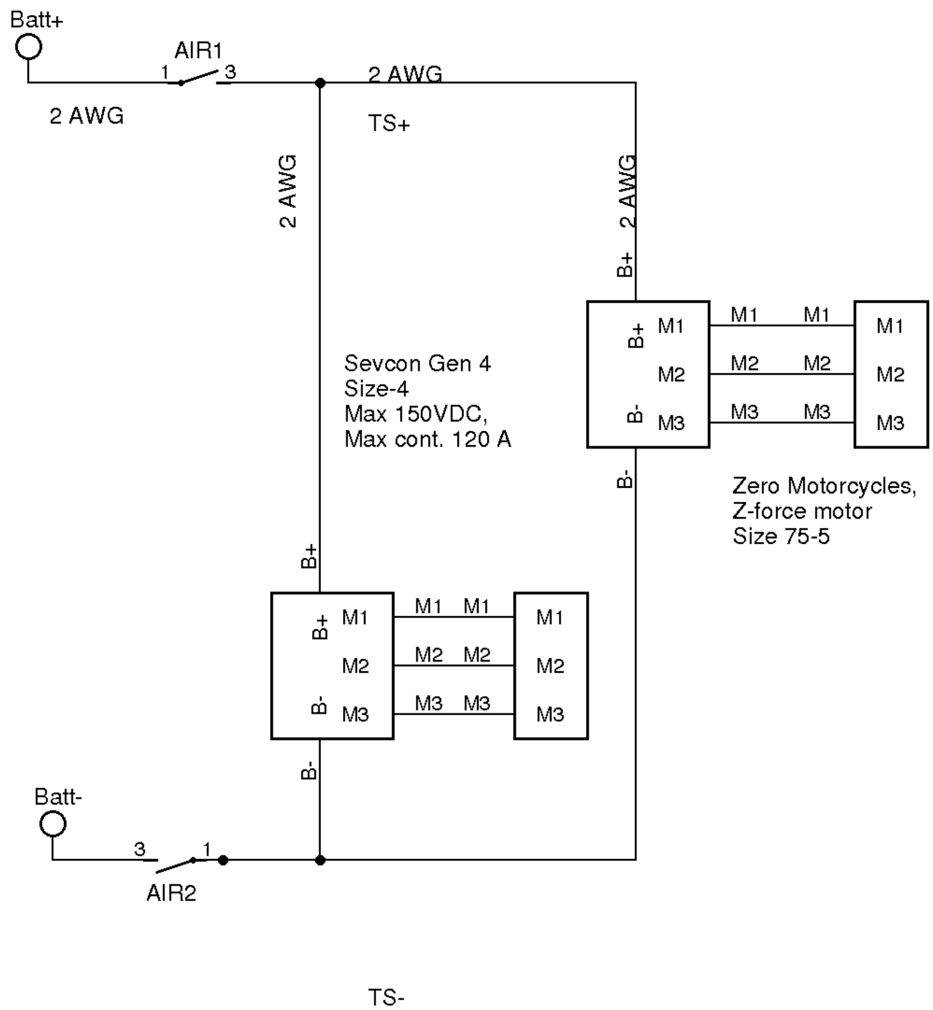

Figure 46: Schematic of the motor and motor controllers, in the tractive system

Both motors will follow the configuration in Figure 46, parallel to the TS system. All high current wire gauges will be 2 AWG: the wire before the split to the motor controller, the wire to each controller, and the wire to each motor. There is a 175A fuse located before the AIRs, which is smaller than the ampacity of 2 AWG wire according to appendix section 83.

5.1.3 Position in Car

The motor controllers are located in the rear of the car, mounted to the main hoop bracing via steel brackets. This configuration is shown in Figures 47, 48, and 49. The controllers are entirely contained within the envelope of the chassis such that in any rollover attitude, the controllers will not make contact with the ground.

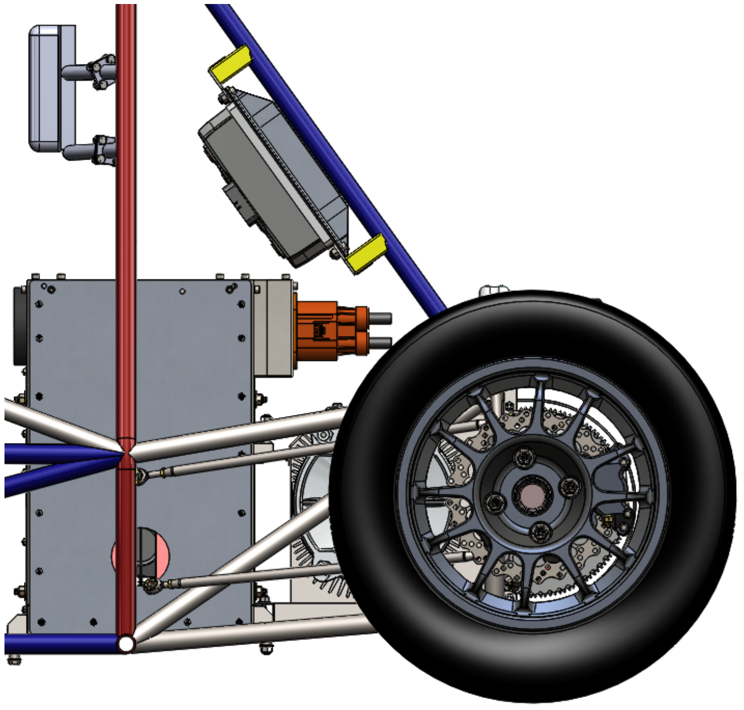

Figure 47: Side view of the motor controllers, mounted

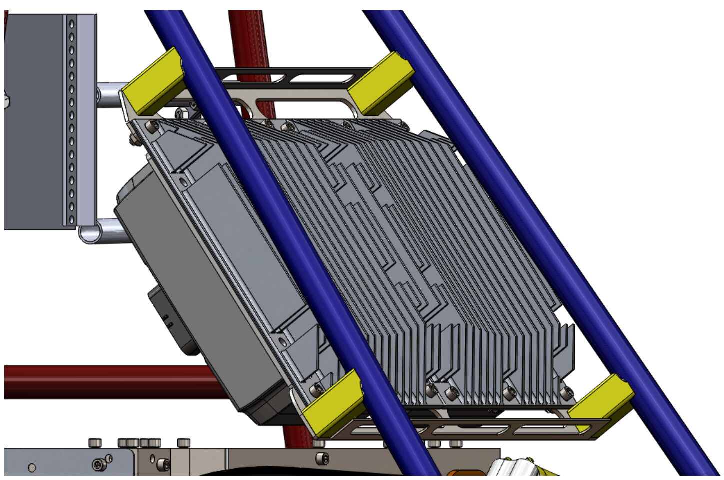

Figure 48: Isometric view of the motor controllers, mounted

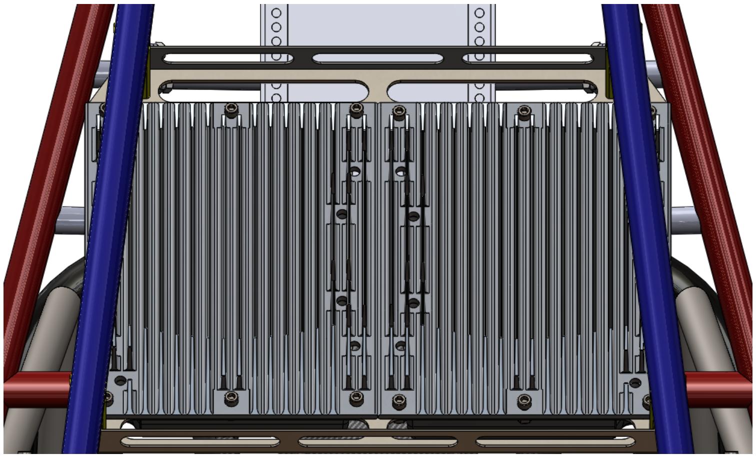

Figure 49: Rear view of the motor controllers, mounted

5.2 Motor Controller 2

The second motor controller used will be exactly identical to that described in the section 5.1. Its wiring is shown in Figure 46.

6 Motors

6.1 Motor 1

6.1.1 Description, Type, Operating Parameters

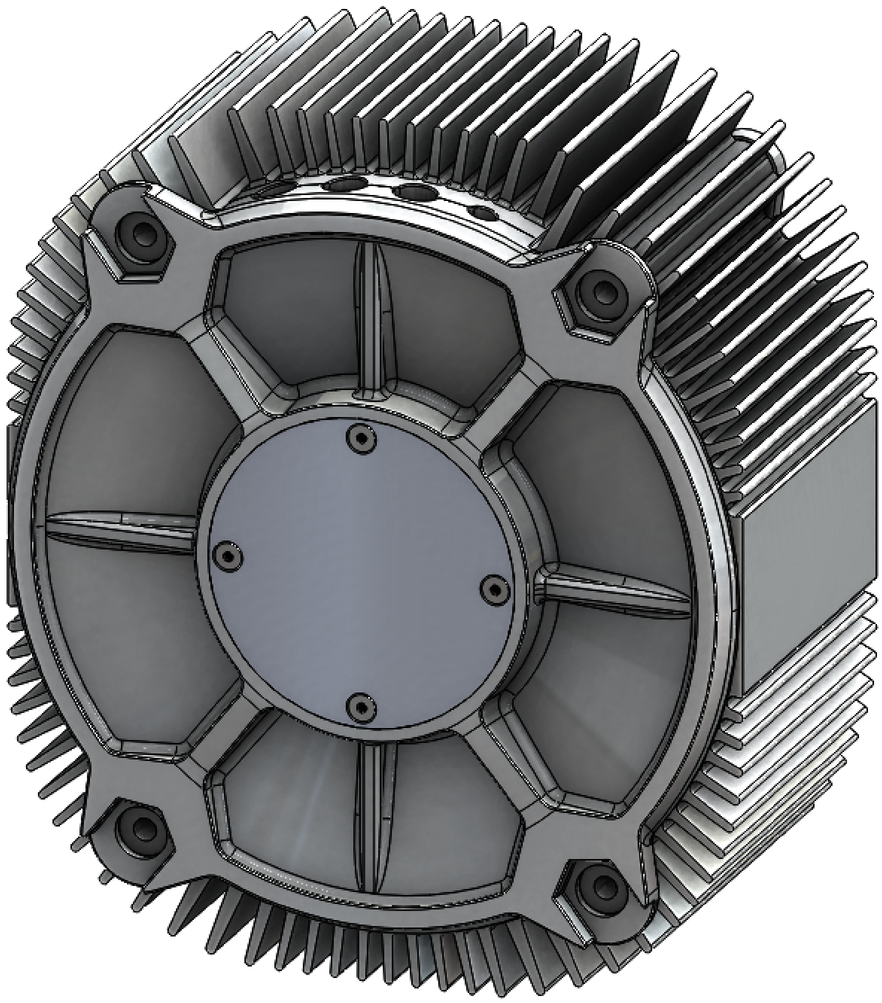

Figure 50: Isometric view of the 75-5 Z-force motor

We will use Zero Motorcycles Z-force BLDC Motors (75-5 Size), shown in Figure 50. They are 3-phase DC brushless motors, compatible with the motor controllers used and described in Section 5.1.

Motor Manufacturer and Type:	Zero Motorcycles, Model # 30-0534
Motor principle	DC Brushless
Maximum continuous power	24.9 kW per motor
Peak Power	41.8 kW per motor
Input voltage	99.6V
Nominal current	250 A
Peak current	420 A
Maximum torque	85 ft-lb
Nominal torque	75 ft-lb
Cooling method	Air

Table 25: General motor data

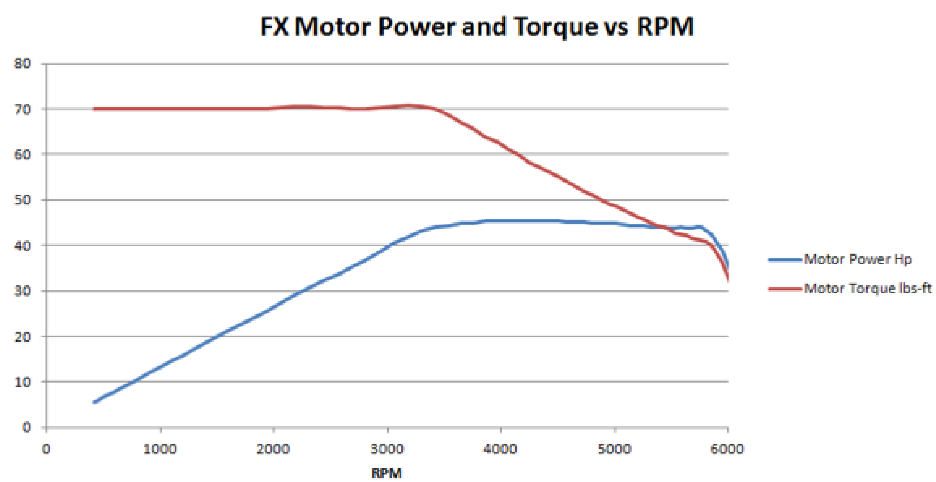

Figure 51

The motor's maximum power and torque were measured by Zero Motorcycles and graphed in figure 51. The accumulator used in the motorcycle for this motor has a lower operating voltage. Assuming a linear relationship between voltage and torque, approximately 85-ft-lbs of peak torque in the flat linear range is expected.

6.1.2 Wiring, Cables, Current Calculations, Connectors

The wiring from the motor controllers will simply connect the M1, M2 and M3 outputs of the motor controllers to the motors' inputs. Refer to Figure 46 for the schematic of motor 1 and motor 2. All power wires will be 2 AWG, described in Section 5.1.2.

6.1.3 Position in Car

The motors will be located behind the driver and accumulator, as shown in figures 53- 54. It is mounted to a steel face plate and a single stage chain transmission.

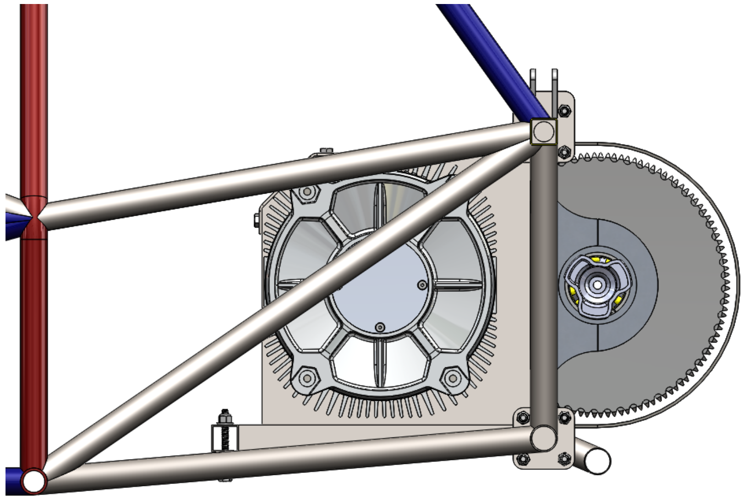

Figure 52: Side view of the motor mount

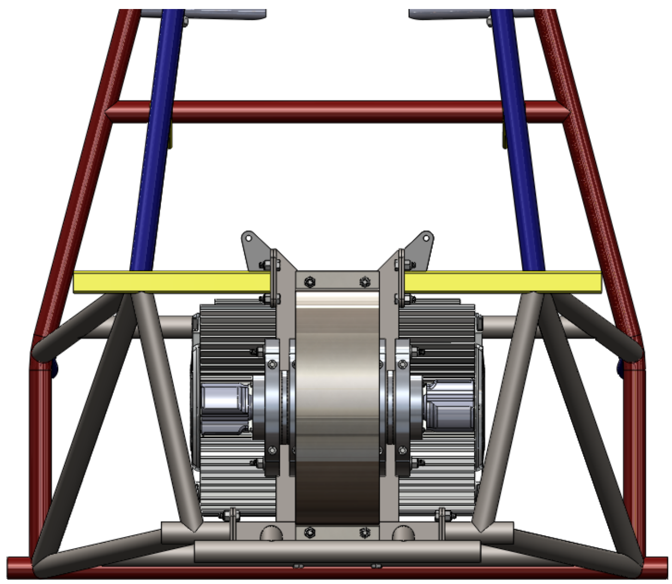

Figure 53: Rear view of the motor mount

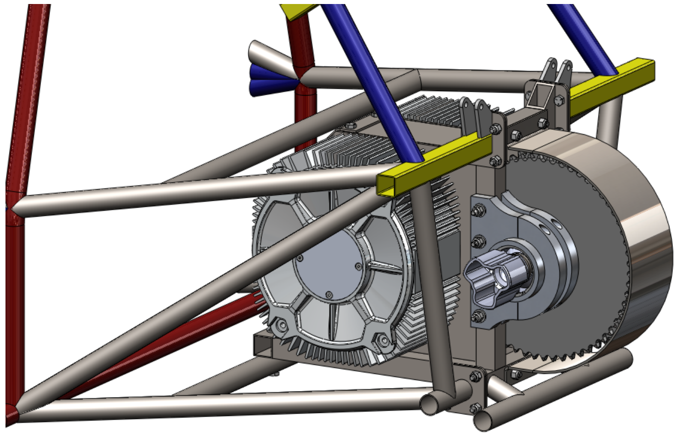

Figure 54: Isometric view of the motor mount

6.2 Motor 2

The second motor used will be exactly identical to that described in section 6.1 and its wiring is also shown in figure 46.

7 Torque Encoder

7.1 Description/Additional Circuitry

Two rotary potentiometers are mechanically housed in one unit from Active Sensors (P/N MHR5621) and mounted to the rotating shaft of the throttle pedal assembly. The use of a single housing eliminates concerns regarding mechanical backlash and misalignment. Each output from the potentiometers will go to a CAN connected atmega16M1, which will compare the two outputs and send a message via CAN bus to the motor controllers with the requested torque.

Torque encoder manufacturer and type:	MHR5621 from Active Sensors
Torque encoder principle	Potentiometer
Supply voltage	5V
Maximum supply current	15 mA
Operating temperature	-55 to 150 °C
Used output	0-5V

Table 26: Torque Encoder data

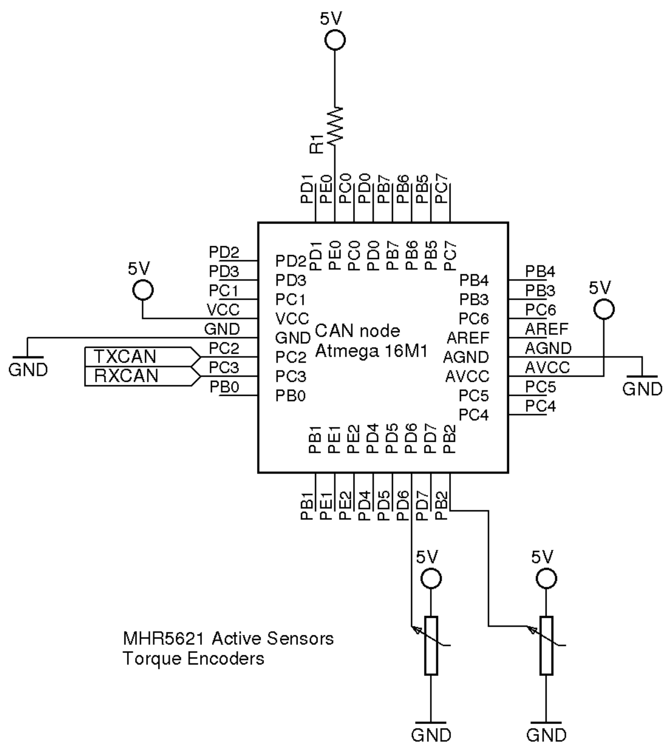

Figure 55: Schematic for the CAN node on the torque encoders

7.2 Torque Encoder Plausibility Check

Two potentiometers are mounted on the torque pedal. A CAN node probes the voltage dividers. The Atmega will compare the two independent voltages and will only send non-zero torque commands if the sensors read a voltage within 10% of each other. If a short circuit or wiring failure with either potentiometer occurs, the input will be outside the normal operating range, and the motor controllers will not be sent torque requests. The node will log the error in the CAN bus.

There will also be a Pegasus Brake light pressure switch (part number 3601, recommended by Formula Hybrid) on the brakes, wired to a CAN node with 22 gauge wire. If the pressure switch indicates actuation of the brake and the potentiometers measure more than 25% pedal travel, the power to the motors will be completely stopped until the torque pedal indicates less than 5% pedal travel.

7.3 Wiring

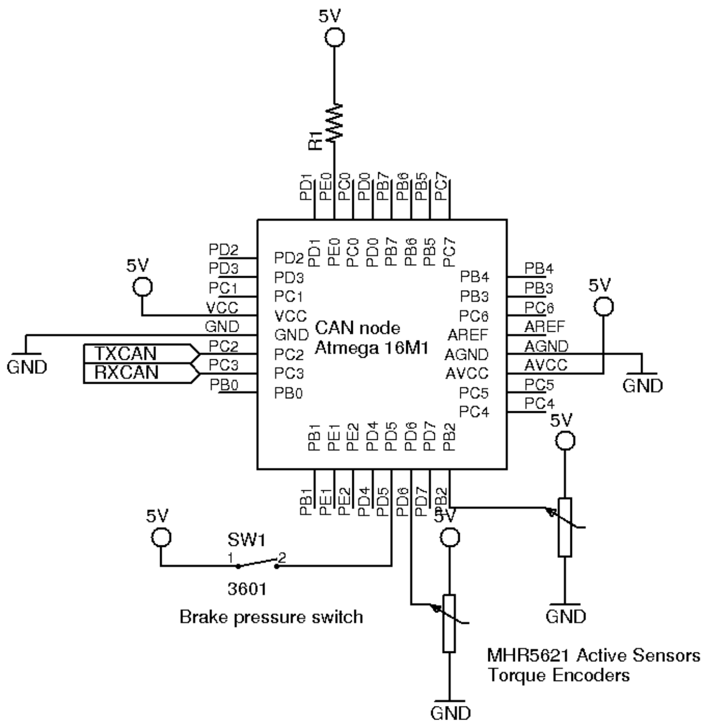

Figure 56: Schematic of the torque encoder plausibility check

Two potentiometers are wired with their output to the CAN analog input pins. The potentiometers are given separate power lines of 5V, parallel, to the supply power of the CAN node itself. The brake switch is positioned to trip at a level of hard braking, and when triggered will deliver 5V to a CAN input pin. The CAN node is wired to send and receive messages to the other nodes.

7.4 Position in Car/Mechanical Fastening/Mechanical Connection

The torque encoder is bolted to the accelerator pedal assembly with 4x $\frac{1}{4}$”-20 bolts. The bolts are safety-wired to prevent loosening. The torque encoder is manufactured with a D-shaft. This is rotationally fixed to the accelerator pedal axle by a 4-40 set screw. The set screw is bonded with Loctite Purple to prevent loosening. This allows the torque encoder to measure the angular position of the accelerator pedal axle. The accelerator pedal axle is prevented from moving axially by retaining rings. The mounting of the torque encoder does not affect the relative plausibility check. The sensor used contains two independent encoders, each measuring the position of the single shaft.

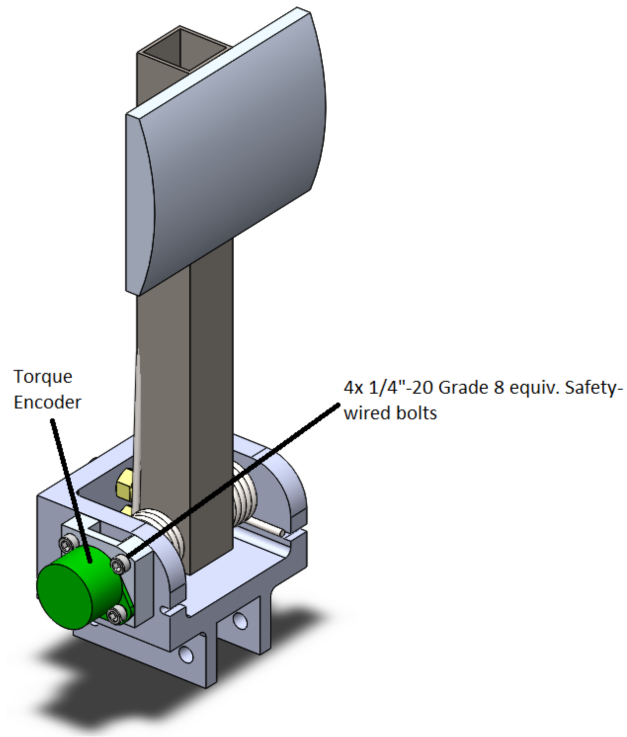

Figure 57: Mechanical fastening and connection to the throttle pedal. Note that the torque encoders are two encoders housed in one package

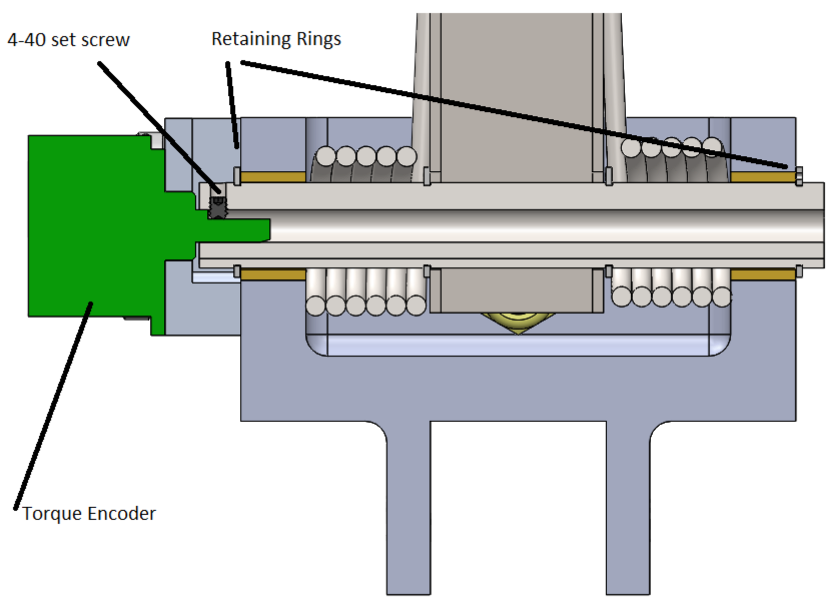

Figure 58: Side view of how the torque encoder connects to the pedal and measures the throttle

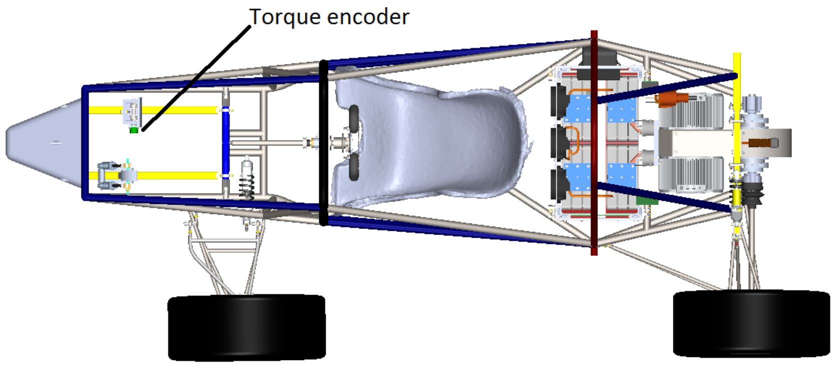

Figure 59: Overall view of the torque encoder's position in the car, top down view

8 Additional LV-parts Interfering with the Tractive System

8.1 LV Part 1: DC-DC converter

8.1.1 Description

The GLV system will be powered via a DC/DC converter which will convert the 100V system to a 13.5V line for powering CAN nodes and other LV devices. This voltage will be regulated down to 12V and 5V for the LV devices. Before the DC-DC converter, there is a fuse for the GLV system as a whole, with a rating of 4A.

8.1.2 Wiring, Cables

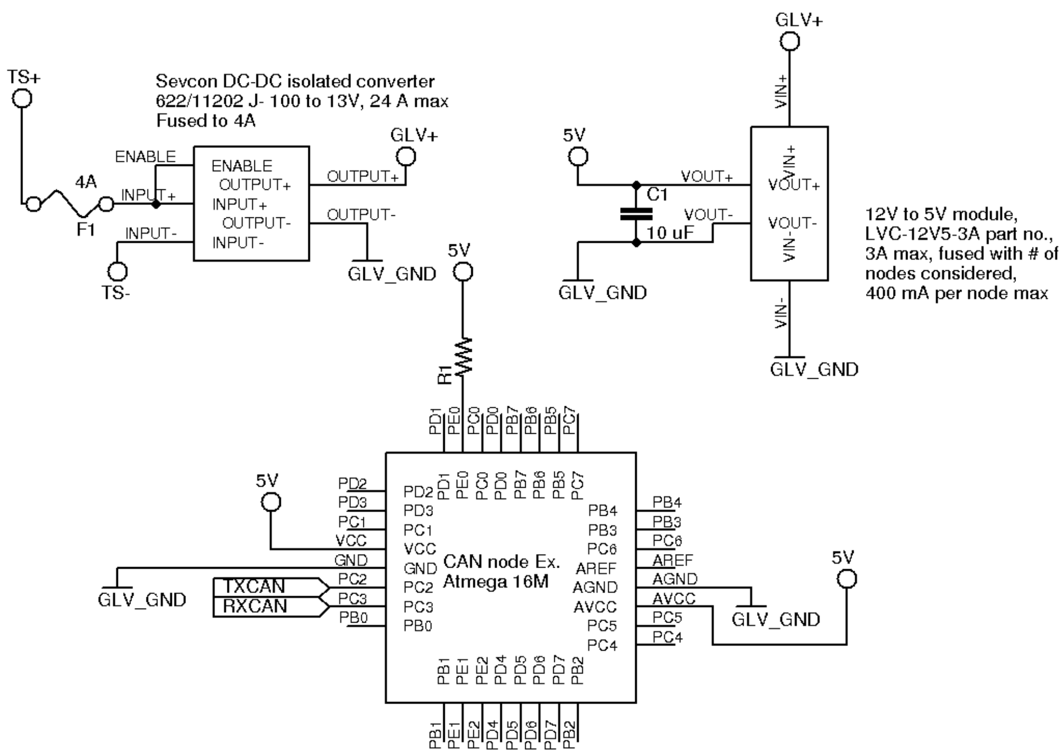

Figure 60: DC-DC converter and its attachment to the GLV and then CAN node systems through a module

The DC-DC converter's power line is expected to carry less than 4A at all times. Its output will be fused to 4A, and then used for the GLV system as 12V. The GLV system voltage will be then regulated to 5V for the sake of the CAN Atmega. All of these wires, past the DC-DC converter, will be 22 AWG.

8.1.3 Position in Car

The DC-DC converter will be located within the accumulator, so the output leads will go out of the accumulator. Figure 61 shows the CAD model of the DC-DC converter, and its position in the car is on top of the cell boards shown in figure 36.

Figure 61: CAD model of the DC-DC converter for the GLV system

8.2 LV Part 2: Dashboard Node

8.2.1 Description

The Dashboard node will have a variety of tasks. It will act as the Control Panel interface (for displaying information to the driver and receiving data from the driver), Emergency Button sensor, and steering sensor.

The control panel interface is used for debugging. The CAN system has nodes all over circuits in the car, so it knows, for instance, what triggered a shutdown circuit opening. If the CAN system is still live (when an E-stop hasn't been pushed and the GLV master switch is on), then this CAN node will alert the driver.

The node is connected to a linear potentiometer on the steering rack. The potentiometer's value corresponds to the steering angle, so the CAN node can transmit the information on all of the turns. This node is used for driver training, practice, and team information in later years. If time permits, this data can be used to help in the development of a virtual differential.

Lastly, the emergency button sensing node has an input from right after the E-stop of the cockpit shutdown button. Therefore, the CAN system knows if it has been pushed or not by if it is a high value (not pushed, as the button is normally closed), or low value. The other E-stops around the car (right and left, on the back), will be wired to closer nodes.

8.2.2 Wiring, cables

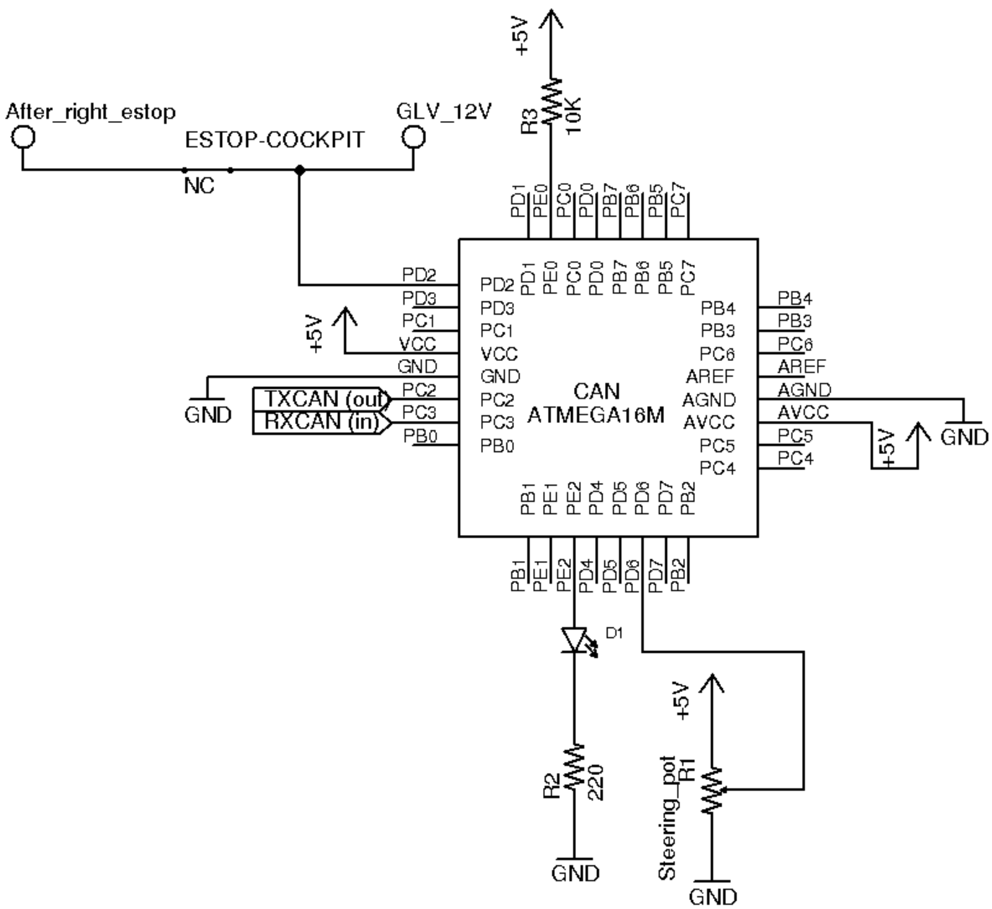

Figure 62: Dashboard node schematic

The dashboard node is wired to have the steering angle potentiometer and E-stops as input and the control panel interface (the LED) as an output. It listens to all CAN messages around the car. The interfacing LED will notify the driver of anything deemed important, such as the AMS detecting the temperature of the accumulator cells was getting too high. Therefore, the dashboard's interfacing light will mostly be telling the driver why the shutdown system shut down through a series of flashes. Only if one of the E-stops are pressed will the CAN system shut down and therefore the interfacing light will not tell the driver what has happened to the shutdown circuit.

8.2.3 Position in Car

The dashboard node will be located behind the dashboard, and connecting to certain switches and lights on the dashboard. The dashboard CAD render can be shown in Figure 63.

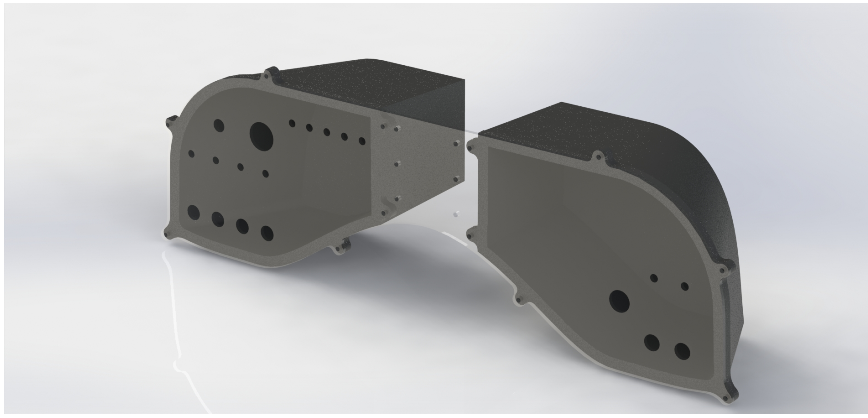

Figure 63: Render of the Dashboard, the location of the dashboard node.

8.3 LV Part 3: IMD, Ready to Drive Sound, and Watchdog Node

8.3.1 Description

The node located next to the IMD and ready to drive sound monitors the IMD's output and will activate the ready to drive sound when the car is in ready mode. It will receive input from behind each of the two side e-stops, so if one is pushed, the CAN system knows and can tell the driver the reason for shutdwon circuit shutdown. It will also be connected to the rest of the CAN system around the car and listen to CAN messages for anomalies. If the Watchdog node receives a CAN error message that indicates danger to the driver or the vehicle it will open the watchdog switch in the shutdown circuit. This will be useful for maintaining the health of the motor controllers.

8.3.2 Wiring, Cables

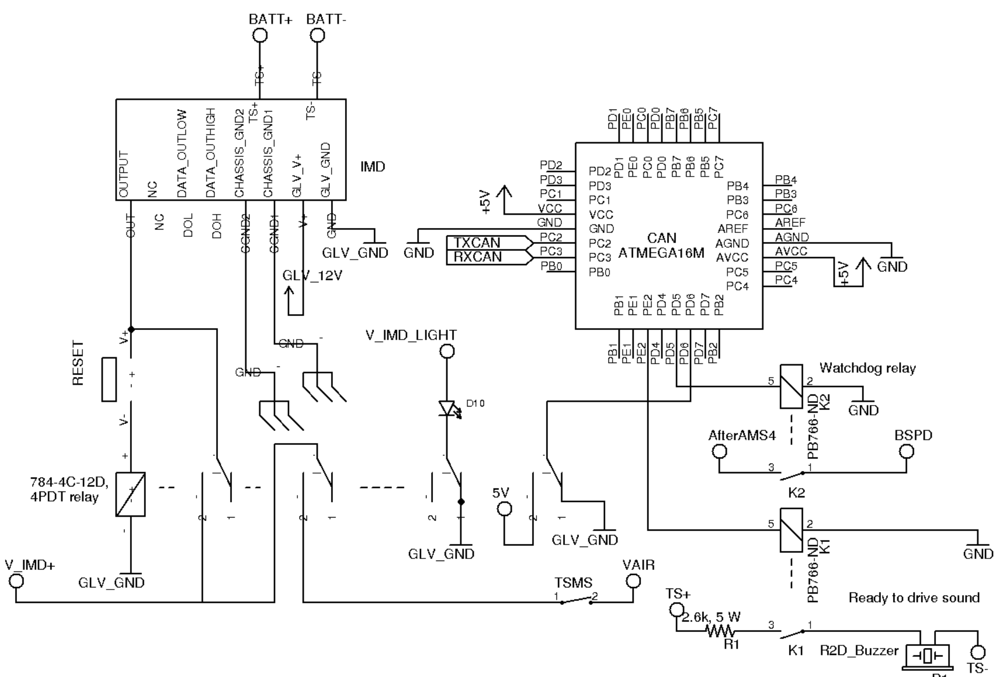

Figure 64: Schematic for the node on the ready to drive sound, watchdog, and side e-stops and IMD

As shown in Figure 64, both the IMD and the ready to drive sound relay are wired to the CAN node located in the back of the car.

The CAN node is wired to the fourth pole of the IMD relay, so the node will always read high until the pole is no longer pulled because the IMD's output is low and the IMD has found a ground fault.

As an output, the CAN node is also wired to a relay's coil controlling a switch in the tractive system parallel to the motors. When the CAN system knows it's in ready to drive mode, it'll send the message to send 5V to this coil, therefore closing the switch that will give the ready to drive sound buzzer power to make noise.

Also an output of the CAN node is the watchdog relay that controls a switch in the shutdown circuit. As watchdog of the CAN system, if a CAN node goes silent and suddenly stops messaging the rest of the system, this node will take notice and stop sending 5V to this coil, making it open the shutdown circuit. This will protect the motor controllers and offer redundancy for the rest of the shutdown circuit.

8.3.3 Position in Car

The IMD/Ready to Drive sound/Watchdog node will be contained in the enclosure shown in Figure 4.

9 Overall Grounding Concept

9.1 Description of the Grounding Concept

The chassis is used as GLV ground. This ground is established at the panel mount holding many of the shutdown components and the TSMPs. All mechanical systems in the vehicle, such as the accumulator, drivers seat, and pedal box, achieve low resistance to ground because they are either welded directly to the chassis, or fastened using uncoated, conductive metal fasteners. Electrical systems that are satellite to the main panel mount that need to establish a connection to ground for sense purposes are grounded to the chassis using ring terminals. Ring terminals can be included in the bolt stack up of mechanical systems to ensure a secure connection to ground that is positively retained with a lock nut.

9.2 Grounding Measurements

The conductive components within 100mm of the tractive system or a GLV component will be measured with a multimeter to have less than 300 mΩresistance to ground. All fastened mechanical systems will be measured for a ground connection individually and exhaustively. Continuity will be checked during manufacture and assembly before the GLV system is in place.

Carbon fiber will be used in body panels and floor close outs, but these designs are not yet complete. We will be measuring the resistance to chassis ground and inserting copper mesh as needed to achieve at minimum 5 Ωresistance to ground.

10 Firewall

10.1 Firewall 1

10.1.1 Description/Materials

The firewall is constructed of two layers. The layer facing the tractive system is 1.5 mm Aluminum sheet metal, with a chamfered edge. The second layer facing the cockpit is 1/8 in. Flame-Retardant Multipurpose Garolite (G-10/FR4). The assembly is fastened together using sheet metal rivets. The chassis has welded sheet metal tabs that fasten to the firewall with bolts and lock nuts. Because the firewall is fastened to the chassis using conductive fasteners it is connected to GLV ground.
All high voltage and high temperature systems are contained in the rear of the vehicle, so only one firewall will be used. There are GLV systems in the dashboard and pedal box so a small grommeted hole will be made in the firewall for GLV wiring.

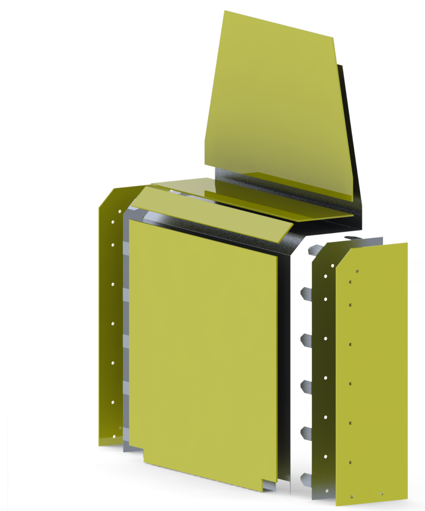

Figure 65: Exploded view of the firewall

10.1.2 Position in Car

The firewall is located between the driver and the accumulator, to protect the driver from the TS. Figure 66 shows the position with the driver seat removed for visual aid. The seat will go in the gap between the wheel and the firewall, facing away from the firewall. The top corner of the extruded part of the firewall is chamfered in order to protect the driver and will also be covered with padding.

Figure 66: CAD render of the firewall's position in the car

10.2 Firewall 2

There is only one firewall in the vehicle.

11 Appendix

11.2.1.1 Shutdown Switches

Cockpit E-Stop Button Datasheet here.
Right and Left E-Stop Buttons Datasheet here.
Tractive System and GLV System Master Switches, product link here, no datasheet available.
Main connector to the accumulator, also an interlock, datasheet here.
See section 11 for the AMS and BSPD relays. See section 11 for the IMD relay. See section 11 for the HVD. See section 11 for the inertia switch.

11.2.2 IMD datasheet

Supply voltage U_S	DC 10…36 V
Nominal supply voltage	DC 12 V / 24 V
Voltage range	10 V…36 V
Max. operational current I_S	150 mA
Max. current I_k	2 A 6 A / 2 ms Rush-In current
Power dissipation P_S	<2 W
Line L+ / L- Voltage U_n	AC 0 V…800 V peak; 0 V…560 V rms (10 Hz…1 kHz) DC 0 V…800 V
Protective separation (reinforced insulation) between	(L+ / L-) – (Kl.31, Kl.15, E, KE, M_{HS}, OK_{HS})
Voltage test	AC 3500 V / 1 min
Load dump protection	< 40 V
Under voltage detection	0 V…500 V; Default: 0 V (inactive)
System leakage capacity C_e	≤ 1 µF
Reduced measuring range and increased measuring time at C_e	> 1µF (E.g. max. range 1 MΩ @ 3 µF, t_{an} = 68 s @ change over R_F 1MΩ > R_{an}/2)
Measuring voltage U_m	+/- 40 V
Measuring current I_m at $R_F = 0$	+/- 33 µA
Impedance Z_i at 50 Hz	≥ 1.2 MΩ
Internal resistance R_i	≥ 1.2 MΩ
Measurement range	0…10 MΩ
Measurement method	Bender AMP Technologie
Relative error at SST (≤ 2 s)	Good > 2 * R_{an}; Bad < 0.5 * R_{an}
Relative error at AMP	0…85 kΩ ▸ +/-20 kΩ 100 kΩ…10 MΩ ▸ +/-15 %
Relative error Output – M (base frequencies)	+/- 5 % at each frequency (10 Hz; 20 Hz; 30 Hz; 40 Hz; 50 Hz)
Relative error under voltage detection	U_n ≥ 100 V ▸ +/-10 %; at U_n ≥ 300 V ▸ +/-5 %
Response value hysteresis (AMP)	25 %
Response value R_{an}	100 kΩ…200 kΩ ▸ higher tolerances at R_{an} < 85 kΩ; (Default: 100 kΩ)
Response time t_{an} (OK_{HS}; SST)	t_{an} ≤ 2 s (typ. < 1 s at U_n > 100 V)
Response time t_{an} (OK_{HS}; AMP)	t_{an} ≤ 10 s
Switch-off time t_{ab} (OK_{HS}; AMP)	t_{ab} ≤ 26 s
Self test time	10 s (only at power on)

Figure 67: Response value information from IMD datasheet

Full IMD Datasheet here.
IMD 4PDT Relay Datasheet Here. Referred from section 11.
Fuse that protects the IMD, 251/253 series (1A)

11.2.3 Inertia switch

Sensata Resettable Crash sensor datasheet here. Referred from section 11.

11.2.4 Brake Plausibility Device

BSPD relay. Reffered from section 11 (shutdown system), section 11 (ready to drive sound), section 11 (precharge system), and section 11 (AMS).
See section 11 for the brake sensor's datasheet.

11.2.7 Tractive System Active Light

DC-DC converter for the TSAL datasheet.
Product information for the TSAL.
Zener with 56V breakdown, for activating the TSAL.

11.2.8.2 Tractive System Measuring Points

Expected multimeter to measure the TS voltage, datasheet here.
5K, 1.5W resistors for the TSMP datasheet here.
Red and Black TSMP 4mm banana jack datasheet here.

11.2.9 Precharge System

Please see section 11 for the relay used for the keyswitch's power.

11.2.10 Discharge system

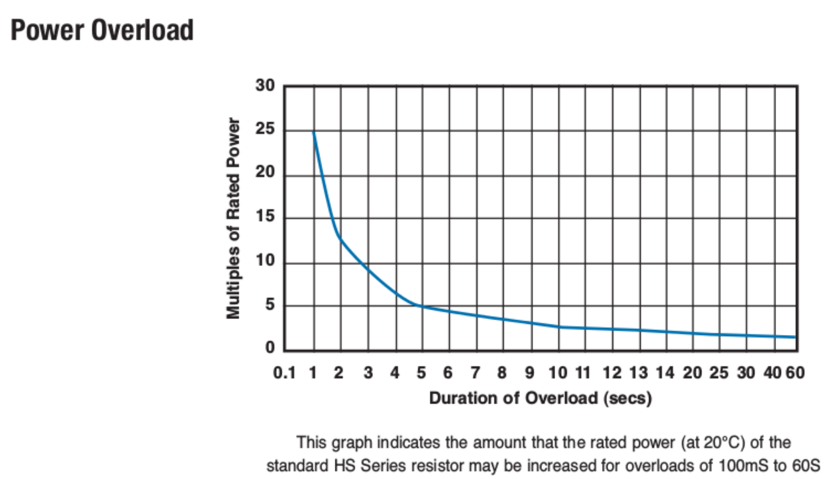

Figure 68: Power overload graph of the 100W discharge resistor

Discharge resistor datasheet here.
Discharge relay datasheet here.
Referred from section 2.10

11.2.11 HVD

HVD Anderson connector datasheet here. Referred from section 11.

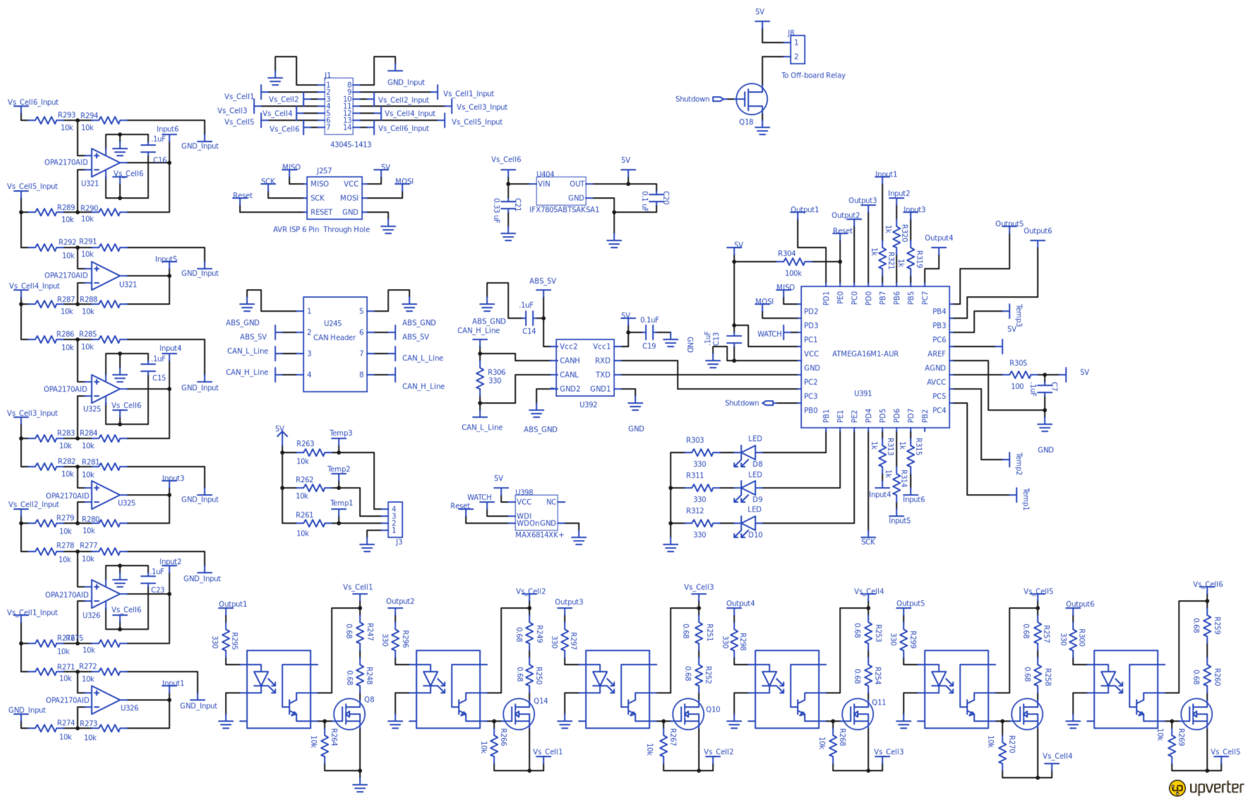

Figure 69: Schematic of one of the accumulator monitoring boards

11.2.12 Ready to Drive Sound

Ready to drive sound buzzer datasheet.
Please refer to section 11 for the relay of the ready to drive sound.

11.3.1.2 Cell Description

We are working with Nissan to allow us to use their datasheet for the modules.

11.3.1.4 Cell Temperature Monitoring

Thermistors measuring cell temperature datasheet.

11.3.1.5 Accumulator Monitoring System

Please see figure 69 for the schematic of the AMS boards. Referred from section 3.1.5. The AMS looks at the voltage of each cell by having differential amplifiers between two cells and get a relative voltage. This relative voltage for each cell is then put through an optocoupler, which then connects a power resistor and transistor to shunt the cell when necessary. There is an isolated CAN node attached to the board so it can communicate to the rest of the shutdown system and activate a relay to open the shutdown circuit when necessary. The BMS connects to the cell-top boards, shown in figure 33.
Please see section 11 for the AMS relay.

11.3.1.8 Accumulator Insulation Relays

Accumulator Insulation Relay datasheets here.

11.3.1.9 Fusing

Referred from section 3.1.9.

Catalog Symbol: LPJ -_SP
Dual-Element, Time-Delay – 10 seconds (minimum) at 500% rated current
Current-Limiting
Ampere Rating: 70 to 600A
Voltage Rating: 600Vac (or less)*
Interrupting Rating: 300,000A RMS Sym.
Agency Information:
UL Listed – Special Purpose†, Guide JFHR, File E56412
CSA Certified, Class J per CSA C22.2 No. 248.8, Class 1422-02, File 53787

*0-600A rated 300Vdc and 20 KAIC.
†Meets all performance requirements of UL Standard 248-8 for Class J fuses.

Figure 70: Ratings for the Bussman LPJ series 175A main TS fuse

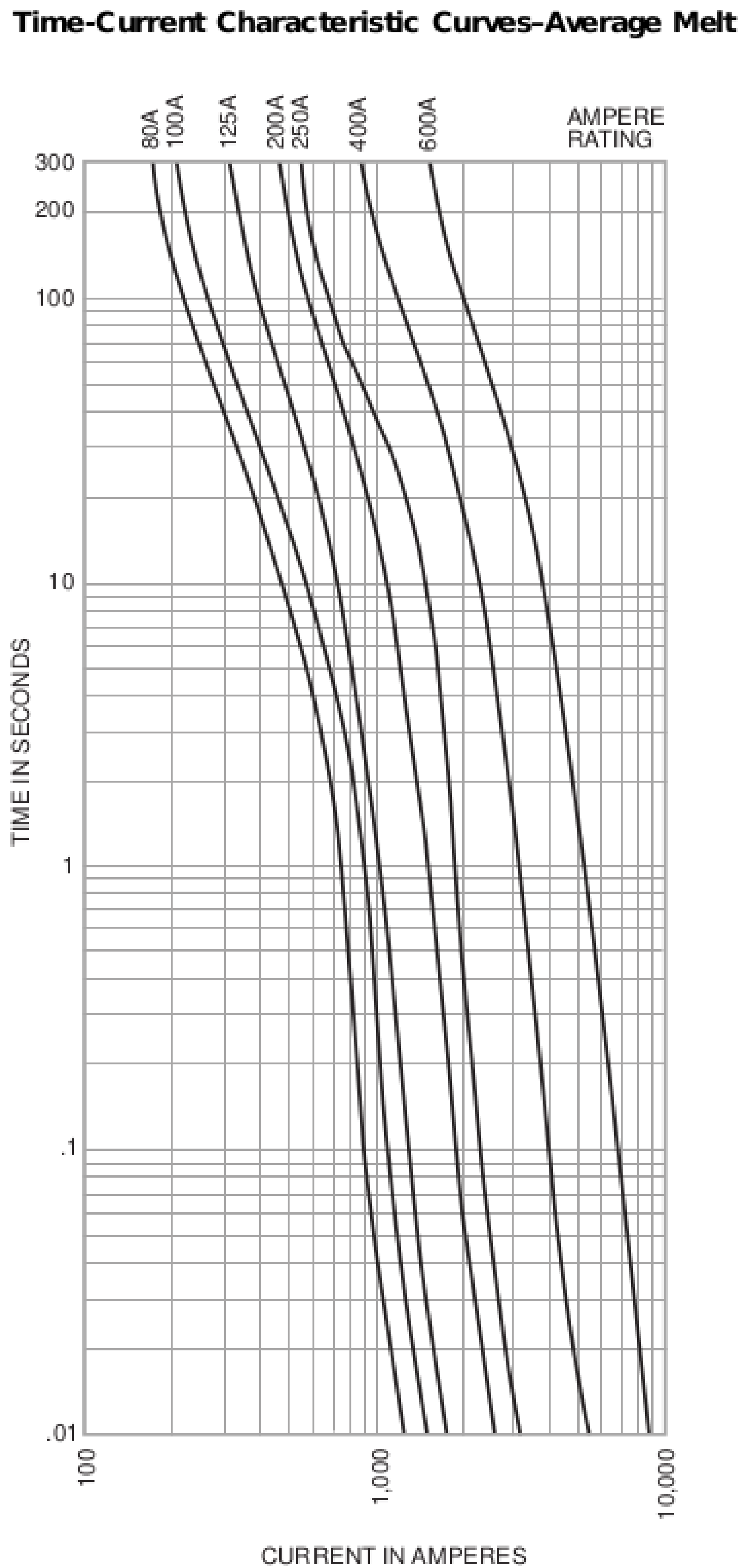

Figure 71: Time-current curve for Bussman LPJ series 175 A main TS fuse

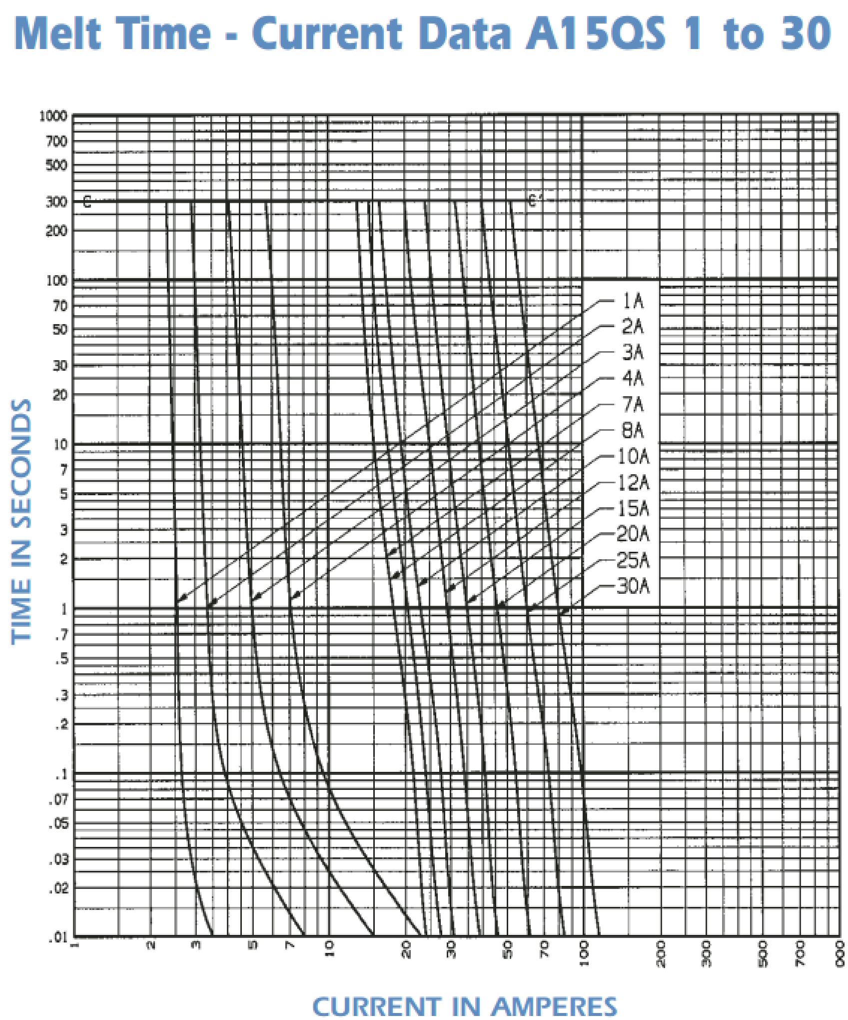

Figure 73: Time-Current curve for A15QS, 7A Keyswitch fuse

All information found from the datasheet of: Full Bussman Fuse LPJ 175A datasheet here.

Ratings
- AC: 1-6000A 150VAC, 100kA I.R.
- DC: 1-6000A 150VDC, 100kA I.R.

Approvals
- UL Recognized Component
- AC: UL Guide No. JFHR2 (1-4000A)
- DC Tested to UL Standard 198L parameters (1-4000A)

Highlights
- Fast Acting
- Current Limiting
- Low I^2t
- Indicator Options Available

Applications
- Protection of heavy duty devices such as electrochemical rectifiers

Figure 72: Ratings taken from the A15QS, 7A Keyswitch fuse

All information found from the datasheet of: Keyswitch Fuse datasheet, Semiconductor AC A15QS.

Electrical Specifications by Item

Ampere Rating (A)	Amp Code	Ordering Number (Std.)	Ordering Number (Mil.)	Max Voltage Rating (V)	Interrupting Rating	Nominal Cold Resistance (Ohms)	Nominal Melting I²t (A² sec)	Nom Voltage Drop (V)	Agency Approvals: UL	CSA	PSE	TUV	QPL 253 Series Only	CCC
.062	.062	251.062	253.062	125	300 A @ 125VDC 50A@125VAC For CCC 7A: 70A@125VAC For CCC 10A: 100A@ 125VAC	7.000	0.000113	1.4	x	x			x	
.125	.125	251.125	253.125	125		1.700	0.00174	0.285	x	x			x	
.200	.200	251.200	253.200	125		0.895	0.0048	0.345	x	x				
.250	.250	251.250	253.250	125		0.665	0.0116	0.24	x	x			x	
.375	.375	251.375	253.375	125		0.395	0.0296	0.215	x	x			x	
.500	.500	251.500	253.500	125		0.302	0.0598	0.2165	x	x		x	x	x
.630	.630	251.630		125		0.205	0.08	0.188	x	x				
.750	.750	251.750	253.750	125		0.175	0.153	0.176	x	x		x	x	
1.00	001.	251001.	253001.	125		0.128	0.256	0.194	x	x	x	x	x	x
1.25	1.25	2511.25		125		0.100	0.390	0.2	x	x	x			
1.50	01.5	25101.5	25301.5	125		0.0823	0.587	0.21	x	x	x	x	x	
2.00	002.	251002.	253002.	125		0.0473	0.405	0.141	x	x	x	x	x	x
2.50	02.5	25102.5		125		0.0360	0.721	0.132	x	x	x	x		x
3.00	003.	251003.	253003.	125		0.0295	1.19	0.131	x	x	x	x	x	x
3.50	03.5	25103.5		125		0.0240	1.58	0.1205	x	x	x	x		
4.00	004.	251004.	253004.	125		0.0204	2.45	0.114	x	x	x	x	x	x

Figure 74: 251/253 series, 1A TS low current fuse

Average Time Current Curves

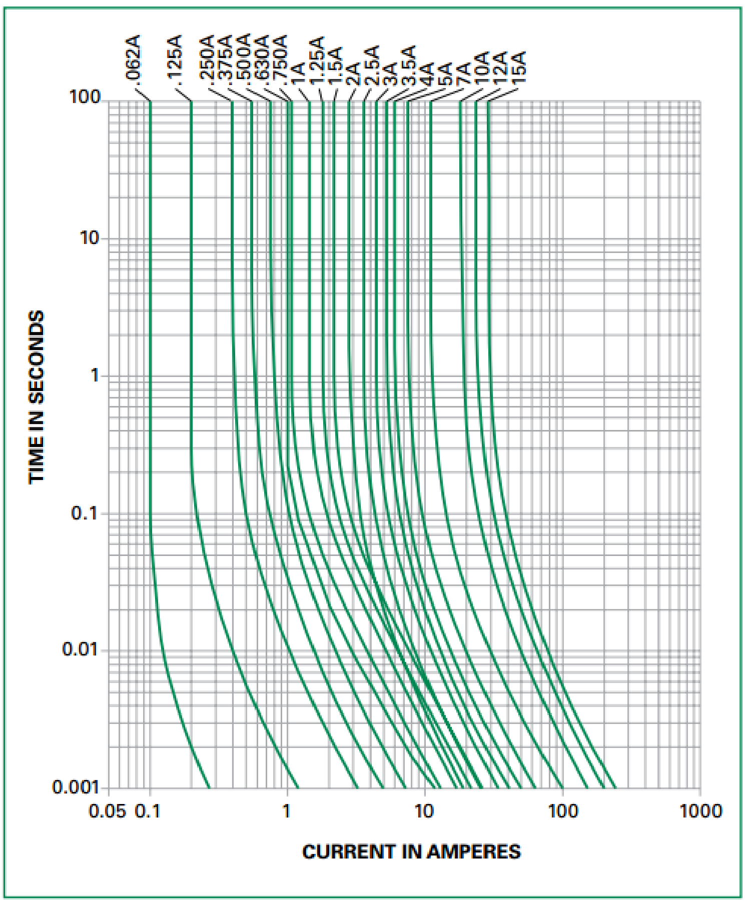

Figure 75: Time-Current curve for 251/253 series 1A TS low current fuse

All information found from the datasheet of: TS to IMD, TSMP and Lights DC-DC converter, 1A 251/253 Series

Electrical Specifications
Ferrule Version

AMPERAGE	AMP CODE	ORDERING NUMBER	UPC	VOLTAGE	INTERRUPTING RATING		NOM COLD RESISTANCE (ohm)	WATTS LOSS AT 100% RATED CURRENT (W)	WATTS LOSS AT 80% RATED CURRENT (W)	TOTAL CLEARING I²t (A² s) 10 kA	TOTAL CLEARING I²t (A² s) 20 kA	AGENCY APPROVALS		
				DC	AC	DC						UL	VDE	CSA
1	001.	0SPF001.T	07945816907	1000	–	20 kA	0.394	0.602	0.410	0.554	0.554	•		•
2	002.	0SPF002.T	07945816910	1000	–	20 kA	0.237	1.586	0.851	1.175	4.755	•	•	•
3	003.	0SPF003.T	07945816913	1000	–	20 kA	0.11	1.504	0.824	5.007	7.882	•	•	•
3.5	03.5	0SPF03.5T	07945880087	1000	–	20 kA	0.07787	1.365	0.778	11.297	11.297	•		•
4	004.	0SPF004.T	07945816916	1000	–	20 kA	0.06127	1.491	0.839	23.031	23.031	•	•	•

Figure 76: SPF Series, 4A Main GLV fuse

Time Current Curve (1-12 A)

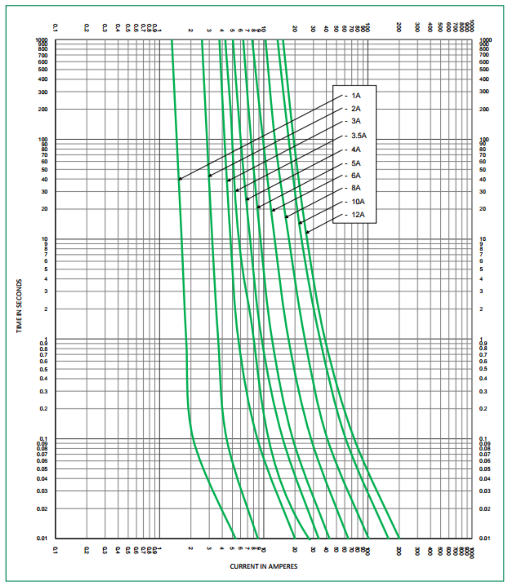

Figure 77: Time-current curve for SPF series 4A GLV main fuse

All information found from the datasheet of: GLV main fuse, 4A SPF type.

CURRENT IN AMPERES

Electrical Specifications

Catalog Number	Ampere Rating (A)	Nominal Cold Resistance (ohm)	Nominal Volt-drop @100% In (Volt) max.	Voltage and Interrupting Ratings	Melting I²T <10 m Sec (A² Sec)	Melting I²T @10 In (A² Sec)	Nominal Power Dissipation @100% In (W)	Agency Approvals		
								cULus	cRUus	CSA
C1Q 250	250mA	0.85	0.250	See Table of Safety Approvals on Page 1 for Voltage and associated Interrupting Ratings	0.0018	0.0001	0.06	Y		Y
C1Q 375	375mA	0.48	0.222		0.0044	0.0004	0.08	Y		Y
C1Q 500	500mA	0.32	0.195		0.008	0.001	0.10	Y		Y
C1Q 750	750mA	0.175	0.163		0.019	0.002	0.12	Y		Y
C1Q 1	1A	0.124	0.156		0.035	0.004	0.16	Y		Y
C1Q 1.25	1.25A	0.092	0.149		0.057	0.006	0.19	Y		Y
C1Q 1.5	1.5A	0.075	0.142		0.084	0.010	0.21	Y		Y
C1Q 2	2A	0.054	0.140		0.15	0.019	0.28	Y		Y
C1Q 2.5	2.5A	0.042	0.138		0.25	0.032	0.35	Y		Y
C1Q 3	3A	0.035	0.136		0.37	0.050	0.41	Y		Y
C1Q 3.5	3.5A	0.030	0.140		0.53	0.072	0.49	Y		Y
C1Q 4	4A	0.028	0.144		0.67	0.094	0.58	Y		Y
C1Q 5	5A	0.022	0.154		1.10	0.16	0.77	Y		Y
C1Q 7	7A	0.015	0.160		3.10	0.37	1.12		Y	

Consult manufacturer for other ratings

Specifications subject to change without notice

Figure 78: Ratings for C1Q 3A Cell series to AMS fuse

Safety Agency Approvals

SAFETY AGENCY	SAFETY AGENCY CERTIFICATE	VOLTAGE RATING (V)	AMPERE RANGE / VOLT @ I.R. ABILITY*
	LR39772	250mA - 5A / 125V AC 63V DC 7A / 63V AC & DC	250mA - 5A / 125V AC @ 100A 63V DC @ 50A
	E20624		
	E20624		7A / 63V AC & DC @ 50A

* I.R. = INTERRUPTING RATING = SHORT CIRCUIT RATING (AMPS)

Figure 79: Approved Ratings of C1Q series 3A Cell to AMS fuse

Average Time Current Curve

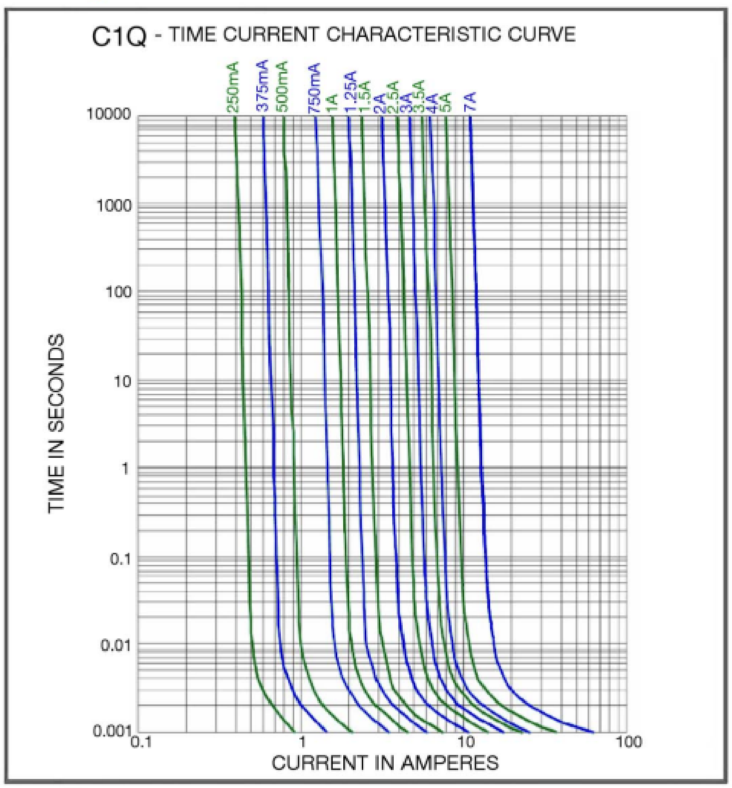

Figure 80: Time-current curve for C1Q series, 3A Cell to AMS fuse

All information found from the datasheet of: Cell to AMS fuse, C1Q type.

Specifications

Interrupting Rating:	1000A @ 32 VDC
Voltage Rating:	32 VDC
Operating Temperature Range:	-40˚C to +125˚C
Terminals:	Ag plated zinc alloy
Housing Materials:	PA66
Complies with:	Meets SAE J2077 ISO 8820-3 UL 248 Special Purpose Fuses

Figure 81: Ratings for MINI series, 2A Shutdown circuit and GLV 12V fuses

Time-Current Characteristic Curves

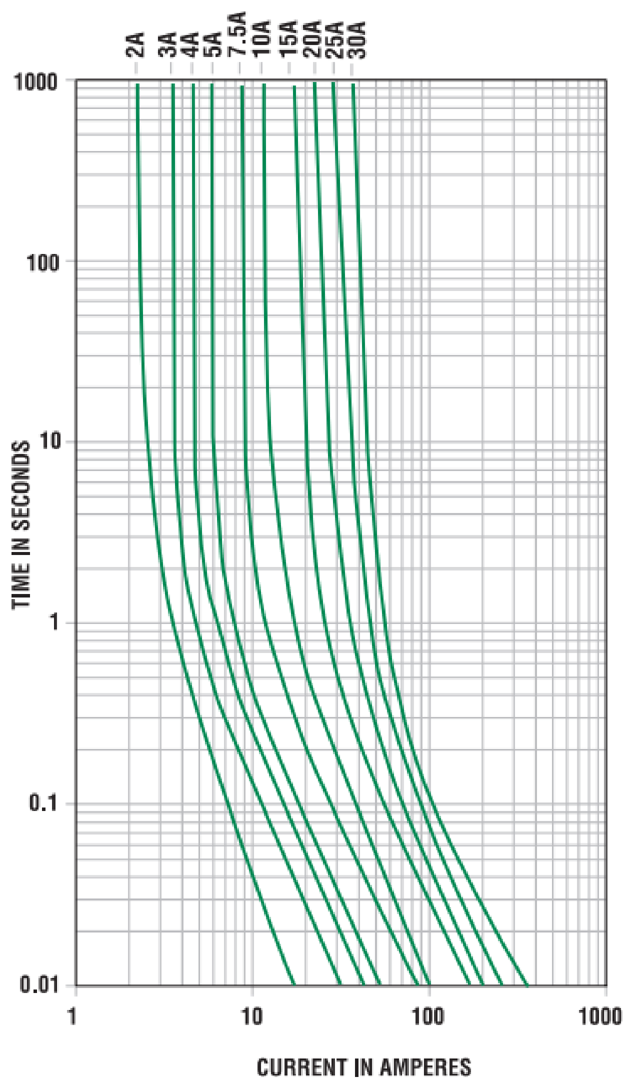

Figure 82: Time-current curve for MINI series, 2A Shutdown and GLV 12V fuses

AWG gauge	Conductor Diameter Inches	Conductor Diameter mm	Ohms per 1000 ft.	Ohms per km	Maximum amps for chassis wiring	Maximum amps for power transmission	Maximum frequency for 100% skin depth for solid conductor copper	Breaking force Soft Annealed Cu 37000 PSI
0000	0.46	11.684	0.049	0.16072	380	302	125 Hz	6120 lbs
000	0.4096	10.40384	0.0618	0.202704	328	239	160 Hz	4860 lbs
00	0.3648	9.26592	0.0779	0.255512	283	190	200 Hz	3860 lbs
0	0.3249	8.25246	0.0983	0.322424	245	150	250 Hz	3060 lbs
1	0.2893	7.34822	0.1239	0.406392	211	119	325 Hz	2430 lbs
2	0.2576	6.54304	0.1563	0.512664	181	94	410 Hz	1930 lbs
3	0.2294	5.82676	0.197	0.64616	158	75	500 Hz	1530 lbs
4	0.2043	5.18922	0.2485	0.81508	135	60	650 Hz	1210 lbs
5	0.1819	4.62026	0.3133	1.027624	118	47	810 Hz	960 lbs
6	0.162	4.1148	0.3951	1.295928	101	37	1100 Hz	760 lbs
7	0.1443	3.66522	0.4982	1.634096	89	30	1300 Hz	605 lbs
8	0.1285	3.2639	0.6282	2.060496	73	24	1650 Hz	480 lbs
9	0.1144	2.90576	0.7921	2.598088	64	19	2050 Hz	380 lbs
10	0.1019	2.58826	0.9989	3.276392	55	15	2600 Hz	314 lbs
11	0.0907	2.30378	1.26	4.1328	47	12	3200 Hz	249 lbs
12	0.0808	2.05232	1.588	5.20864	41	9.3	4150 Hz	197 lbs
13	0.072	1.8288	2.003	6.56984	35	7.4	5300 Hz	150 lbs
14	0.0641	1.62814	2.525	8.282	32	5.9	6700 Hz	119 lbs
15	0.0571	1.45034	3.184	10.44352	28	4.7	8250 Hz	94 lbs
16	0.0508	1.29032	4.016	13.17248	22	3.7	11 k Hz	75 lbs
17	0.0453	1.15062	5.064	16.60992	19	2.9	13 k Hz	59 lbs
18	0.0403	1.02362	6.385	20.9428	16	2.3	17 kHz	47 lbs
19	0.0359	0.91186	8.051	26.40728	14	1.8	21 kHz	37 lbs
20	0.032	0.8128	10.15	33.292	11	1.5	27 kHz	29 lbs
21	0.0285	0.7239	12.8	41.984	9	1.2	33 kHz	23 lbs
22	0.0254	0.64516	16.14	52.9392	7	0.92	42 kHz	18 lbs
23	0.0226	0.57404	20.36	66.7808	4.7	0.729	53 kHz	14.5 lbs
24	0.0201	0.51054	25.67	84.1976	3.5	0.577	68 kHz	11.5 lbs

Figure 83: Power Stream Wire Gauge Chart Reference. Reffered from section 3.1.9

All information found from the datasheet of: GLV 12V power and Shutdown circuit fuses, MINI series 2A

11.3.1.10 Charging

QuiQ 1000 Charger Specifications

DC Output	24 VDC	36 VDC	48 VDC	72 VDC	96 VDC
Maximum DC output power	695 W	875 W	1000 W	1000 W	945 W
Maximum DC output current	25 A	21 A	18 A	12 A	8.5 A
Maximum DC output voltage	34 V	51 V	68 V	100 V	135 V
Deep discharge recovery (minimum voltage)	6 V	9 V	12 V	18 V	24 V
Maximum interlock current	1 A	1 A	1 A	0.5 A	0.5 A
Battery type	Lead acid (Wet / AGM / GEL), lithium ion				
Reverse polarity	Electronic protection with auto-reset				
Short circuit	Electronic current limit				

AC Input	
AC input voltage range	85-265 VAC
Nominal AC input voltage	120 VAC / 230 VAC
Supported AC sources	Single phase
AC input frequency	45-65 Hz
Maximum / nominal AC input current	12 A / 9.5 A @120 VAC; 5 A rms @230 VAC
Nominal AC power factor	>0.99 @ 120 VAC; >0.98 @ 230 VAC

Regulatory	
Efficiency	93%; California Energy Commission (CEC) compliant
Safety	UL approved to UL1564 3rd Ed. and CSA 107.2, EN 60335-2-29 Designed to meet UL2202 1st Ed.
Emissions	FCC Part 15 / ICES 003 Class A, EN 55011
Immunity	EN 61000-3-2, EN 61000-3-3, EN 61000-6-2, EN 61000-6-4

Figure 84: Important data of the 96V charger, from datasheet

Delta Q Technologies 96VDC charger datasheet.

11.5.1 Motor Controller

Motor controller Sevcon Gen 4 Size 4 with battery voltage 96-120V datasheet here.
Sevcon Gen4 Product Manual

11.7 Torque Encoder

Brake light switch datasheet here, part number 3601. Reffered from section 11.

MHR5200 - Electrical & mechanical specification

Input Specification

Supply voltage (Vs)	5.0±10% regulated	8 to 30 unregulated	V DC
Over voltage protection	Up to 50		V DC
Supply current	<15		mA
Reverse polarity protection	Up to -10		VDC
Power on settlement time	<100		mS
Input voltage rise time	0.25 minimum		V/mS

Output Specification

Output type	Analogue		
Output direction	Clockwise or Anticlockwise (specified at time of order)		
Voltage output (Vout)	0-Vs (+5v)	0 - 5.0	V DC
Line regulation	Ratiometric with Vs	<0.01% FS/V	
Monotonic range	1 - 100% measurement range		Vout
Load resistance	>10K		Ohms
Output noise	<5		mV rms

Performance Specification

Measurement angle	20 to 360 ±2 in 1° increments		°
Resolution	0.025		% of measurement angle
Non-Linearity (see note 4)	<±0.25%		FS
Temperature coefficient	<±0.003%	<±0.011%	FS/°C
Update rate	>500 Nom		Hz
Max operating speed	600		rpm

Figure 85: Important parameters of the MHR5621 Active Sensors Torque Encoder

MHR5621 Active Sensors Torque Encoder datasheet.

11.8.1 LV Part 1: DC-DC converter

12V to 5V module datasheet here.
Sevcon DC-DC converter product information here.

11.8.2 LV Part 2: Dashboard node

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CAN node microcontroller (Atmega16M1) datasheet here.