2024 Formula Hybrid+Electric Electrical System Form 2 (ESF-2).

University Name: Worcester Polytechnic Institute

Team Name: WPI Goat Fast Racing

Car Number: 204

Main Team Contact for ESF related questions:

Name: Evelyn Maude

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Formula Hybrid Abbreviations

AIR	Accumulator Isolation Relay
AMS	Accumulator Management System
BRB	Big Red Button
FH Rules	Formula Hybrid Rule
GLV	Grounded Low-Voltage
GLVMS	Grounded Low Voltage Master Switch.
IMD	Insulation Monitoring Device
IMI	Insulation Monitoring Interrupter
RTDS	Ready To Drive Sound
SMD	Segment Maintenance Disconnect
ESOK	Safety Systems OK
TS	Tractive System
TSAL	Tractive System Active Light
TSMP	Tractive System Measurement Point
TSMS	Tractive System Master Switch.
TSV	Tractive System Voltage

WPI FSAE Abbreviations

ISO	Isolated Electrical Network
BMS	Battery Management System
HV	High Voltage (= Tractive System Voltage)
BOTS	Brake Over-Travel Switch
SDC	Shutdown Circuit
SGTM	Sounds Good To Me
COTS	Consumer Off The Shelf

Section 1 **Vehicle Overview**

Person primarily responsible for this section:

Name: Evelyn Maude

e-mail: emaude@wpi.edu

Check the appropriate boxes:

Vehicle is

- ☒ **New (built on an entirely new frame)**
- ☐ New, but built on a pre-existing frame
- ☐ Updated from a previous year vehicle

Architecture

- ☐ Hybrid
  - ☐ Series
  - ☐ Parallel
- ☐ Hybrid in Progress (HIP[1])
- ☒ **Electric-only**

Drive

- ☐ Front wheel
- ☒ **Rear wheel**
- ☐ All-wheel

Regenerative braking

- ☐ Front wheels
- ☒ **Rear wheels**
- ☐ None

[1] HIP does not need to be declared prior to the competition. If unsure, check "Hybrid"

NARRATIVE OVERVIEW

Provide a brief, concise description of the vehicles main electrical systems including tractive system, accumulator, hybrid type (series or parallel) and method of mechanical coupling to wheels. Describe any innovative or unusual aspects of the design.

Our team has won the IEEE Excellence in Electrical Engineering award for two years consecutively due to the great work of our electrical team. With an opportunity to build the electrical systems for our new car from the ground up, we set our standards substantially higher. We believe that performance and reliability come from good engineering, and that guided our design choices on all aspects of this car.

On the HV side, we are running a cylindrical cell accumulator powering a single Emrax 228 that drives the back wheels through a limited slip differential. The accumulator is made up of 8 identical removable segments with a custom battery management system (BMS). Our custom BMS communicates over an isolated CAN bus to our central accumulator management system (AMS) board, a single custom PCB that manages the entire accumulator. That PCB connects via a coplanar mezzanine connector to our main GLV board inside of our GLV box. Our GLV box contains a carrier board for all of our subcomponents as well as our GLV battery.

Our GLV battery is based directly on our segment electronics, also running at 12s for a nominal voltage of 43.2. By duplicating our efforts between GLV and HV battery management, we are able to achieve substantial density and safety improvements compared to off the shelf battery packs without compromising on time investment.

All main GLV power is done off of a 24V bus that stays at a stable 24V regardless of battery voltage. We utilize a bidirectional buck/boost converter to charge our GLV battery over that same bus for safety and topology reasons. By having a stable bus voltage that doesn’t deviate during events we reduce the complexity of designs and increase consistency. By using buck converters for our high-powered DC:DC converters, we save on BOM cost, space, and efficiency.

For telemetry collection, we have designed a tiny (~1 square inch) sensor PCB that daisy chains through the front and back of the car. We utilize a single standard CAN Bus to transfer telemetry data between every component. We’ve set up our CAN Bus in a way that allows us to formally guarantee maximum message latencies without sacrificing bus bandwidth. We can maintain 200Hz data collection of ~70 data channels while maintaining a maximum of 1ms latency for critical packets and 20ms of latency for all packets including telemetry.

Telemetry collection is critical to the development of effective and performant systems, and we hope to use this telemetry to make more educated engineering decisions in the future.

Included below is the following figures:

- **Figure 1** – an electrical system block diagram showing all major parts associated with the tractive-system. (Not detailed wiring).
- **Figure 2** – Drawings or photographs showing the vehicle from the front, top, and side
- **Figure 3** – A wiring diagram superimposed on a top view of the vehicle showing the locations of all major TS components and the routing of TS wiring.
- **Figure 4** -- A complete TSV wiring schematic per FH Rule **EV13.2.1** showing connections between all TS components.

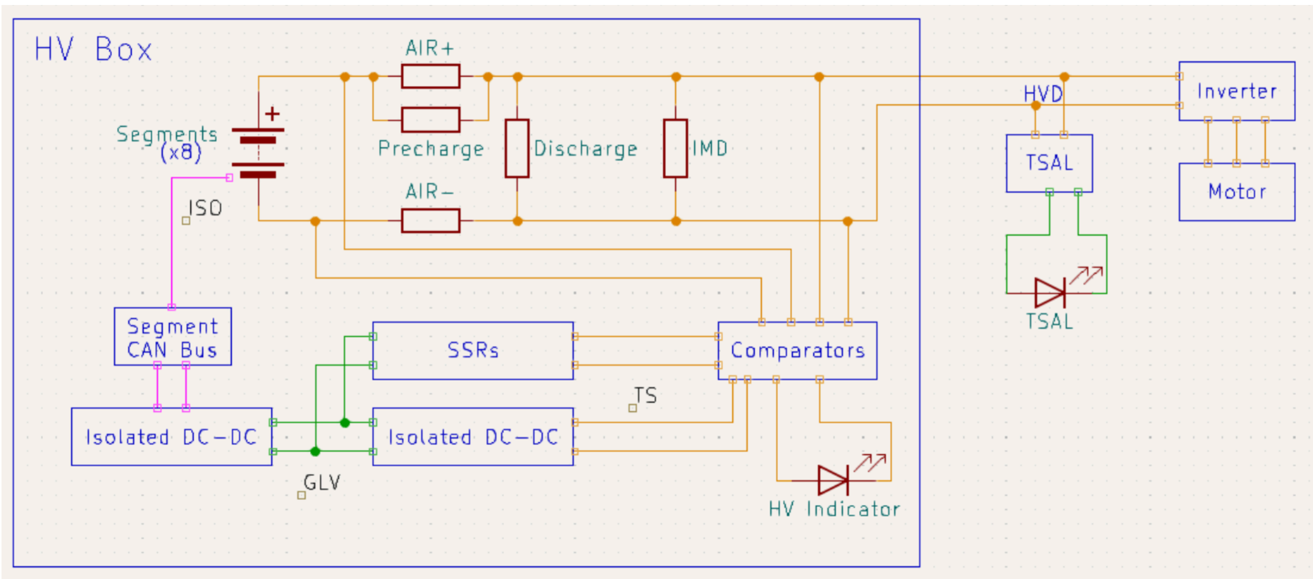
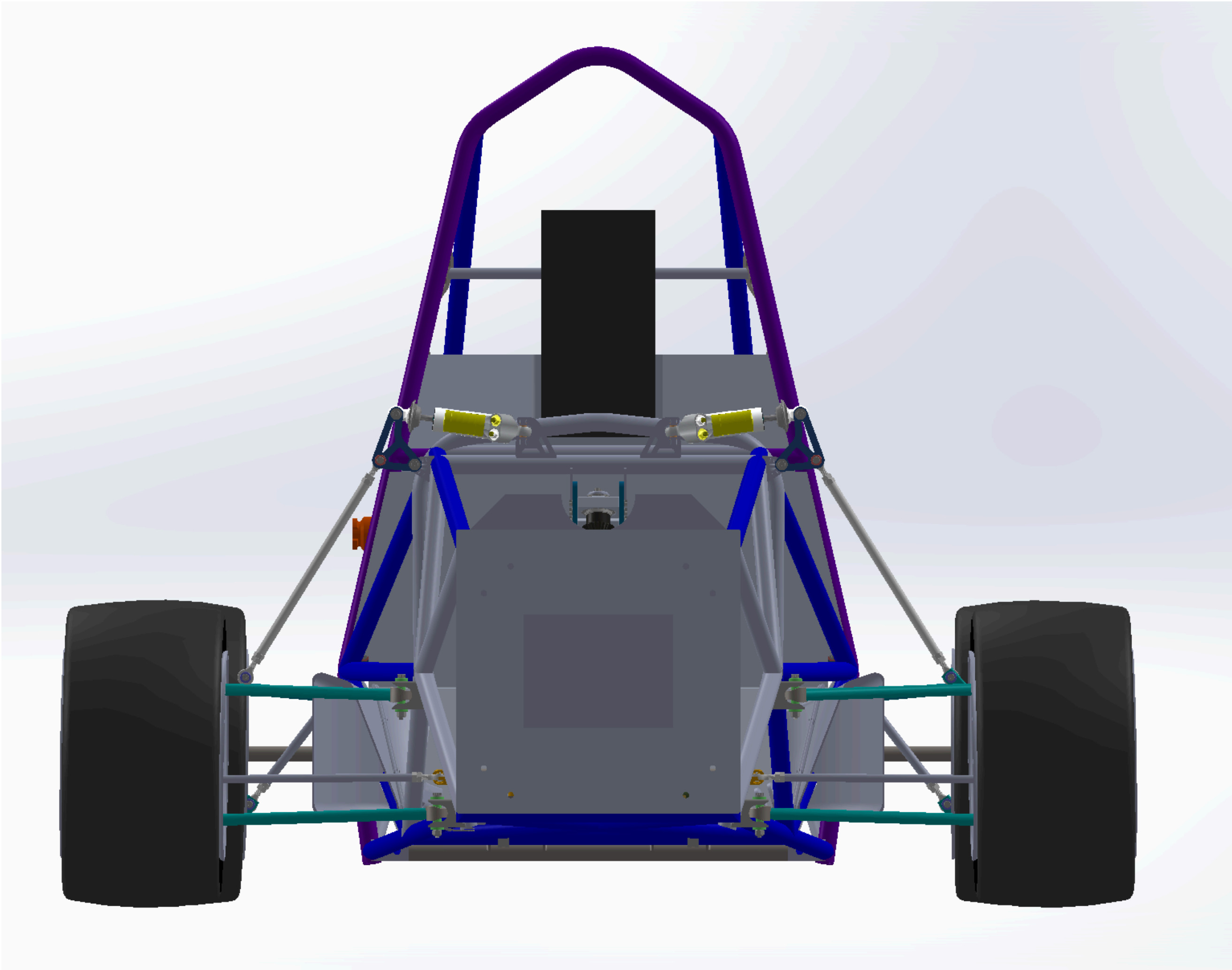
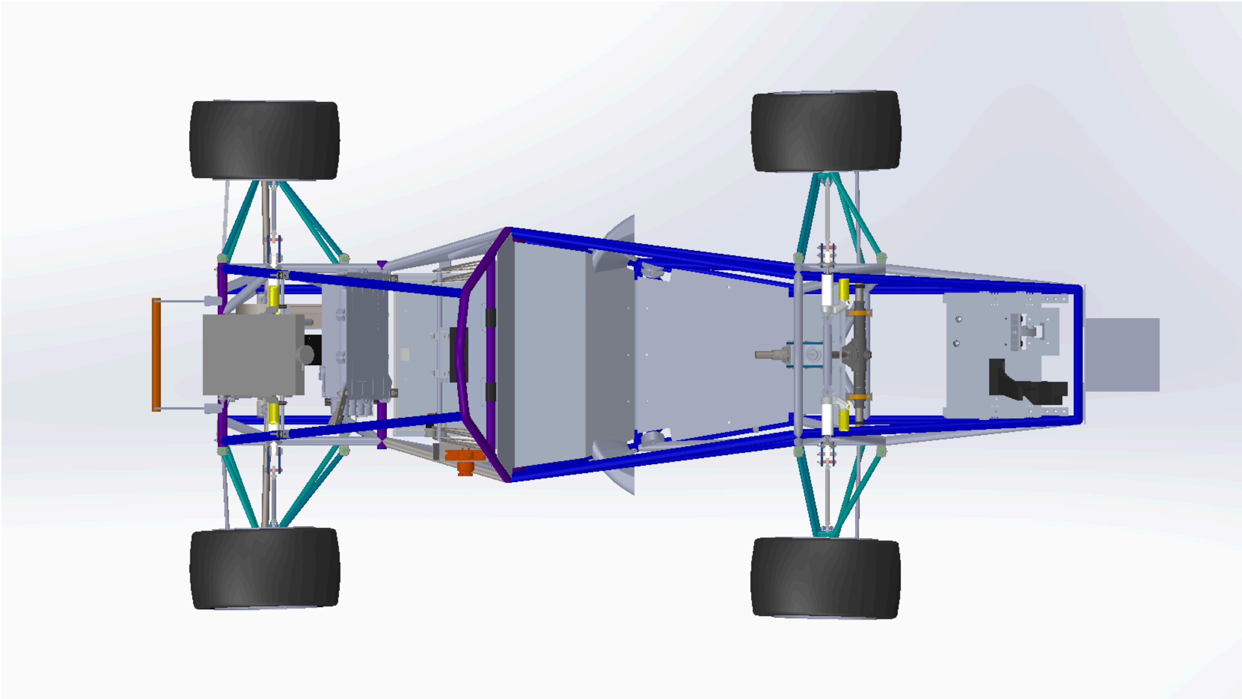


Figure 1 - Electrical System Block Diagram





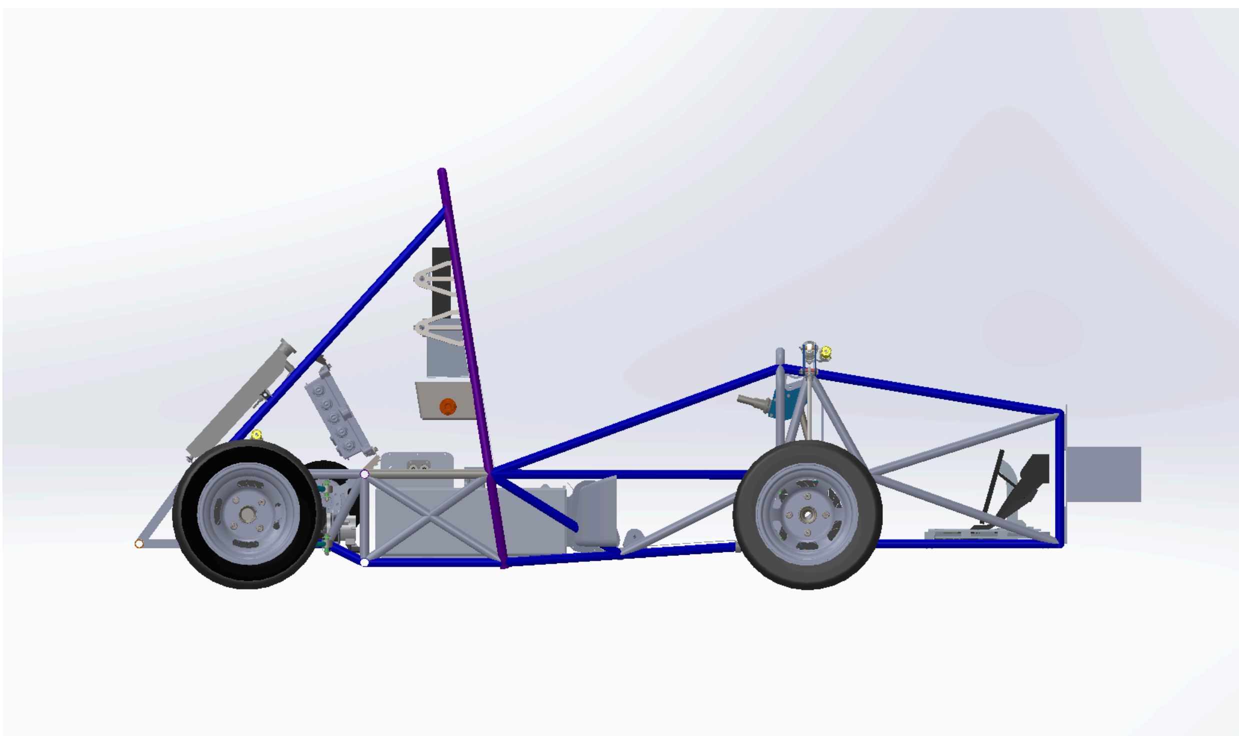


Figure 2 - Drawings showing the vehicle from the front, top, and side

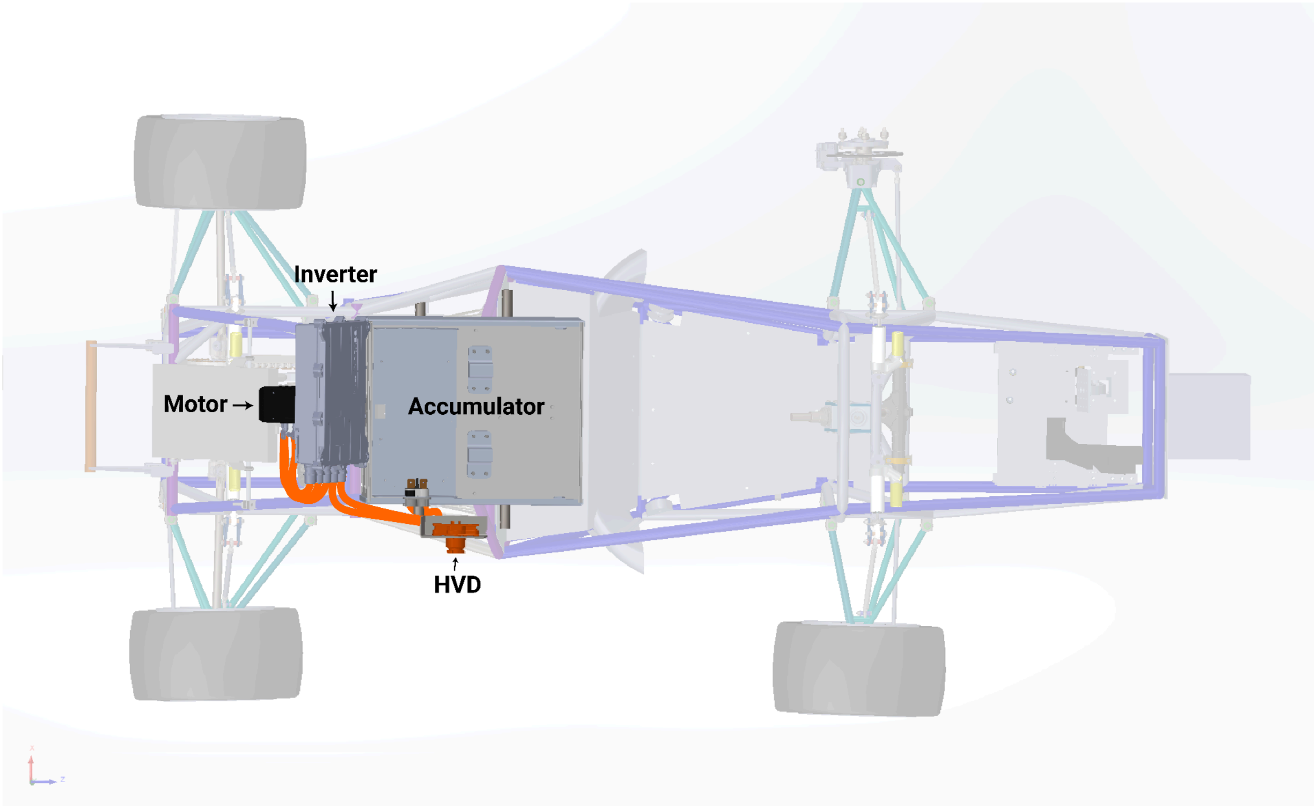


Figure 3 - Locations of all major TS components

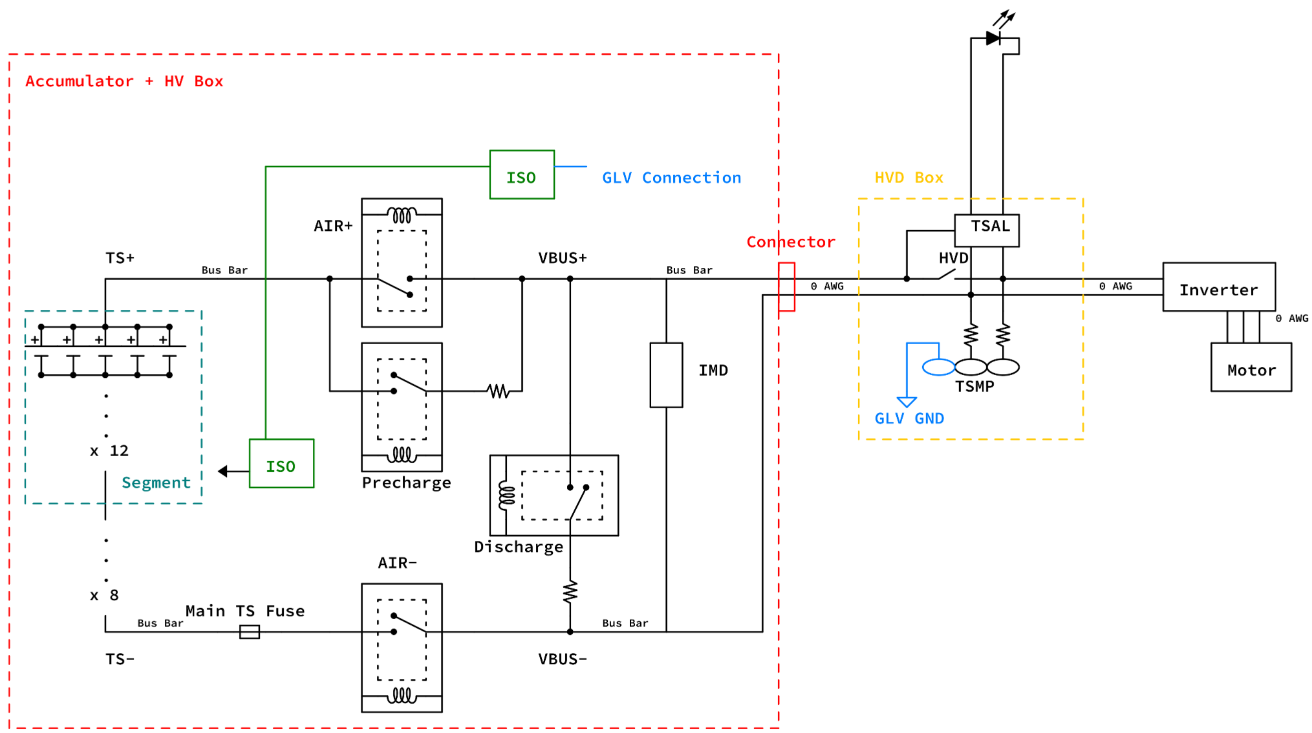


Figure 4 - TSV Wiring Schematic

Section 1 **Operating Voltage**

Person primarily responsible for this section:

Name: Evelyn Maude

e-mail: emaude@wpi.edu

Fill in the following table:

Item	Data
Nominal Tractive System Voltage (TSV_{nom})	345.6 VDC
Maximum Tractive System Voltage (TSV_{max})	403.2 VDC
Control System Voltage / Grounded Low Voltage System (GLV_{bus})	24 VDC

Table 1- General Electrical System Parameters

All wiring outside of our main GLV Box has a maximum voltage of 24 VDC. Our GLV battery is nominally 43.2 VDC.

Section 2 **Safety Circuit**

Person primarily responsible for this section:

Name: Carson Graham

e-mail: cjgraham@wpi.edu

2.1 Shutdown Circuit

Include a schematic of the shutdown circuit for your vehicle including all major components in the loop

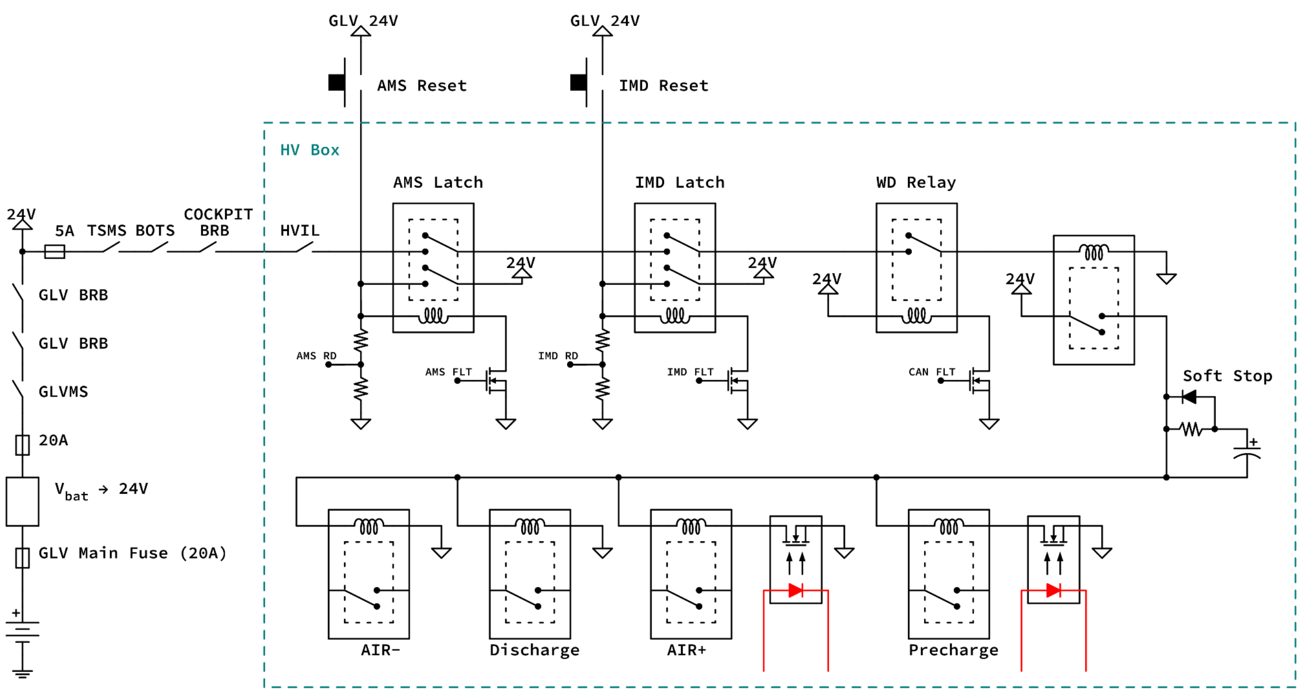


Figure 5 – Safety Shutdown Circuit Schematic

The *Soft Stop* circuit contains a 1.3mF capacitor that is used to hold both AIRs closed for 100ms after the shutdown loop is closed. This allows for the inverter to be commanded to stop drawing current through the AIRs before they open. The AIRs are not rated for a substantial number of break cycles at high current so this is critical to preserving the longevity and safety of the shutdown circuit. A parallel resistor/diode configuration is used to stop inrush current to the capacitor. This circuit has been validated with real life testing. The extra 100ms do not decrease the safety of the system in any capacity. The circuit has been deliberately designed such that the SDC still completely removes all energy sources besides this capacitor when it is tripped.

Describe the method of operation of your shutdown circuit, including the master switches, shut down buttons, brake over-travel switch, etc. Also complete the following table

Part	**Function (Momentary, Normally Open or Normally Closed)**
Main Switch (for control and tractive-system; CSMS, TSMS)	Normally Open
Brake over-travel switch (BOTS)	Normally Closed
Shutdown buttons (BRB)	Normally Closed
Insulation Monitoring Device (IMD)	Normally Open
Battery Management System (AMS)	Normally Open
CAN Bus Watchdog	Normally Open
HV Connector Interlock	Normally Closed

Table 2 - Switches & devices in the shutdown circuit

Describe wiring and additional circuitry controlling AIRs. Write a functional description of operation

Total Number of AIRs:	2
Coil holding current per AIR:	100 mA
Current drawn by other components wired in parallel with the AIRs.	40 mA
Total current in shutdown loop:	21.8 mA

Table 3 - Shutdown circuit Current Draw

Provide CAD-renderings showing the shutdown circuit parts. Mark the parts in the renderings

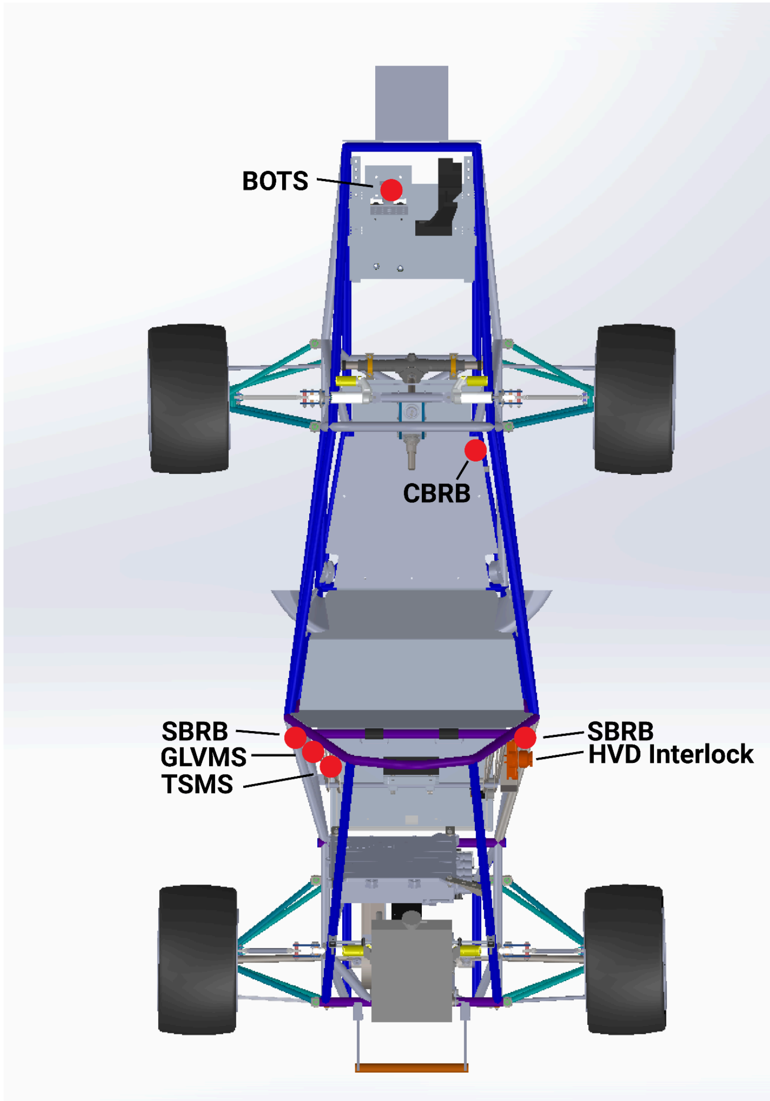


Figure 6 – Location of Shutdown Circuit Components

If your shutdown state diagram differs from the one in the Formula Hybrid rules, provide a copy of your state diagram (commented as necessary).

Our state diagram is identical to the one in the Formula Hybrid rules.

N/A

Figure 7 - Shutdown State Diagram (if non-standard)

2.2 Shutdown System Interlocks

(If used) describe the functioning and circuitry of the Shutdown System Interlocks. Describe wiring, provide schematics.

We have an additional interlock on the main HV connector as well as the HVD for added safety that is not required by the rules.

Section 3 **Indicator Operation**

Person primarily responsible for this section:

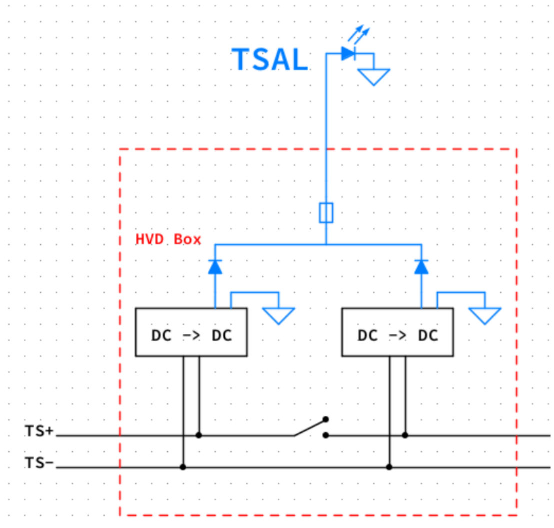
Name: Carson Graham

e-mail: cjgraham@wpi.edu

3.1 Tractive System Active Lamp (TSAL)

Describe the tractive system active lamp components and method of operation. Describe location and wiring, provide schematics. See ***EV9.1.***

The TSAL is powered by a TS/GLV PCB inside the HVD box. Schematics for isolation are shown in the PCB section of the ESF2. The TSAL is wired as shown below and uses two isolated DC/DC converters to isolate TS and GLV.



3.2 Safety Systems OK Lamp (ESOK)

Describe the Safety Systems OK Lamp components and method of operation. Describe location and wiring, provide schematics. See ***EV9.3***

Our car does not include ESOK light as per **EV9.3**

3.3 Ready-To-Drive-Sound (RTDS)

Describe your design for the RTDS system. See ***EV9.2.***

The ready to drive sound will activate when the drive button on the dashboard is pressed and the shutdown circuit is enabled. This will trigger a check if the car is ready to drive. If so, the dashboard will trigger a buzzer to sound a unique 3.1 kHz sound at 125 dBA for 2 seconds.

Section 4 **TSMP**

Person primarily responsible for this section:

Name: Evelyn Maude

e-mail: emaude@wpi.edu

4.1 Tractive System Measurement Points (TSMP)

*The TSMP must comply with FH Rule **EV10.3**. Describe the TSMP housing and location. Describe TSMP electrical connection point.*

The TSMPs are shrouded 4 mm banana jacks that accept shrouded (sheathed) banana plugs with non-retractable shrouds. The TSMPs live in the same housing as the HVD and are electrically downstream from the HVD. This housing is mounted flush to the side of the bodywork on the right side of the car and is clearly noticeable with the letters TSMP on it as well as the HVD disconnect label. A ground tap is also included and is isolated from TS inside this enclosure

TSMP Output Protection Resistor Value	15	kΩ
Resistor Voltage Rating	500	V
Resistor Power Rating	35	W

Table 4 – TSMP Resistor Data

Section 5 **Cables & Fusing**

Person primarily responsible for this section:

Name: Carson Graham

e-mail: cjgraham@wpi.edu

5.1 Fusing & Overcurrent Protection

List data for Primary TS and GLV fuses (or circuit breakers) and cross-reference to schematic.

Row	Mfg.	Fuse Part Number	Cont. Rating (A)	DC Voltage Rating	DC Interrupt Rating (A)	Schematic reference-designators (ref-des)
1	Littelfuse	0297004.WXT	4 A	32 VDC	1000 A	GLV 24V 22 AWG wires, TSAL, SDC
2	Littelfuse	0297020.WXT	20 A	32 VDC	1000 A	Fan, Pump, low side main GLV fuse, main charger fuse
3	Littelfuse	0451020.MRL	20 A	65 VDC	150 A	High side main GLV fuse
4	Littelfuse	0251002.NRT1L	2 A	125 VDC	300 A	Segment Balance Leads, ISO 5v rail fuse
5	Eaton	XEV25-175-SP	175 A	500 VDC	20000 A	Main TS fuse

Table 5 - Fuse Table

5.2 Component Fusing

List data sheet max fuse rating for each major component (e.g., motor controller, dc-dc converter, etc.)
Ensure that the rating of the fuse used is ≤ the maximum value for the component

Component	Max Fuse Rating per data sheet (A)	Conductor (Table 7 line number)	Installed Fuse Rating (A)	Fuse Part Number	Notes

Sevcon Gen5 Size9	400 A	1	175 A	Row 5	
Front GLV Loop	n/a	2	4 A	Row 1	
Back GLV Loop	n/a	2	4 A	Row 1	
TSAL	n/a	2	4 A	Row 1	
Shutdown Loop	n/a	2	4 A	Row 1	
GLVMS/GLV BRB Loop	n/a	3	20 A	row 2	
GLV Battery	45 A	n/a	20 A	row 3	
Radiator Fan	n/a	3	20 A	row 2	
Pump Power	n/a	3	20 A	row 2	

Table 6 - Component Fuse Ratings

5.3 System Wire Tables

*List wires and cables used in the Tractive System and the GLV system – (wires protected by a fuse of 1 A or less may be omitted.) Cable capacity is the value from FH Rules **Appendix E** (Wire Current Capacity).*

	Mfg.	Part Number	Size AWG / mm2	Insulation Type	Voltage Rating	Temp. Rating (C)	Current capacity (A)
1	Champlain Cable	EXRAD-HVX1/0X	1/0	EXRAD XLE	1000V	150	339
2	Alpha Wire	78083 SL005	22 AWG	mPPE	300V	80	7
3	Raychem	55A0811-16-9	16 AWG	XL-ETFE	600V	150	20
4	Alpha Wire	AZ241936 WH005	24 AWG	ETFE	600V	150	5

Table 7 - System Wire Table

Section 6 **Motors**

Person primarily responsible for this section:

Name: Evelyn Maude

e-mail: emaude@wpi.edu

6.1 Motor(s)

Manufacturer and Model:	Emrax 228 HV
Motor type (PM, Induction, DC Brush)	PMSM
Number of motors of this type used	1
Nominal motor voltage (V_{rms} l-l or V_{dc})	403.2 V
Nominal / Peak motor current (A or A/phase)	Nom: 115A / Peak: 240A
Nominal / Peak motor power	Nom: 46 kW/ Peak: 97 kW
Motor wiring – conductor	Table 7 Line Number: 1
Calculated max. road speed	80 MPH

Table 8 - Motor Data

Nominal voltage is our pack voltage. Nominal and peak currents are from the motor datasheet. Nominal and peak powers are calculated from these. We are using 1/0 wire which is somewhat oversized but integrates well with our connectors and motor controller and minimizes system resistance.

$Kv * Vin / ratio * tyre\_r$

$1.026 \frac{rad/s}{V} \cdot 403.2\,V / 2.3 \cdot 0.2m = 25.97 \frac{m}{s}$

6.2 Motor Controller

Manufacturer	Sevcon
Model Number	Gen5 Size9
Number of controllers of this type used:	1
Maximum Input voltage:	420VDC
Nominal Input Current (A)	400A
Output voltage (Vac l-l or Vdc)	403.2V Vac L-L
Isolation voltage rating between GLV (power supply or control inputs) and TS connections	2.3 kVdc
Is the accelerator galvanically isolated from the Tractive System per **EV3.5.7 & EV5.1**?	☑Yes / ☐ No

Table 9 - Motor Controller Data

Currents and voltages are from the datasheet.

Section 7 **Isolation & Insulation**

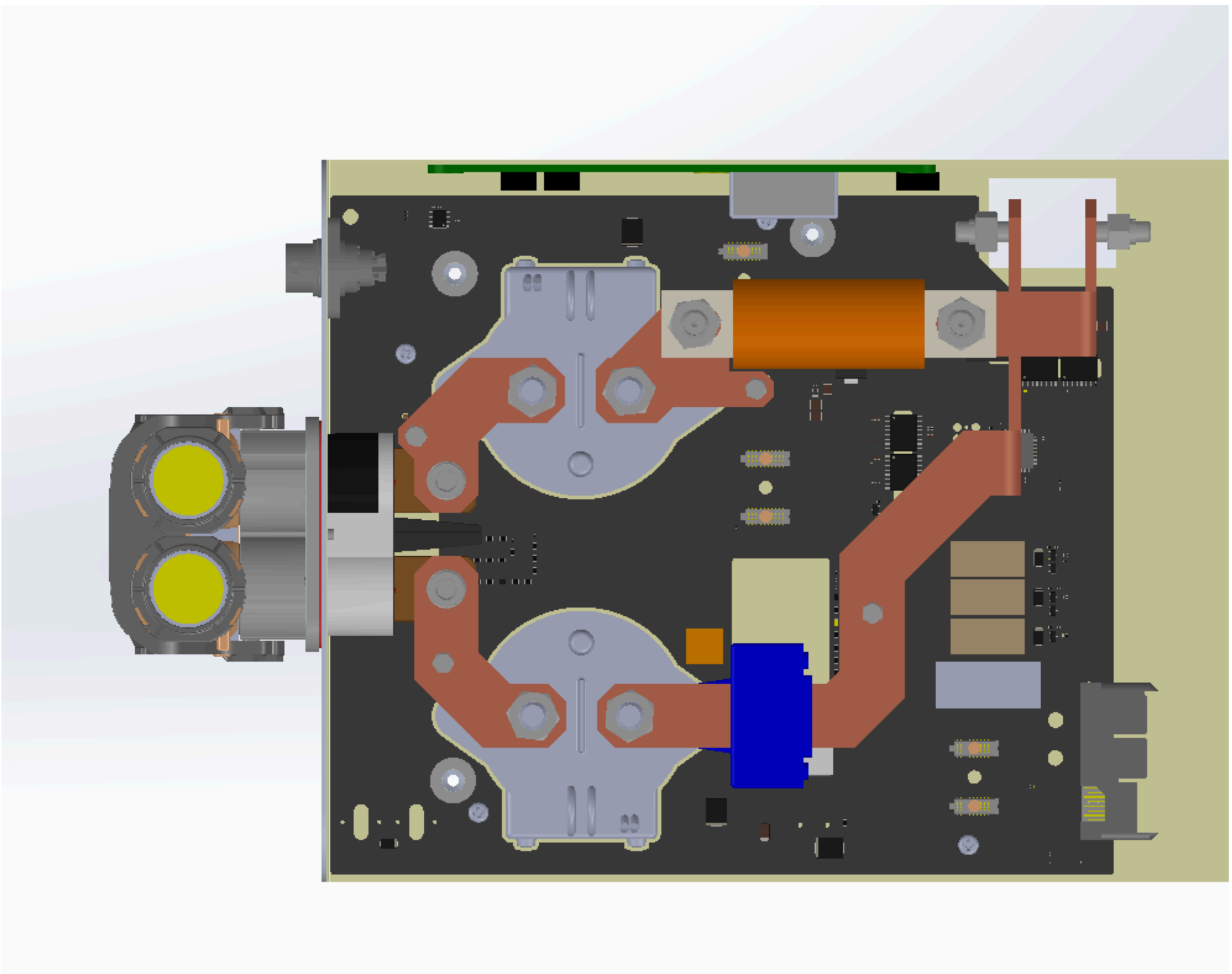
Person primarily responsible for this section:

Name: Evelyn Maude

e-mail: emaude@wpi.edu

7.1 Separation of Tractive System and Grounded Low Voltage System

*Describe how the TS and GLV systems are physically separated (**EV5.3**). Add CAD drawings or photographs illustrating TS and GLV segregation in key areas of the electrical system.*



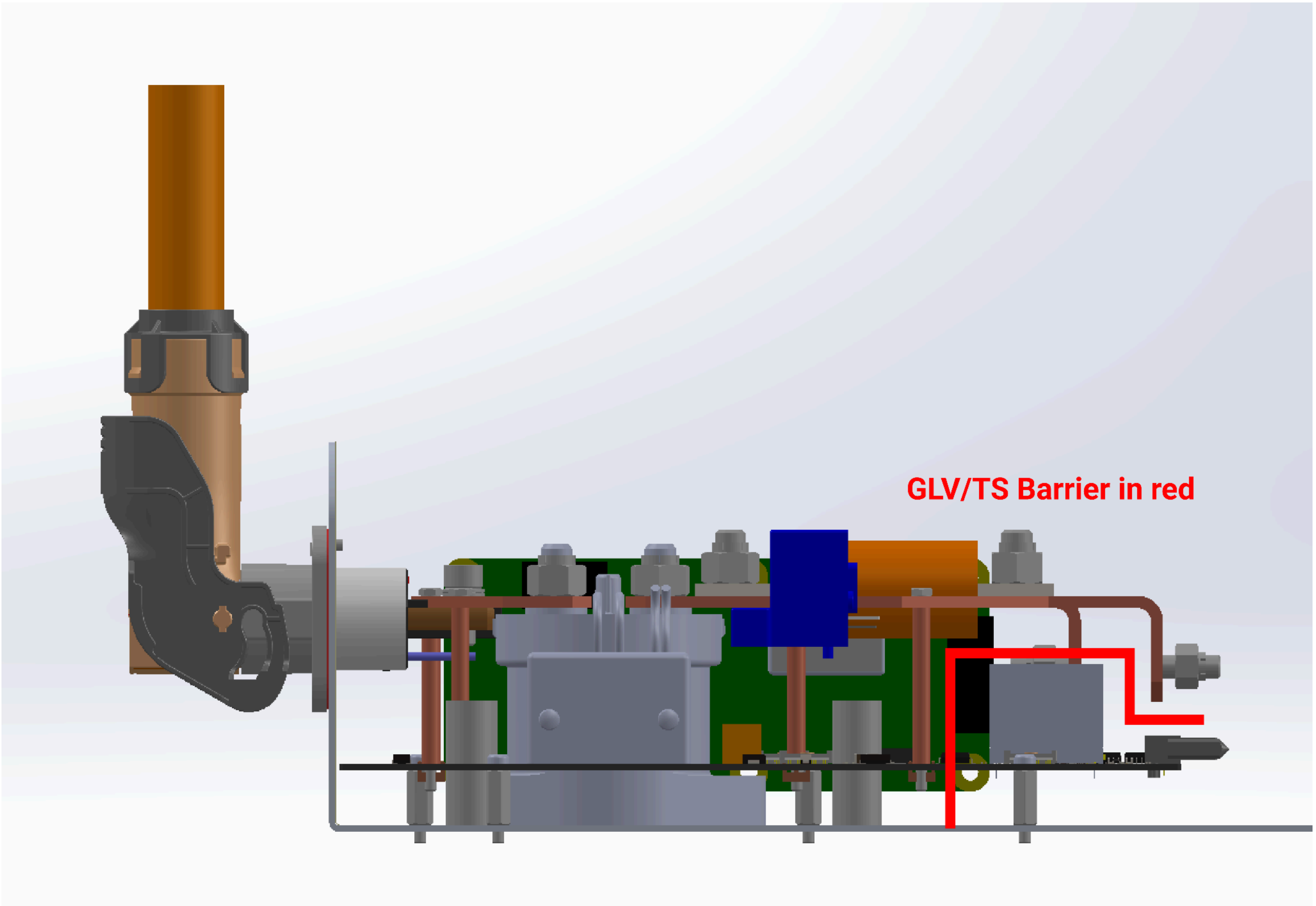


Figure 8 - TS and GLV separation

7.2 Grounding System

*Describe how you keep the resistances between accessible components below the required levels as defined in FH Rules **EV8.1**. If wire is used for ground bonding, state the AWG or mm^2 of the wire*

Our GLV battery negative terminal is bonded to the frame via 12 AWG wire.

7.3 Conductive Panel Grounding

*If carbon fiber or coated conductive panels are used in your design, describe the fabrication methods used to ensure point to point resistances that comply with **EV8.1.2**.*

Our carbon fiber body panels are sanded down in one location around a bolt used to bolt the panel to an unpainted frame tab. Through testing we have validated that this achieves the minimum resistance from any point

List all purchased components that have connections to both TS and GLV

Component	TS/GLV Isolation (V)	Link to Document Describing Isolation	Notes
Sevcon Gen5 Size9	2300	This document is under NDA	Inverter
WURTH 750311564	1500	link	TSAL
AMC3336	1700	link	Isolated ADC
ZB105x-AE	1500	link	Isolated DC/DC Transformer
EVC500	2920	link	AIR
G2RG-2A-X DC24	5000	link	Precharge Relay
S1-24-BDM	1500	link	Discharge Relay
AA36F-R1	3750	link	SSRs between GLV and TS

Table 10 – Purchased Components

7.4 Isolation

Provide a list of containers that have TS and GLV wiring in them. If a barrier is used rather than spacing, identify barrier material used (reference Table 12- Insulating Materials).

Container Name	Segregation by Spacing (Y or N)	How is Spacing maintained	Actual Measured Spacing mm	Alt – Barrier Material P/N	Notes
HV Box	N			Nomex 410 0.25mm	
HVD Box	N			Nomex 410 0.25mm	

Table 11 – List of Containers with TS and GLV wiring

List all insulating barrier materials used to meet the requirements of ***EV2.4.3*** *or* ***EV5.4***

Insulating Material / Part Number	UL Recognized(Y / N)	Rated Temperature ºC	Thickness mm	Notes
Nomex 410	Y	220	0.25	
UHMW	Y	180	>3	machined UHMW parts provide isolation, minimum thickness 3mm

Table 12- Insulating Materials

7.5 Conduit

List different types of conduit used in the design. Specify location and if manufacturer's standard fittings are used. Note Virtual Accumulator Housing FH Rules ***EV2.12*** *requires METALLIC type LFMC.*

Our team uses no conduit

Describe how the conduit is anchored if standard fittings are not used.

n/a

Conduit Type	MFR	Part Number	Diameter Inch or mm	Standard Fittings (Y or N)	Location / Use

Table 13 - Conduit Data

*Is all conduit contained within the vehicle Surface Envelope per **EV3.1.6**? (**Y or N**). n/a*
*Does all conduit comply with **EV3.2**? (**Y or N**). n/a*

7.6 Shielded dual-insulated cable

*If Shielded, dual-insulated cable per **EV3.2.5(a)** used in the vehicle, provide specifications and where used:*

MFR	Part Number	Cross Section mm2	Shield grounded at both ends (Y or N)	Location / Use
Champlain Cable	EXRAD-HVX1/0X	77	Y	All TS wiring outside accumulator

Table 14 - Shielded Dual Insulated Cable Data

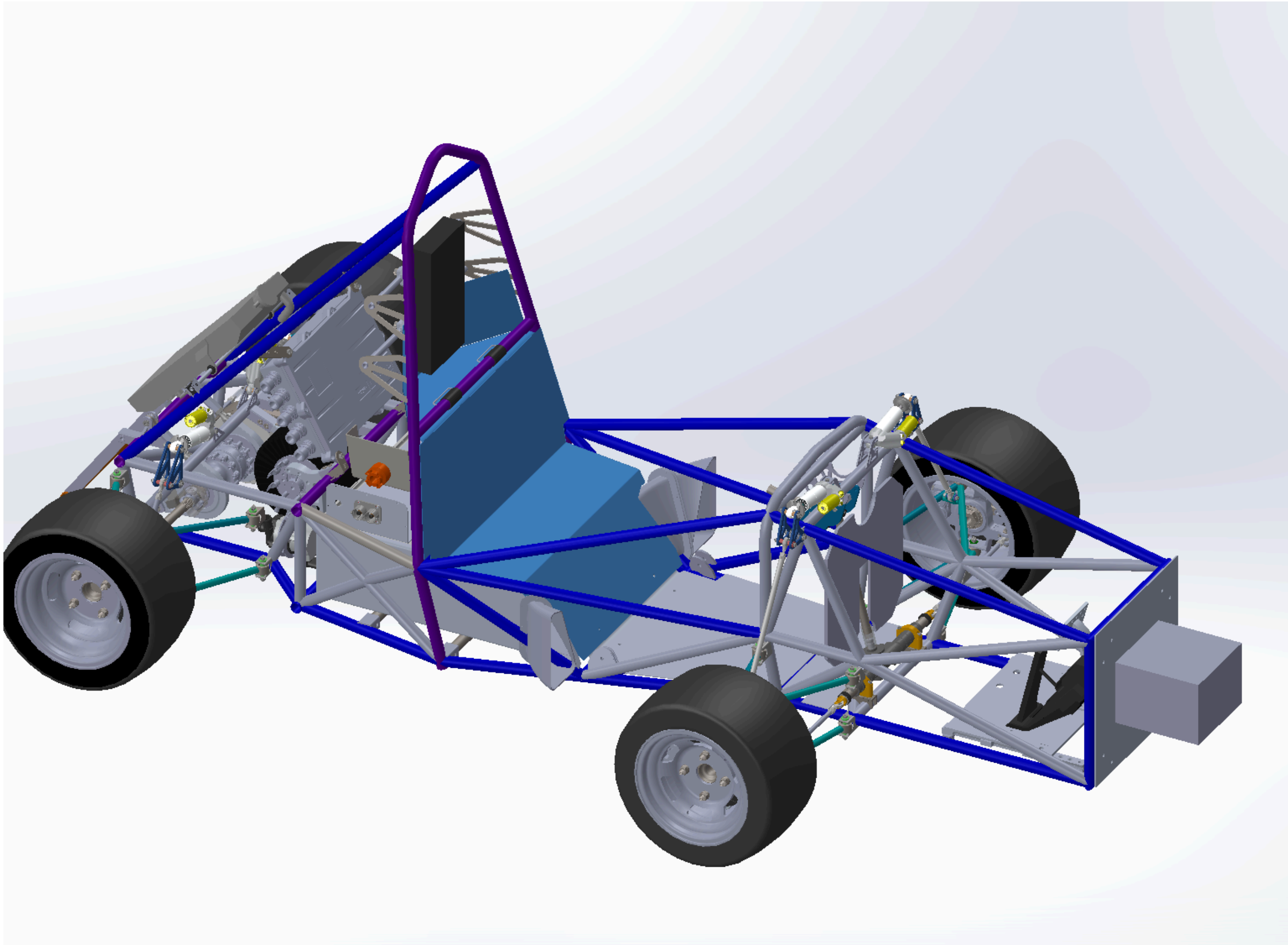
7.7 Firewall(s)

Description/materials

*Describe the concept, layer structure and the materials used for the firewalls. Describe how all firewall requirements in FH Rules **T4.5** are satisfied. Show how the low resistance connection to chassis ground is achieved.*

The firewall is made of 1.5mm thick aluminum(**T4.5.2)** and separates the driver from all parts of the car described in **T4.5.1.** The firewall is completely sealed where it interfaces with the frame as per **T4.5.3**. Two female jacks back to back in a box of the same material allow for GLV wiring to pass through the firewall without the need for a grommet (**T4.5.4**).

Position in car *Provide CAD-rendering or photographs showing the location of the firewall(s).*



Section 8 **Printed Circuit Boards**

Person primarily responsible for this section:

Name: Carson Graham

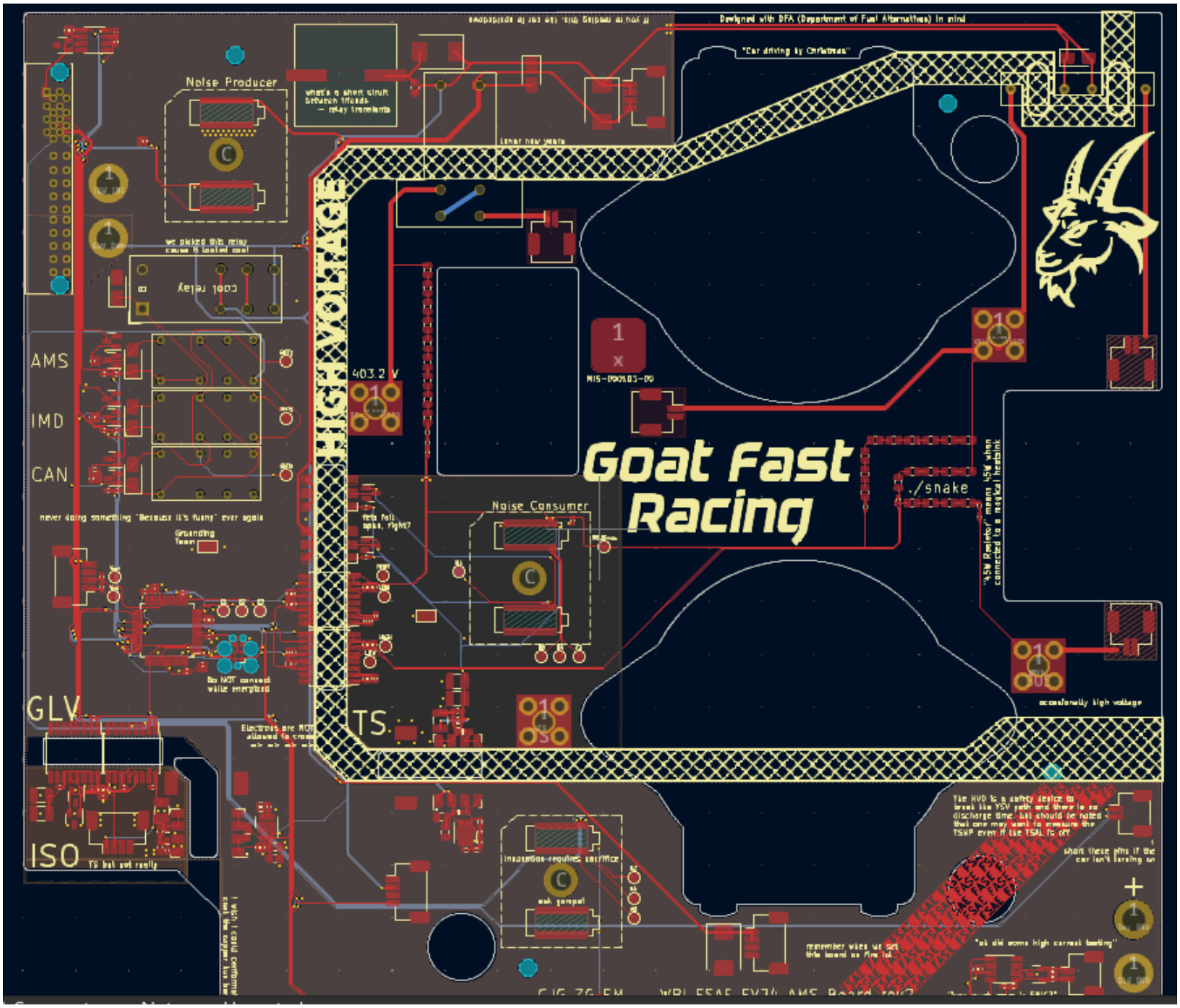
e-mail: cjgraham@wpi.edu

List all electrical circuit boards designed by the team that contain TS and GLV voltage in the following table.

Device / PCB	TS Voltage Present (V)	Minimum Spacing mm	Thru Air of Over Surface	Notes
AMS Board	402.3 VDC Max	6	over surface	with 4mm wide holes to ensure conformal coat application
TSAL Board	403.2 VDC Max	6	over surface	with 4mm wide holes to ensure conformal coat application

Table 15 - PCB Spacings

Add a figure (board layout drawing) <u>for each</u> team-designed PCB showing that spacings comply with ***EV5.5.***



Noise Producer
HIGH VOLTAGE
AMS
IMD
CAN
GLV
ISO
TS
403.2 V
Noise Consumer
Goat Fast
Racing
./snake

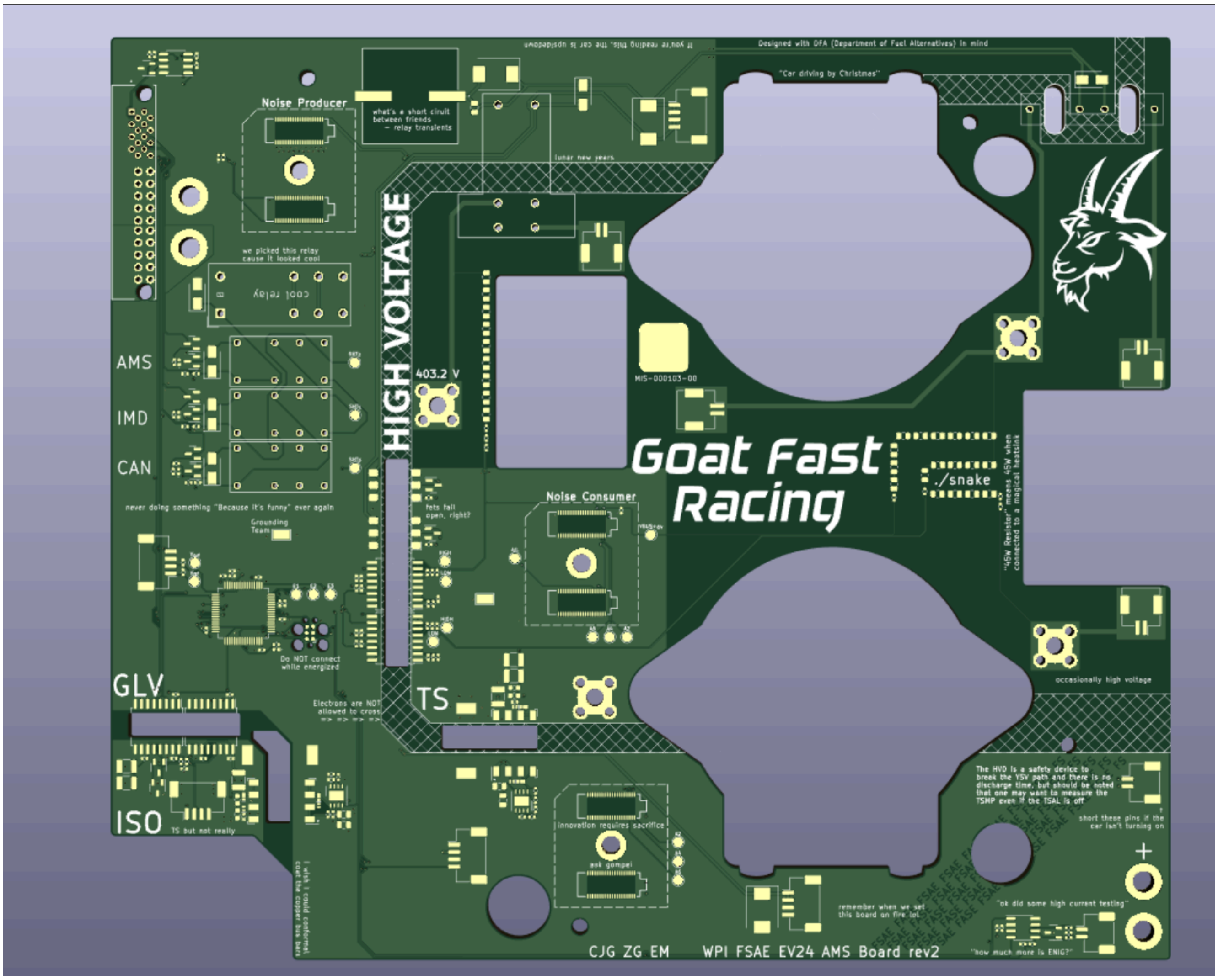


Figure 9.1 - AMS Board Team Designed PCB Layout

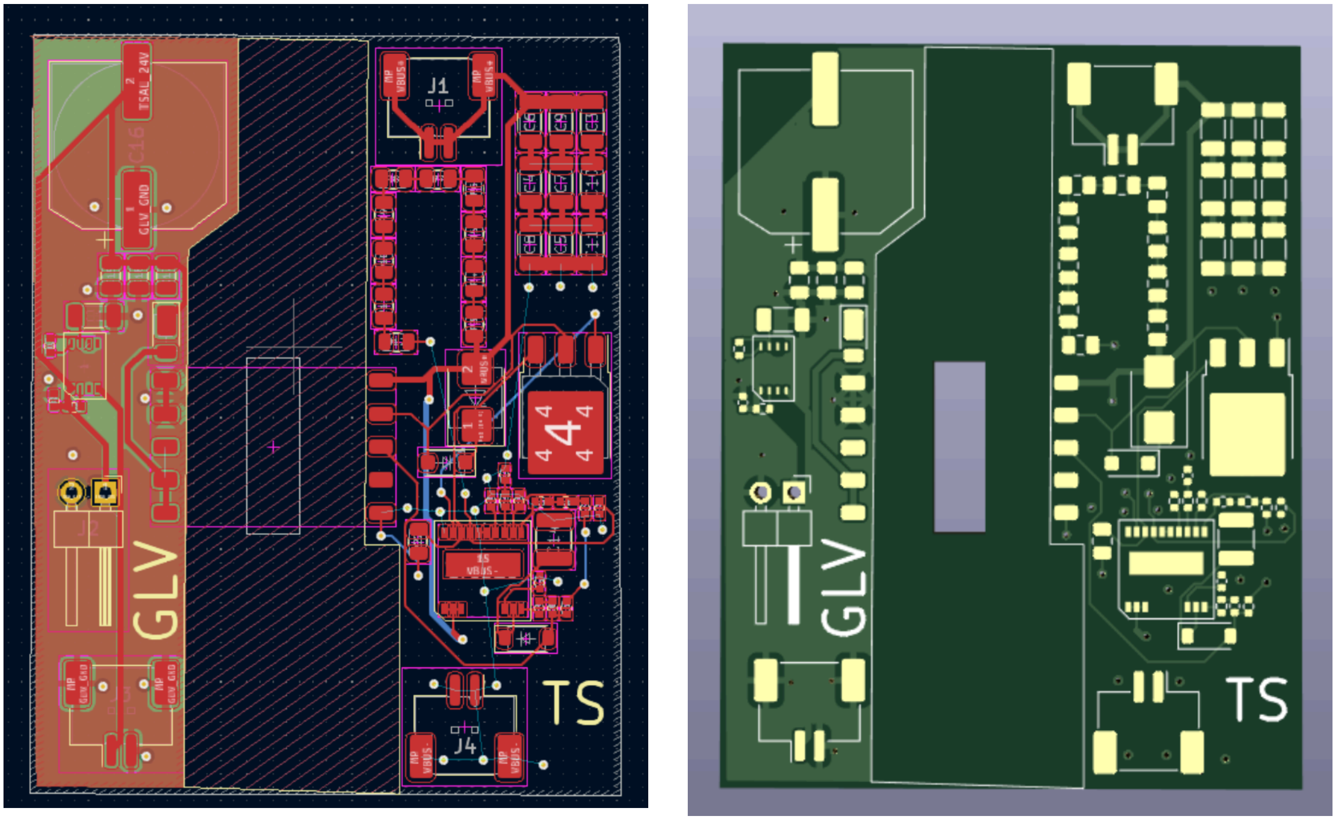


Figure 9.2 - TSAL Team Designed PCB Layout

Section 9 **IMD**

Person primarily responsible for this section:

Name: Evelyn Maude

e-mail: emaude@wpi.edu

9.1 IMD

Describe the IMD used and use a table for the common operation parameters, like supply voltage, temperature, etc. Describe how the IMD indicator light is wired. Complete the following table.

MFR / Model	Bender ISOMETER® IR155-3204
Set response value:	273 kΩ (677 Ω/Volt)

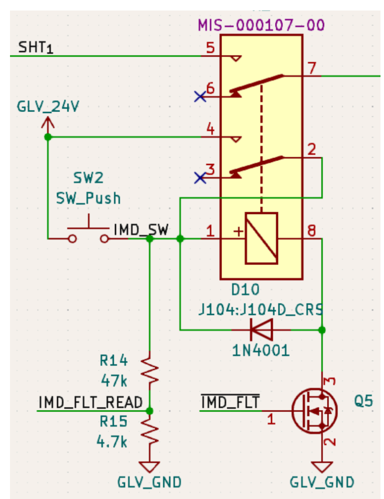
Table 16 - Parameters of the IMD

Describe IMD wiring with schematics.

9.2 Reset / Latching for IMD and AMS

Describe the functioning and circuitry of the latching/reset system for a tripped IMD or AMS. Describe wiring, provide schematics.

Fig <todo, below>. demonstrates our latching logic for our IMD. The logic is identical for the AMS, with a different fault signal source. SW2 is located off-board (which is what the IMD_SW label is for) but electrically this schematic is 100% accurate. When the relay is in the off position, pin 1 of the relay is electrically connected to nothing except the high impedance sense line. When SW2 is pressed, IMD_SW is brought high. If the fault MOSFET Q5 is in a high impedance state, this will bring both pin 1 and pin 8 of the relay high, not turning on the relay. If Q5 is in an ON state, current will travel from 24V to GND through SW2 and Q5, turning on the relay. The lower pole/throw of the relay is used to short SW2 and conduct current regardless of the state of the switch. This is the "unfaulted" state and is the only state where current is allowed to travel through the SDC.



If at any point in time, ~{IMD_FLT} is brought low, the current flowing through the relay coil is interrupted and both poles close, requiring the switch to be pressed before the micro

IMD_FLT_READ is used to read the latched status of the latch. ~{IMD_FLT} is connected directly to the IMD, and on the AMS schematic, connected directly to the AMS microcontroller.

Section 10 **AMS**

Person primarily responsible for this section:

Name: Carson Graham

e-mail: cjgraham@wpi.edu

10.1 Accumulator Management System (AMS)

Manufacturer	WPI FSAE
Model Number	N/A
Number of AMSs	1
Upper cell voltage trip	4.2 V
Lower cell voltage trip	2.7 V
Temperature trip	60 °C Discharge 45°C Charge

Table 17 - AMS Data

The main AMS system has been designed to high standards of isolation for safety reasons. The main AMS board contains a TS, GLV, and ISO zone. ISO is considered TS as per the rules, but as a team we consider it a completely separate power domain and internally enforce our TS/GLV isolation rules. Each zone is galvanically isolated from one another with at minimum 6mm of creepage/clearance with a 4mm cutout below every bridging component to ensure complete conformal coat application. ISO has an isolated 5V power rail and a CAN bus referenced to that power rail and is used to communicate to each segment. ISO ground is <u>not</u> referenced to any TS or GLV voltage. Y-caps are used for proper EMI suppression between ISO/GLV and TS/GLV.

- *Describe how the AMS meets the requirements of **EV2.11.***

Our car is compliant with all of the rules in the rulebook. Listed are all of the rules in **EV2.11** and descriptions of how we are rules compliant:

EV2.11.1 The AMS board monitors the state of the battery at all points in time that it is supplied with GLV power. This must be true before TS can be activated or the charger electrically connected to TS.

EV2.11.2 Each segment board monitors the voltage of all cell groups (12) in the segment. The segment board also monitors 18 individual thermistors which are bonded with thermal epoxy to two cells each, monitoring 36 of 60 cells per segment. The main AMS board receives these cell voltages and temperature readings from the segments over an isolated CAN bus and asserts an AMS fault if they exceed safe boundaries or stop being sent. This fault disables the SDC and turns off the car and opens the AIRs.

EV2.11.3 The fault reset button is located behind the left shoulder and is unreachable while seated in the car, even without wrist straps. The fault latching and fault reset logic is done entirely with analog electronics.

EV2.11.4 See **EV2.11.2** compliance

EV2.11.5 See **EV2.11.2** compliance

EV2.11.6 See **EV2.11.2** compliance. Thermistors are distributed equally throughout the segment.

EV2.11.6 Voltage sense wires are fused inline. These are used for balancing. See row 4 of table 5.

EV2.11.7 The electronics for the BMS on each segment are referenced to the negative terminal of the segment. The segment board has an isolated connection to the ISO CAN bus with the same standard as any isolated gap on our car. This isolated is rated for at least double the maximum TS voltage. GLV/TS boundaries on the AMS board, such as for controlling TS relays, follow the same isolation standard. See Section 8 for more details.

EV2.11.8 All GLV/TS boundary crossings are documented in Section 8 and are compliant with all isolation rules in the rulebook

EV2.11.9 The AMS microcontroller is dedicated to the task of managing the AMS board and fault status and will act independently. It is connected to other GLV microcontrollers via the car's main shared CAN bus for telemetry purposes, but cannot be commanded to change parameters or alter its behavior via this connection.
There are three watchdog timers on the AMS board that help keep the safety of the system in check

- A software watchdog on the AMS microcontroller that ensures data is still arriving from the segments
- A hardware watchdog on the AMS microcontroller that resets the chip and faults if the monitoring loop stops running and updating the status of the fault pin

- A dedicated watchdog microcontroller that interrupts the SDC with a relay if communication stops on the ISO CAN bus

We believe our watchdog setup exceeds the expectations set in the rulebook.

EV2.11.10 Our steering wheel, which is connected to the AMS board via CAN, has a clearly labeled red LED that mirrors the current status of the latched AMS fault relay. The labels are done with vinyl and are clearly visible the sunlight

- *Describe other relevant AMS operation parameters.*

N/A

- *Describe how many cells are monitored by each AMS board, the configuration of the cells, the configuration of the boards and how AMS communications wiring is protected and isolated.*

Each segment board monitors 60 cells. The cells are configured with 12 groups of 5 parallel cells in series. All cell groups connections are wired to the segment board for monitoring and balancing. The entire board is conformal coated.

- *Describe how the AMS opens the AIRs if an error is detected*

The AMS microcontroller receives all of the relevant data and holds AMS Fault MOSFET on while the data it receives continues to be sent. If the data stops being received, or if it becomes noncompliant, the AMS microcontroller turns the MOSFET off, latching the AMS relay into an OFF state. This interrupts the SDC current flow and turns off the AIRs. This satisfies **EV2.11.2**/**EV2.11.4/EV2.11.5**.

When the AMS microcontroller turns on (when GLV power is applied), the default state of the AMS fault is faulted. The AMS Fault MOSFET is held off for at least 1 second on startup to guarantee that the relay is in the unlatched state before turning on if the system is safe to turn on. The AMS microcontroller implements a hardware-level watchdog that ensures the AMS Fault MOSFET control pin status is fed with the correct state on a regular interval, and that watchdog hard restarts the microcontroller. This watchdog guards against flaws in the programming of the chip, and with luck will never actually be invoked outside of direct testing. This watchdog is not required for rules compliance.

- *Indicate in the AMS system the location of the isolation between TS and GLV*

There is an isolated 5V flyback DC-DC converter that powers TS with 5V from the GLV side. The two AIRs, the precharge relay, and the discharge relay are also TS/GLV boundaries. There are also two isolated SSRs and two isolated ADCs that bridge the TS/GLV boundary.

Section 11 **Accumulator and Container**

Person primarily responsible for this section:

Name: Evelyn Maude

e-mail: emaude@wpi.edu

11.1 Accumulator Pack

Provide a narrative design of the accumulator system and complete the following table.

Maximum Voltage (during charging):	403.2 VDC
Nominal Voltage:	VDC
Total number of cells:	480
Cell arrangement (x in series / y in parallel):	96 Series / 5 Parallel
Are packs commercial or team constructed?	☐ Commercial / ☒ **Team**
Total Capacity (per FH Rules **Appendix A**[2]):	5.391 kWh
Maximum Segment Capacity	5.98752 MJ
Number of Accumulator Segments	4

Table 18 - Main accumulator parameters

*Describe how pack capacity is calculated. Provide calculation at 2C (0.5 hour) rate. How is capacity derived from manufacturer's data? If so, include discharge data or graph here. Include Peukert calculation if used (See FH Rules **Appendix A**)*

Energy (Wh) = Vnom x Inom x Total Number of Cells x 80%

[2] This includes an 80% derating for available traction energy

5.391 kWh = 3.6 V (Vnom) * 3.9 Ah (Inom) * 480 * 0.8

Show your segment energy calculations. The segment energy is calculated as:

$$Vnom\ x\ Cell\ AH\ (2C\ rate)\ x\ Number\ of\ Cells\ x\ 3.6\ (kJ)$$

5.98752 MJ = 3.6 V * 3.9 Ah * 480 * 0.8

(Note: The 80% factor is not applied for this calculation.)

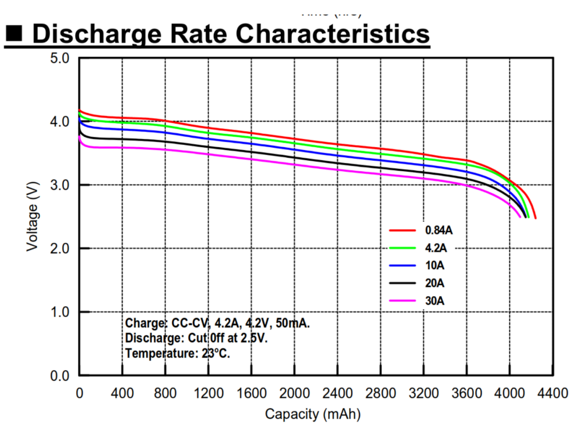
11.2 Cell description

Describe the cell type used and the chemistry and complete the following table.

Cell Manufacturer	Molicel
Model Number	INR-21700-P42A
Cell type (prismatic, cylindrical, pouch, etc.)	Cylindrical
Are these pouch cells	☐Yes / ☒ **No**
Cell nominal capacity at 2C (0.5 hour) rate:	3.9Ah at 2C rate
Data sheet nominal capacity	4.2 Ah
Maximum Voltage (during charging):	4.2 VDC
Nominal Voltage (data sheet value):	3.6 VDC
Minimum Voltage (AMS setting):	2.7 VDC
Maximum Cell Temperature (charging - AMS setting)	45 °C
Maximum Cell Temperature (discharging - AMS setting)	60 °C
Cell chemistry:	NMC

Table 19 - Main cell specification

IMPORTANT: *Show your calculations here for 2C nominal AH capacity if the data sheet uses a different discharge rate. Refer to FH rules* ***Appendix A***



11.3 Cell configuration

Describe cell configuration, show schematics, cover additional parts like internal cell fuses etc.

Describe configuration: e.g., N cells in parallel then M packs in series, or N cells in series then M strings in series.

Our cells are in a 5p96s configuration.

Does the accumulator combine individual cells in parallel without cell fuses? ☒Yes / ☐ No

*If Yes, explain how **EV2.6.3** is satisfied.*

As discussed in Ticket #3531, "EV2.6 Rules Question and Possible Exemption," our Molicel INR21700-P42A cells have sufficient internal fusing to be compliant with EV2.6.3. As specified in EV2.6.5 (b), they do not produce heat, sparks, or flames when subjected to a short circuit condition or to a 300% rated current condition.

11.4 Segment Maintenance Disconnect

Describe segment maintenance disconnect (SMD) device, locations, ratings etc.

Is HVD used as an SMD?	☐Yes / ☒No	
Number of SMD Devices / Number of Segments	8/4	
SMD MFR and Model	Molex EXTreme PowerMass 3.18mm Pitch, 150A Module	
SMD Rated Voltage (if applicable)	600	V
SMD Rated Current (if applicable)	150	A
Segment Energy (6 MJ max[3])	5.98	MJ
Segment Energy Discharge Rate (Ref FH Rules **Appendix A**)	15	C

Table 20 - SMD Data

11.5 Lithium-Ion Pouch Cells

The vehicle accumulator uses individual pouch cells. Yes ☐ **No** ☒

[3] Note *Segment energy = rated AH x nominal voltage*. The 80% derating is NOT applied for this calculation.

Note that designing an accumulator system utilizing pouch cells is a substantial engineering undertaking which may be avoided by using prismatic or cylindrical cells.

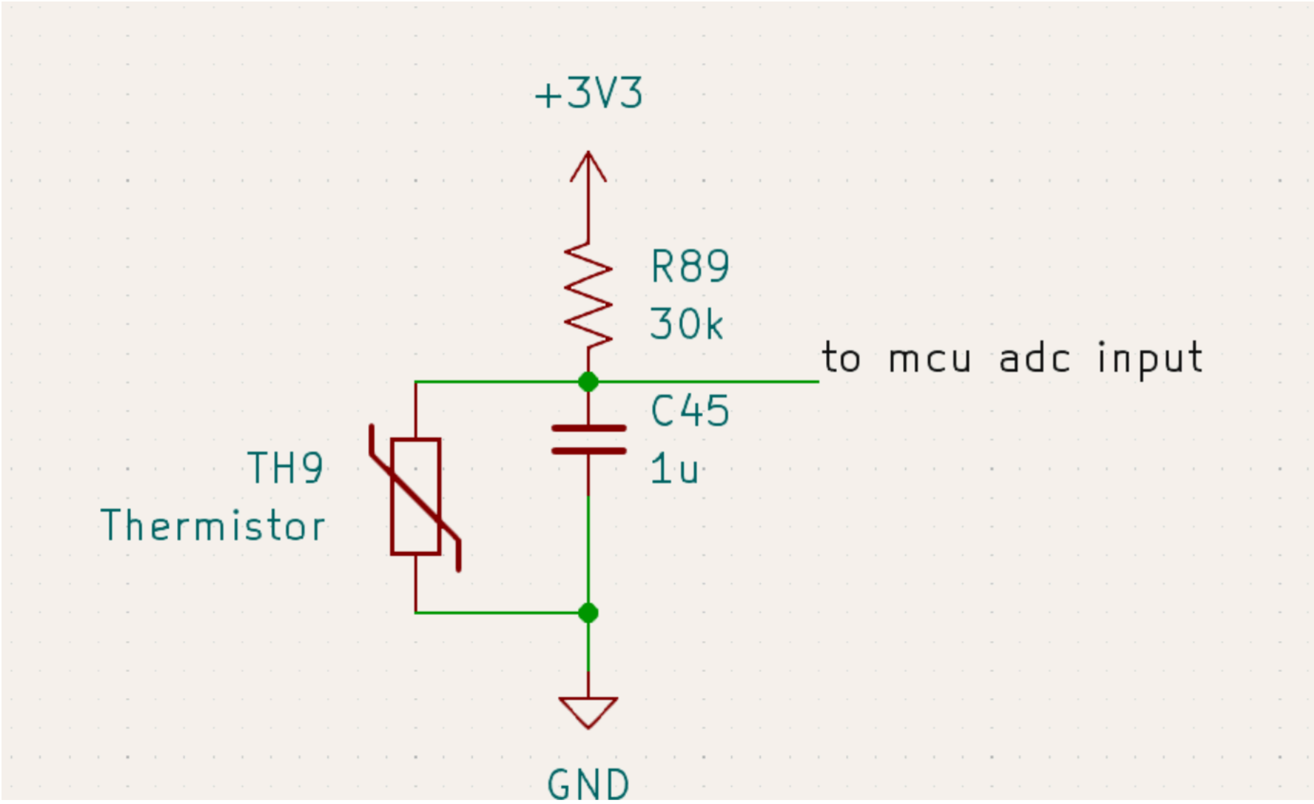
*If your team has designed your accumulator system using individual Lithium-Ion pouch cells, include drawings, photographs and calculations demonstrating compliance with all sections of rule **EV11.** If your system has been issued a variance to **EV11** by the Formula Hybrid rules committee, include the required documentation from the cell manufacturer along with a copy of the variance.*

11.6 Cell temperature monitoring

Describe how the temperature of the cells is monitored, where the temperature sensors are placed, how many cells are monitored, etc. Show a map of the physical layout. Provide schematics for team-built electronics.

Number of Cells with Temperature Monitoring	272 cells with 144 thermistors
Total Number of Cells	480
Percentage Monitored $(monitored\ /\ total)$	56%
Percentage Required by FH Rules: **Table 11**	30%
If each sensor monitors multiple cells, state how many:	2 for the vast majority of sensors, 1 for some.

Table 21 - Cell Temperature Monitoring



11.7 Accumulator Isolation Relays (AIR)

Describe the number of AIRs used and their locations. Also complete the following table.

We have two AIRs on the negative and positive sides of the tractive system main current path. They are located in the HV box. The negative side AIR is wired directly to the shutdown circuit. The positive side of the AIR is connected to the shutdown circuit through a low-side isolated SSR that is controlled by precharge circuitry. See Section 12 (Precharge) for more information.

Manufacturer	TE Connectivity
Model Number	TE P/N 2098190-1
Contact arraignment:	Form X - SPST-NO-DM
Continuous DC current rating:	500 A
Overload DC current rating:	2000 A for 15 sec

Maximum operation voltage:	900 VDC
Nominal coil voltage:	24 VDC
Normal Load switching:	Make and break up to 650 A

Table 22 - AIR data

11.8 Accumulator wiring, cables, current calculations

Describe internal wiring with schematics if appropriate. Provide calculations for currents and voltages and show data regarding the cables and connectors used. Discuss maximum expected current, whether DC or AC, and duration Compare the maximum values to nominal currents

We fuse at 175 A and use 1/0 gauge wire for all TS wiring. This puts our wire substantially thicker than would be needed for rules compliance fusing, and we are not concerned at all with the overheating of these wires.

11.9 Accumulator indicator

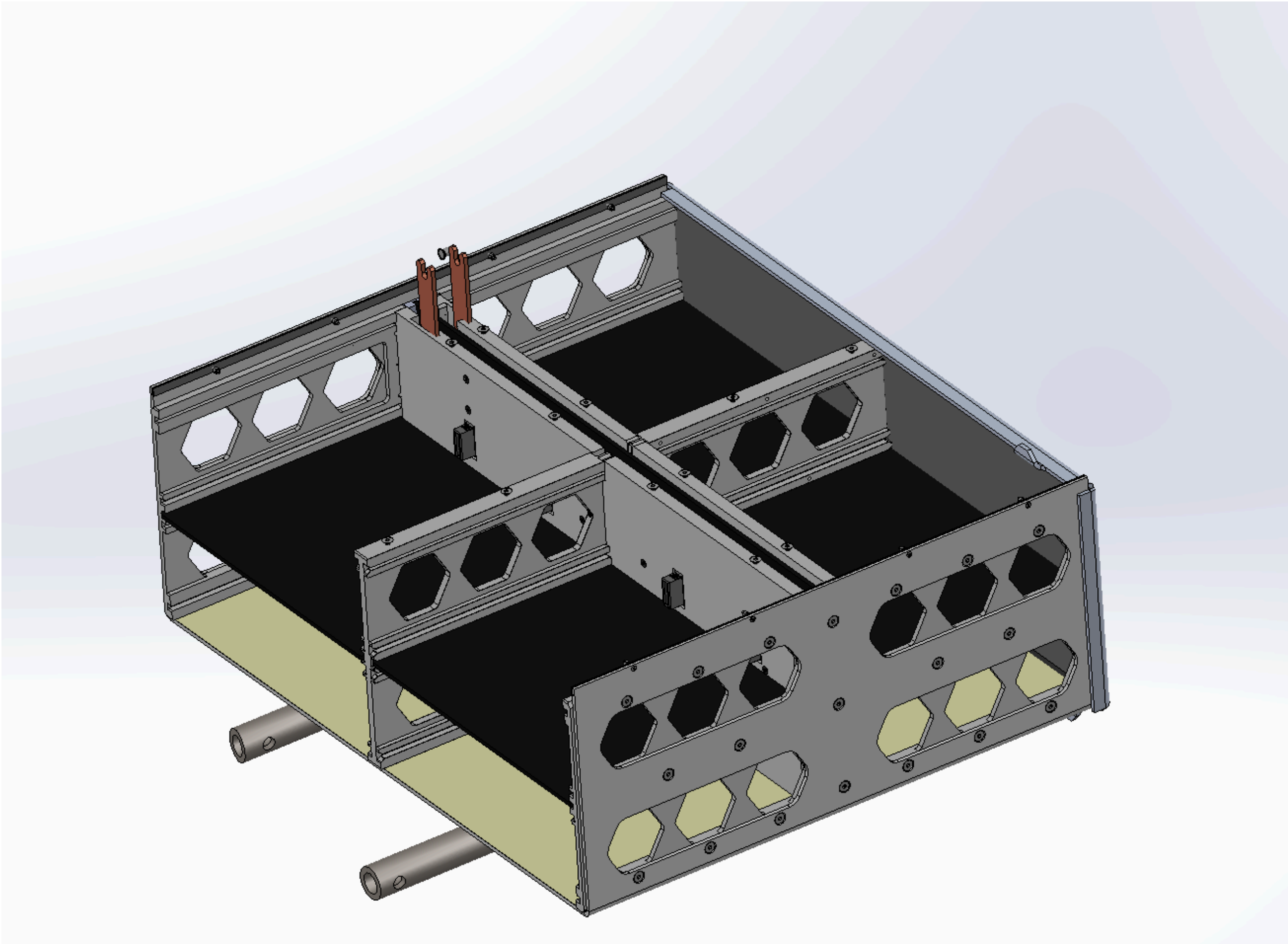
If accumulator container is removable, describe the voltage indicator, including indicating voltage range

We have our HVI driven by op amps comparators on externally facing TS voltage to illuminate the HVI when the voltage outside the accumulator is above 30 VDC

11.10 Accumulator Container/Housing

Describe the design of the accumulator container. Include the housing material specifications and construction methods. Include data sheets for insulating materials. Include information documenting compliance with UL94-V0, FAR25 or equivalent.

The accumulator is made from bent aluminum. We use Nomex 410 0.25mm as an insulator on every relevant surface. Plastic screws are used in any metal parts or in any parts near cells. G10 FR4 is used for the firewall in the center separating segments on the left and right side of the container. G10 FR4 is also used for the horizontal firewall which separates segments on the top and bottom side of the container.



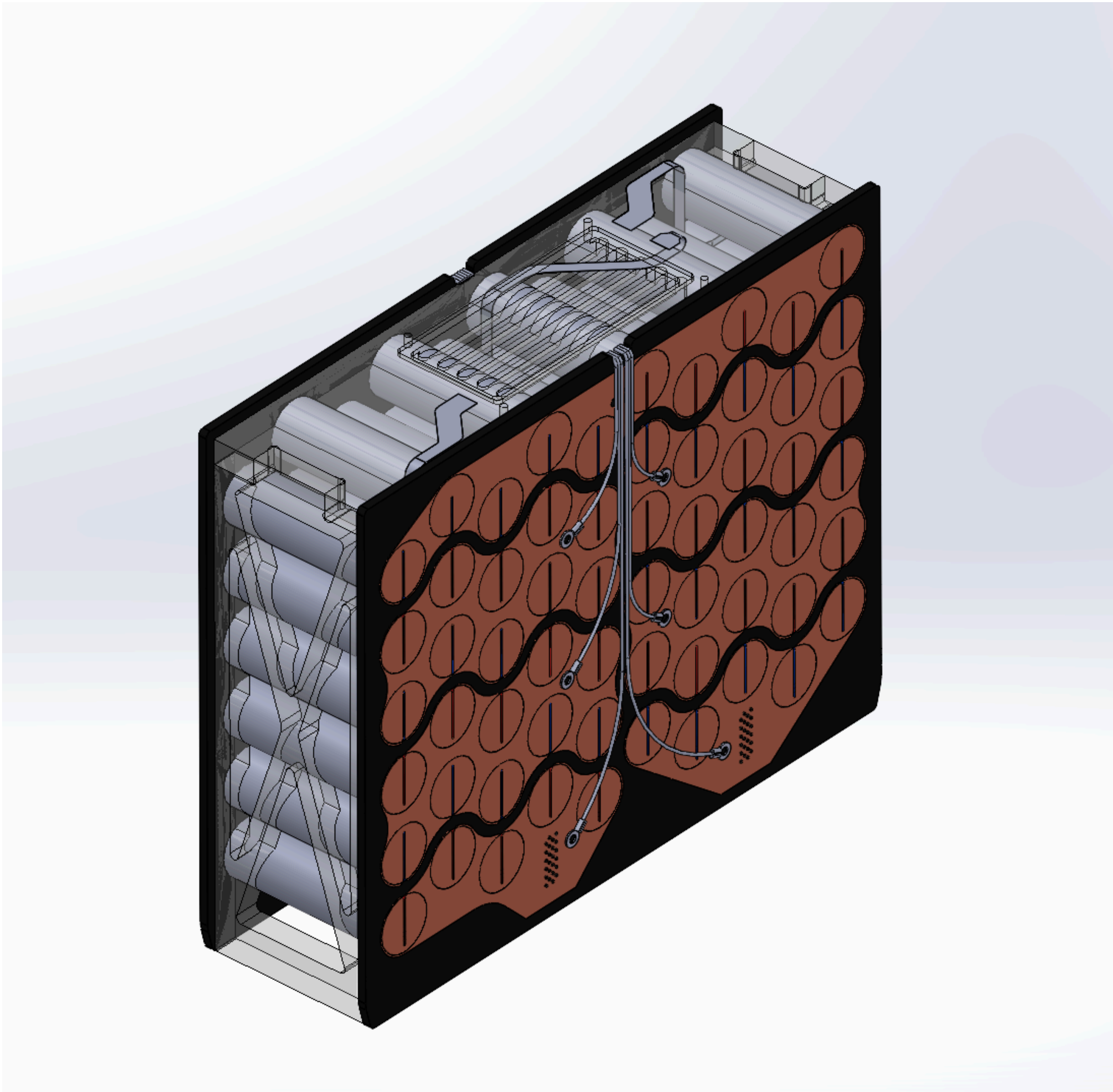
G10 firewalls shown in black

If the housing is made of conductive material, include information on how the poles of the accumulators are insulated and/or separated from the housing, and describe where and how the container is grounded to the chassis.

The container is grounded to the chassis at its attachment points to unpainted frame tabs. The inside face of the container is covered in Nomex 410 0.25mm in all relevant places.

*Include additional photographs if required, to illustrate compliance with rule **EV2.4.***

*Show how the cells are mounted, use CAD-Renderings, sketches or photographs showing compliance with FH Rule **EV2.4.7.***



The cells are epoxied to two G10 FR4 plates which are held in place inside the accumulator.

11.11 HV Disconnect (HVD)

*Describe your design for the HVD and how it is operated, wiring, and location. Describe how your design meets all requirements for **EV2.9.***

EV2.9.1 The HVD we use is an EM30MSD. It is located in the TS main current path and is mounted flush to our body work for ease of accessibility.
EV2.9.2 It is a twist lock and is operable without tools
EV2.9.3 We believe it is easy enough to understand that an uninformed person could disconnect it within 10 seconds if asked

EV2.9.4 We will.

EV2.9.5 The adjacent bodywork next to the HVD will be marked with the appropriate sticker

EV2.9.6 The HVD when in it’s disconnected state has a cap that is fully removed.

EV2.9.7 The HVD will be fully removed when the car goes through full lockout tagout procedure

EV2.9.8 n/a

Note: The HVD must be prior to TSMPs such that TSMPs are de-energized when the HVD is open.

Our TSMPs are directly downstream of the HVD so that they are de-energized when the HVD is open and the inverter capacitors are discharged.

Section 12 **Pre-charge / Discharge**

Person primarily responsible for this section:

Name: Carson Graham

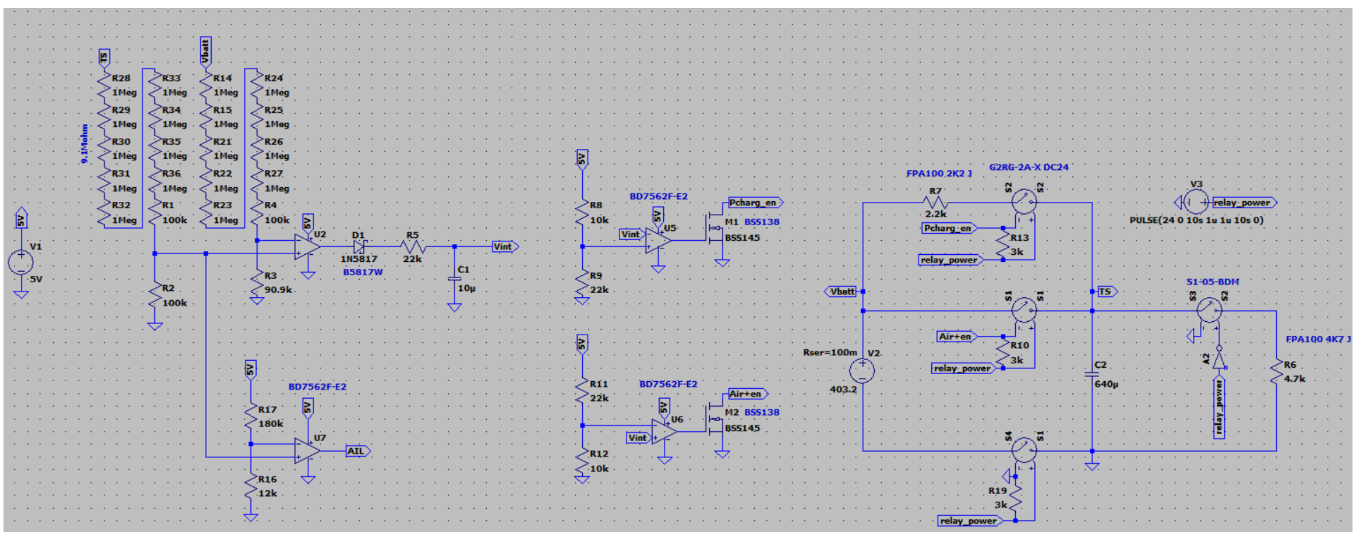
e-mail: cjgraham@wpi.edu

12.1 Pre-Charge circuitry

Describe your design for the pre-charge circuitry. Describe wiring, connectors and cables used.

- *Include a schematic of the pre-charge circuit*
- *Include a plot of calculated TS Voltage vs. time*
- *Include a plot of calculated Current vs. time*
- *Include a plot of resistor power vs time.*

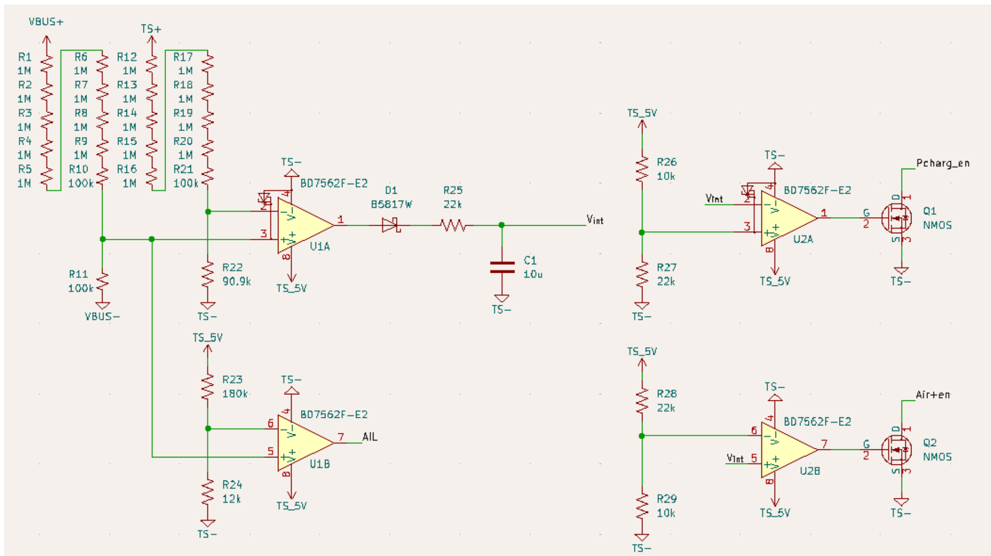
The precharge circuit is designed to bring up the voltage of the Traction system to ~90% (362.88V) before closing the main Accumulator Isolation Relays (AIR). The precharge circuit consists of two main elements: the control circuit and the relays.



Full Precharge & Discharge Circuit LTSpice model

The control circuit itself is split into two parts which control when the precharge relay is closed and when the AIR is closed. Both parts use a BD7562F-E2 IC which has two op-amps built in. The first pair of op-amps are used to set a reference level called Vint and to power the traction system voltage indicator. The second pair of op-amps drive a pair of BSS138 NMOS to control the precharge and AIR relays.

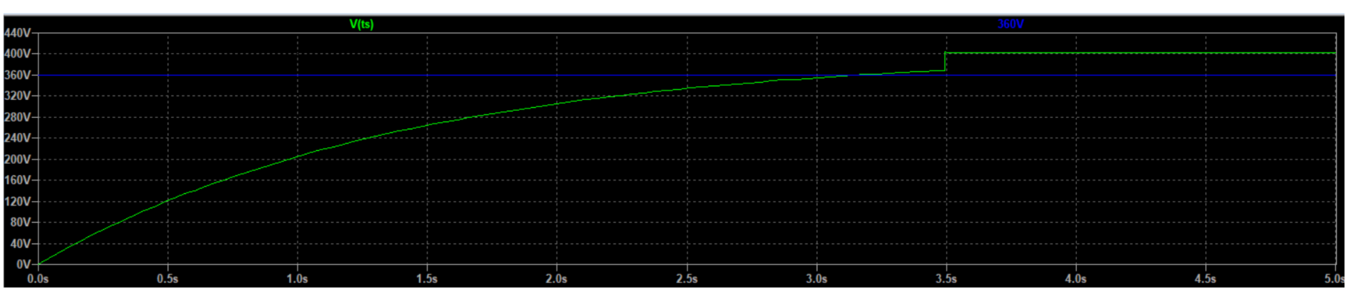
Both the accumulator and the traction system voltage are fed into voltage dividers that apply roughly 1% of the voltage to the inputs of the first op-amp (U1A). The output of the op-amp will then be used as a reference(Vint) for the subsequent parts of the circuit. The output of Vint will be 0V until the traction system reaches a voltage above 366.87V or 90.9% of the accumulator voltage. This same behavior is repeated with the op-amp below it (U1B) which activates the traction system voltage indicator LED when the TS voltage is higher than 28.75V.



Precharge control circuit: KiCAD model

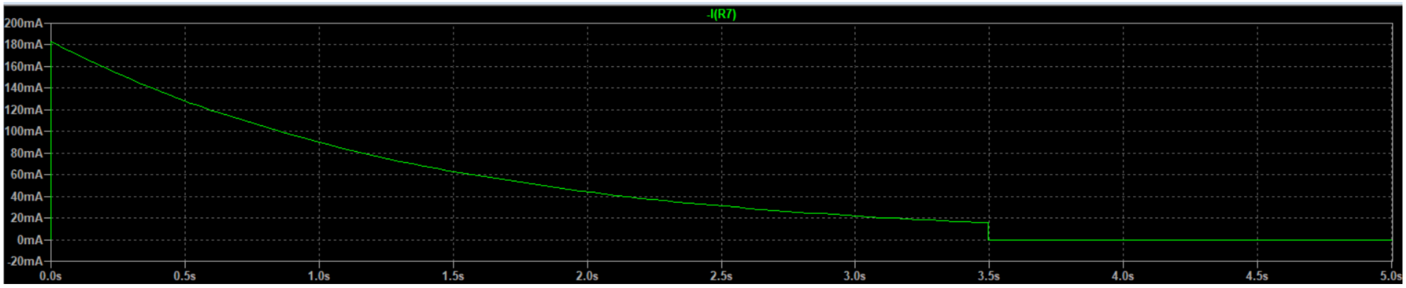
Vint is used as the inverting input offset for the precharge op-amp (U2A). The non-inverting input is set to 3.4375V which means the precharge circuit will be active until Vint goes high. The output of the op-amp is used to drive the gate of a NMOS which when active will create a path for current to flow for the precharge relay.

For the AIR op-amp (U2B) Vint is used as the reference for the non-inverting input. The inverting input is set to 1.5625V which will ensure that the accumulator isolation relay will turn on before the precharge relay turns off. This can be seen from the TS voltage as the sudden jump from 366.87V to 403.2V which ensures a smooth transition from one relay to another.

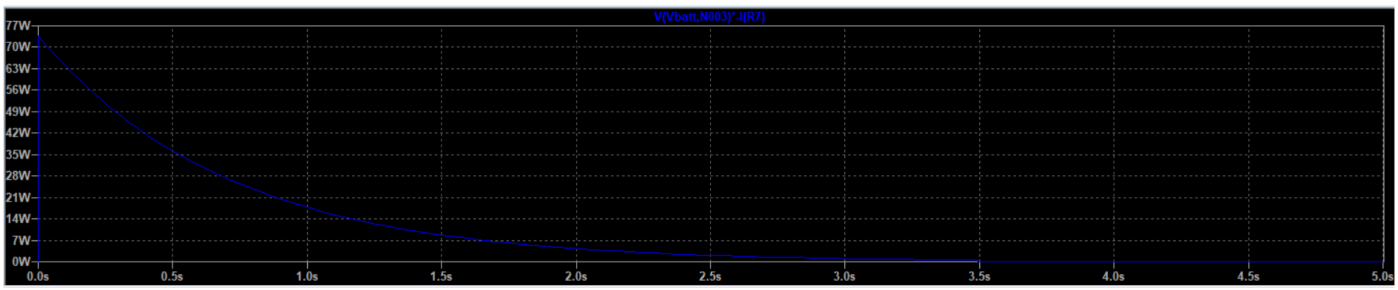


TS voltage vs. time.

Besides the control circuit the precharge circuit consists of the precharge resistors and relay. The resistor is a FPA100 2K2 J in series with a G2RG-2A-X DC24 normally open power relay. Once the precharge circuit is active there is about 183mA of peak current going through the precharge resistors which results in a peak power dissipation of 73.89W.



Current vs. time through precharge resistor



Power dissipation vs. time through precharge resistor

Provide the following information:

Resistor Type:	FPA100 2K2 J
Resistance:	2200 Ω
Continuous power rating:	100 W
Overload power rating:	n/a

Voltage rating:	1000 V

*Table 23 - Data for the pre-charge resistor (***FPA100 2K2 J***)*

Relay MFR & Type:	G2RG-2A-X DC24
Contact arrangement: (e.g. SPDT)	DPST
Continuous DC contact current:	10 A
Contact voltage rating:	500 Vdc

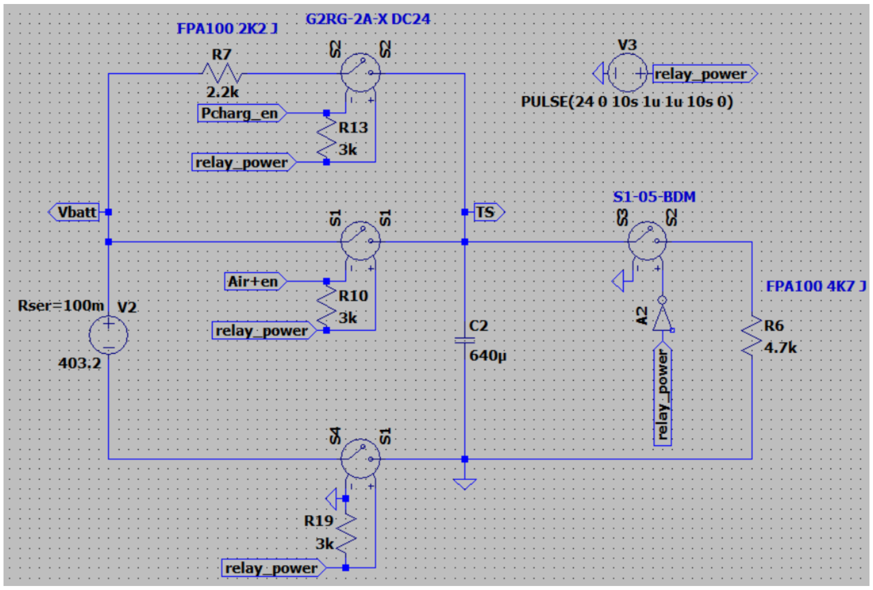
*Table 24 - Data of the pre-charge relay (***G2RG-2A-X DC24***)*

1.1 Discharge circuitry

Describe your concept for the discharge circuitry. Describe wiring, connectors and cables used.

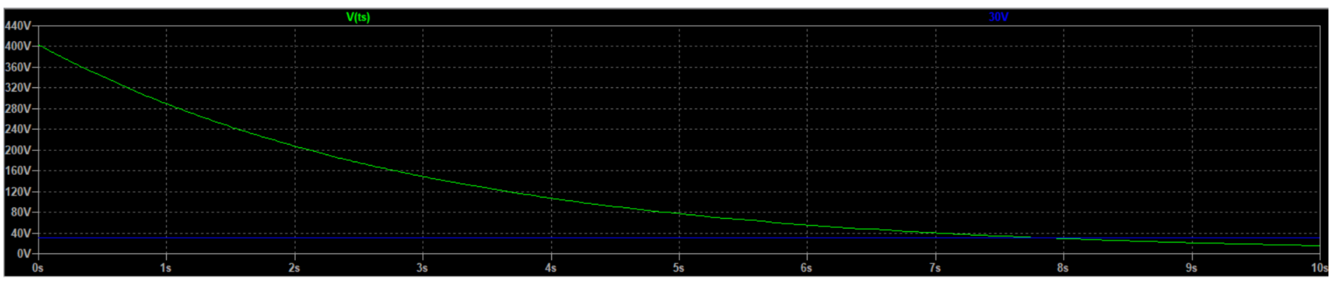
- *Include a schematic of the discharge circuit*
- *Include a plot of calculated TS Voltage vs. time*
- *Include a plot of calculated "Discharge current" vs. time*
- *Include a plot of resistor power vs time.*

The discharge circuit is purposefully built to mirror the precharge circuit with the notable exception of having a higher discharge resistor value. The traction system voltage is expected to discharge to just below 30V in about 7.9 seconds. The discharge relay is a S1-05-BDM normally closed reed relay which can handle up to 1.3A. The relay is kept open in normal operation with the same relay power that powers the precharge circuit. In either case of purposefully shutting the traction system off or a fault tripping the safety circuit, relay power will go to zero. Which will open the precharge and accumulator isolation relays and close the discharge relay.

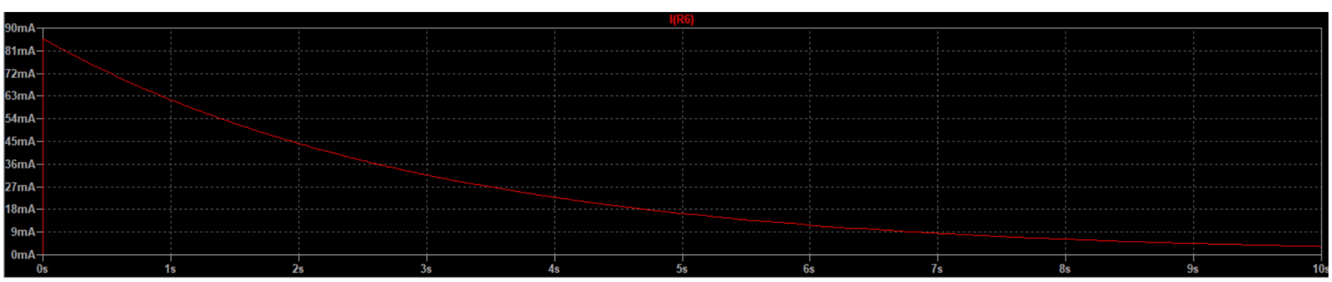


Precharge & Discharge circuit

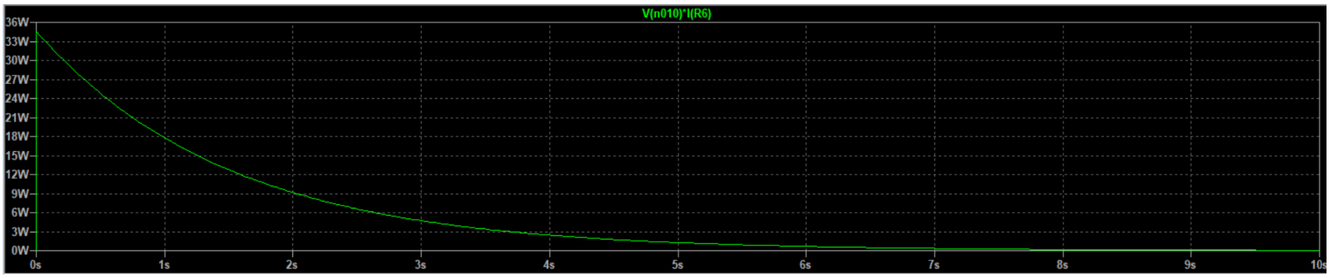
The discharge path is through a FPA100 4K7 J resistor, which has an expected peak current of 85.78mA. The expected power dissipation through the discharge resistor is 34.58W.



TS voltage vs. time



Discharge current vs. time



Power dissipation vs. time through the discharge resistor

Provide the following information:

Resistor Type:	TKH45P500RFE-TR	
Resistance:	4700	Ω
Continuous power rating:	100	W
Overload power rating:		n/a
Voltage rating:	1000	V
Maximum expected current:	0.0857	A
Average current:	0.0544	A

Table 25 - Discharge circuit data

Section 13 **Torque Control**

Person primarily responsible for this section:

Name: evelyn maude

e-mail: emaude@wpi.edu

13.1 Accelerator Actuator / Throttle Position Sensor

*Describe the accelerator actuator and throttle position sensor(s) used, describe additional circuitry used to check or condition the signal going to the motor controller. Describe wiring, cables and connectors used. Provide schematics and a description of the method of operation of any team-built signal conditioning electronics. Explain how your design meets all of the requirements of FH Rules **IC1.6** and **EV3.5.***

Actuator / Encoder manufacturer	BMW
Model Number	3542678628201
Encoder type (e.g.Potentiometer):	Hall effect
Output:	dual analog outputs with different slopes
Is motor controller accelerator signal isolated from TSV?	☑Yes / ☐ No
If no, how will you satisfy rule **EV3.5**?	N/A

Table 26 - Throttle Position encoder data

13.2 Accelerator / throttle position encoder error check

*Describe how the system reacts if an error (e.g. short circuit or open circuit or equivalent) is detected. Describe circuitry used to check or condition the signal going to the motor controller. Describe how failures (e.g. Implausibility, short circuit, open circuit etc.) are detected and how the system reacts if an error is detected. State how you comply with **EV3.5.4.***

To guarantee the safe functioning of our vehicle, we monitor dual outputs from the accelerator pedal, with each output deriving from its distinct slope—one operates at 3.3 volts and the other at 5 volts. After scaling the 5 volt signal down to 3.3 volts both values are continuously monitored by an ADC. This dual-slope approach allows us to verify the plausibility of these readings by ensuring they are within 5% of each other. Additionally, we confirm that the values fall within acceptable ranges, safeguarding against potential shorts to ground or sensor power or an open circuit, which can be detected when a value outside of our plausible range is read. In the case that a fault is detected, a CAN message is dispatched, alerting the motor controller along with other monitoring hardware, this allows the driver and the team to promptly address the issue in a safe manner. Otherwise these values are mapped to the corresponding throttle response, they are dispatched as a heartbeat message to maintain reliable and timely communication with the motor controller. The motor controller treats the accelerator pedal data packet as its enable heartbeat, which ensures that in any case where the pedal stops transmitting, the motor controller will stop.

Section 14 **GLV**

Person primarily responsible for this section:

Name: Carson Graham

e-mail: cjgraham@wpi.edu

14.1 GLV System Data

The majority of our GLV electronics are contained within our GLV box, located physically next to our HV box.

The box houses our GLV Battery, which is connected to an isolated bidirectional buck/boost converter down to 24 VDC. This 24 VDC rail is run through the two GLV BRBs and the GLVMS to supply the entire car with GLV power. We recognize that this slightly violates **EV7.3.1** in the sense that there is Grounded Low Voltage circuitry upstream of the GLV BRB and the GLVMS, however it is isolated (besides a common ground) from all non-battery GLV circuitry.

The bidirectional buck/boost converter chip we are using is the LT8228.

Both sides of the bidirectional buck/boost have 20 A fuses. The high side fuse acts as our main GLV fuse. The low side fuse acts to protect the 16 AWG wire that runs through GLV BRBs and GLVMS loop as well as any downstream circuits that rely on 16 AWG wire. The negative terminal of the battery is attached to the nearest frame member via 12 AWG wire

The bidirectional buck/boost converter chip we are using is the LT8228. The LT8228 drives back-to-back protection MOSFETs on both the high and low sides. These MOSFETs redundantly and fully isolate the battery from the main GLV bus in the event of a fault.

The LT8228 itself faults on the following cases:

- Temperature of the chip exceeds 165℃
- Internal chip power busses fall below allowable voltage values
- Configurable UVLO/OVLO of the low side
- Configurable UVLO/OVLO of the high side
- MOSFET drivers unable to maintain desired MOSFET gate charge
- A short on either the buck MOSFET or boost MOSFET is detected
- Internal redundant reference voltages mismatch
- Internal check of current sense amplifiers fail at startup

Additionally, our custom BMS system checks for the same exact fault conditions as we apply for the high voltage segments. These are listed elsewhere in the ESF-2, but are listed here as well:

- Any single cell is above 60℃ (All cells are directly temperature monitored)
- Any single cell is below 2.7 V
- Any single cell is above 4.2 V
- Any cell deviation of more than 1 V

If any of these occur, the LT8228 is disabled and all four protection mosfets are turned off.

This is semantically equivalent to common COTS lithium-based batteries that contain circuitry to balance and cutoff at low voltages that many teams run in FSAE, without the COTS box. We also believe our solution to be safer or equivalently safe when compared to COTS solutions.

Charging is done by connecting a CV power supply to the 24V GLV Bus, downstream of the BRBs and GLVMS. This prevents charging when either BRB is pressed or the GLVMS is turned off. The charger is tuned to output 24.5 V. The increased voltage on the 24V rail switches the LT8228 into “boost” mode to charge the battery from the 24V bus.

The LT8228 is a current controlled DC-DC converter and has configurable high and low side current monitoring and thresholds that are different for buck and boost modes. In boost mode (charging the GLV battery) we enforce 8.4 A on the high side and 20 A on the low side to stay in compliance with our battery max charging limits and fuse limits respectively. During buck mode (normal car operation) we enforce 20 A limits on both sides.

This 24V bus supplies the shutdown circuit, as well as every other GLV component in the car including the low side of the inverter.

GLV System Voltage (Same as Table 1) (Note: for 2024, Rule EV1.2, the GLV may be 48V max)	24 VDC
GLV Main Fuse Rating	20 A
Is a Li-Ion GLV battery used?	☒ **Yes** / ☐ No
If Yes, is a firewall provided per **T4.5.1**?	☒ **Yes** / ☐ No
Is a dc-dc converter used from TSV?	☐ Yes / ☒ **No**
Is the GLV system grounded to the chassis?	☒ **Yes** / ☐ No
Does the design comply with all requirements of **EV4**?	☒ **Yes** / ☐ No

Table 27- GLV System Data

Section 15 **Charger**

Person primarily responsible for this section:

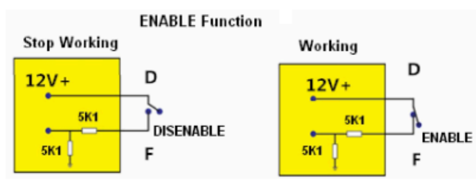
Name: Carson Graham

e-mail: cjgraham@wpi.edu

15.1 Charging

The accumulator will be charged with a 6.6KW UHF CAN bus chargers from Elcon, part number HK-J-H650-12. This charger has been manufactured to a high standard, with air cooling, and connects to the car over a dedicated GLV CAN bus. During charging, our AMS system passively balances the cells, checking for all of the fault conditions outlined in the rules. If any fault state is encountered, the AMS fault is latched and the AIRs opened. Fusing is also included in the charger itself.

The charger comes with it's own fault identification and state reporting



7. LED Colors

1). Initial State
Red Off Green Off Red Off Green Off Red Off Green Off Red Off Green Off

2). Charging State
Red Off Red Off Red Off Red Off Red Off Red Off Red Off Red Off

3). Stand-by State
Green Off Green Off Green Off Green Off Green Off Green Off Green Off Green Off

4). Fault State
Red Green Red Green················Other error status word error
Red Green·······························Wrong Battery
Red Green Red·························Wrong Communication
Green Red·······························Wrong Input Voltage
Green Red Green·····················Internal Temperature Protection
Green Red Green Red················Wrong Hardware

N/A

Figure 10 – Charging Circuit with fusing

We charge through our main accumulator HV connector and use the same fuse.

Complete the table

Charger Manufacturer	Elcon
Model Number	HK-J-H650-12
Maximum charging power:	6.6 kW
Mains Isolation	☒ **Yes** / ☐ No
UL Certification If "no", fill in the line below.	☒ **Yes** / ☐ No
Do you have a waiver from the FH rules committee? If "yes", attach printout of the waiver.	☐Yes / ☒ No
Maximum charging voltage:	650 V
Maximum charging current:	12 A
Interface with accumulator (e.g. CAN, relay etc.)	CAN BUS
Input voltage:	120 VAC (single phase)

Table 28 - Charger data

Hybrid Battery Control Methods

For hybrid vehicles, describe your on-board battery control methods including voltage and current limits. Describe method for dealing with a fully-charged pack (CV/CC algorithm etc.).

N/A

Section 16 **Appendices**

Include only highly-relevant data. A link to a web document in the ESF text is often more convenient for the reviewer.

The specification section of the accumulator data sheet, and sections used for determining accumulator capacity (FH Rules **Appendix A**) should be included here.