

EV Electrical Systems for Student Teams: An Iterative Design Approach with Practical Lessons

by

Anthony Robert McAfee

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The shift toward vehicle electrification has created an urgent need for engineering students to acquire practical knowledge in electric vehicle (EV) systems. While industry and academia offer theoretical instruction, student design teams often lack practical guidance, resulting in preventable errors, safety risks, and incomplete competition vehicles. This thesis addresses that gap by identifying key lessons to learn for building EV electrical systems and offering real-world insights through a case study of the University of Waterloo Alternative Fuels Team (UWAF) during the EcoCAR 5 competition.

The thesis is structured around three primary electrical domains: High Voltage (HV), Low Voltage (LV), and Serial Communication Systems. Each chapter begins with generalized best practices, safety procedures, and design considerations, then explores how UWAF applied—or struggled to apply—these concepts in practice.

In the HV domain, the thesis covers critical safety mechanisms like Isolation Monitoring Devices (IMDs), Emergency Disconnect Systems (EDS), and Lockout/Tagout (LOTO) procedures. It highlights common student pitfalls such as improper cable terminations and the consequences of electromagnetic interference (EMI).

The LV section details harness design, schematic development, wire selection, and assembly techniques essential for powering 12V components safely and reliably. Emphasis is placed on documentation, modularity, and physical protection of circuits.

In the Serial Communication chapter, the CAN bus protocol is explained in the context of a complex vehicle network involving autonomous driving, propulsion control, and diagnostics. The harness assembly techniques from the LV chapter are expanded upon for the specific case of CAN cables. Finally, UWAF's Serial Network Diagram (SND) serves as a practical guide to organizing and troubleshooting communication systems.

Through a combination of foundational theory and applied case study, this thesis equips student teams with a framework for developing safe, functional, and competition-ready EV electrical systems. It also highlights the importance of mentorship, iterative learning, and documentation in engineering education.

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Above all, I owe the completion of this thesis to the Lord Jesus Christ, whose strength sustained me; to my church, whose prayers and encouragement lifted me; and to my wife, whose love, patience, and support carried me through every difficult moment. I could not have done this without you.

Dedication

I dedicate this thesis to the present and future electrical leads of UWAFI who are just starting their journey. May it be the compass I wish I'd had when starting my own.

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List of Abbreviations

AWD	All Wheel Drive – power is delivered to all 4 wheels
CAN	Controller Area Network — a differential serial communication protocol used in automotive systems.
DIB	Data Interface Board — allows data access for diagnostics and competition compliance.
DMS	Driver Monitoring System – an autonomous driving safety feature.
ECU	Electronic Control Unit — microcontroller systems that manage subsystems within the vehicle.
EDS	Emergency Disconnect System — enables immediate shutdown of HV systems during emergencies.
EDU	Electric Drive Unit — a combined motor and inverter used for EV propulsion.
EMI	Electromagnetic Interference — noise disrupting electrical signals, often originating from power electronics.
EVC	Electric Vehicle Challenge – AVTC competition starting in 2022.
HMI	Human Machine Interface – touchscreens, toggle switches, warning lights, etc.
HV	High Voltage — systems operating above 60 VDC or 30 VAC, such as motors and inverters.
HVIL	High Voltage Interlock Loop — disables HV when enclosures or connectors are open.
IMD	Isolation Monitoring Device — monitors for voltage imbalances in the HV system to ensure safety.
iPDS	Intelligent Power Distribution System — a smart module for managing and monitoring 12V power circuits.
ISO	International Organization for Standardization - develops standards for engineering professionals in aerospace, automotive, and commercial industries.

LOTO	Lockout/Tagout — a safety procedure that ensures energy sources are deactivated and locked during work sessions.
LV	Low Voltage — systems operating at or below 12V, such as sensors, lights, and ECUs.
LiDAR	Light Detection And Ranging – a sensor that uses laser light to measure distances and create 3D maps
LnS	Lights and Switches – component of UWAFI’s HMI.
PCB	Printed Circuit Board - connect and support electronic components via printed conductor pathways.
PPE	Personal Protective Equipment — safety gear (e.g., gloves, face shields).
RWD	Rear Wheel Drive – power is delivered to only the rear wheels
SAE	Society of Automotive Engineers - develops standards for engineering professionals in aerospace, automotive, and commercial industries.
SND	Serial Network Diagram — schematic showing communication links among devices.
V2X	Vehicle to X – wireless communication between a vehicle, its neighbor vehicles, and traffic infrastructure.

Chapter 1

Thesis Objectives and Outline

1.1 Introduction

The future of the automotive industry is electrification. More and more of the powertrain, driver input, and safety systems are transitioning to electrical alternatives, replacing the purely mechanical past [1], [2].

To build this future, the industry has been investing in the next generation of automotive engineers through the practice of student design team competitions [3], [4], [5]. Companies are sponsoring undergraduate student teams with industry-grade components and vehicles for them to redesign and assemble. The teams in turn represent their universities and sponsor companies at competitions of engineering prowess. The companies gain a pool of potential employees who are already familiar with their products and practices, and the students gain hands-on experience that cannot be found in a classroom.

However, without proper guidance, those experiences tend towards painful mistakes rather than successes, because the skillsets and techniques required to build electrified vehicles are numerous and often unintuitive.

In an ideal scenario, an experienced professor or industry professional would help the students with each step of the project, guiding them towards what they need to know and away from erroneous assumptions. Unfortunately, some realities restrict this ideal.

First, no individual is an expert on everything that students may require. Second, professors and industry professionals often have limited time to give to students. Third, many students join a design team because they are seeking the freedom to design what they want and may leave if they feel micromanaged. Defining what students need to know and compiling common mistakes to avoid can help fill in the gaps created by these factors.

To build a working vehicle, students must integrate and power a diverse set of devices. Most automotive components operate at 12V or lower, and these are considered Low Voltage (LV). Examples of LV devices include but are not limited to sensors, computers, lights, pumps, and human-machine interfaces. Those with greater power requirements (>60 VDC or >30 VAC) are considered

High Voltage (HV) [6]. Examples of HV devices include motors, inverters, and battery charging components.

A majority of automotive devices require not just power, but also communication with each other. This is accomplished by a serial communication network that enables data exchange between devices, typically over CAN harnesses.

From both the experience of the author and examples found in the literature, past student design teams have made many avoidable mistakes in the HV, LV, and serial communications domains. These led to unsafe practices and project-crippling delays, culminating in vehicles that were not functional in time for their competitions.

For example, when assembling HV wires, a student team assumed they could extend the length of pre-existing cables by adding more wire to the cable with a barrel crimp joining the old to the new. This assumption went unchallenged until the students got to their competition and were informed by the judges that this approach could unintuitively cause a catastrophic failure. Chapter 3 will cover this in more detail, but in short: the students did not consider alternative solutions because they had the barrel crimps on hand from a past project, and they did not understand how to weatherproof their wires professionally.

If not addressed, a lack of knowledge will compound with a desire to get things done fast and cheap, leading student design teams to default to the first apparent solution, only to later realize their mistake once it is too late.

1.2 Thesis Objectives

It would be tedious, if not impossible, to record everything a student team needs to know about building the electrical systems of a modern vehicle. Rather, this thesis provides a compass for student design teams to navigate towards the right fields of knowledge. Team members tasked with building any portion of a vehicle's electrical system should be able to refer to this thesis and start in the right direction, even if they have no electrical background. Furthermore, student leaders and academic advisors should be able to gain an understanding of what skills are valuable to watch for in prospective hires, and what to foster in their volunteer members.

The objective of this thesis is to broadly identify the techniques, tools, and knowledge needed for a student design team to build a safe, complete, and competitive automotive electrical system.

In service of this objective, a design case study has been chosen to provide real-world examples. The University of Waterloo Alternative Fuels Team (UWAF) is a student design team participating in the EcoCAR 5: EV Challenge. They have designed and integrated major sections of an electric vehicle's LV, HV, and serial communication systems, and their successes and mistakes were documented in all three domains.

While the designs set forth as examples are specific to the case study, the methods and reasoning behind the designs will illustrate what is useful to know and provoke the questions students should be asking their advisors.

1.3 Thesis Outline

Chapter 1 is an introduction to the challenges that student teams face in gaining critical skill sets and niche knowledge.

Chapter 2 will review literature sources that have explored similar objectives as this thesis. It also provides context for the case study that will be used to illustrate proper vs. improper techniques. This includes a description of the EcoCAR5 competition and the related design goals pursued by UWAF.

Chapters 3, 4, and 5 cover high voltage, low voltage, and serial communication systems, respectively. The three topics are arranged in descending order of the safety risks associated with each system. Each of these chapters will begin with the fundamental purpose and background theory of the topic system, then provide summaries of the relevant safety considerations. Following that, the best practices for designing, assembling, and debugging the system will be covered. Examples from the UWAF case study are used to draw attention to the successful tactics that students should mimic, as well as the mistakes to avoid. This is represented in part through the team's schematics, which were drawn between Years 2 and 3 of the competition. They are improvements on the Year 2 submissions, adapting to competition feedback, but not yet reviewed by Year 3 judges.

Chapter 6 concludes the thesis with a discussion of the key takeaways of the previous chapters, how these learnings should be taken in combination with expert oversight, and the gaps left to fill in by future works.

Chapter 2

Literature Review and Competition Context

Automotive electrification as a part of combating climate change [7], and the need for a new generation of automotive engineers [8], [9], [10], [11] to implement this electrification are well-established facets of the EV industry. The focus of this literature review will be to survey what others have already done to identify the practical EV-building lessons this next generation needs to learn and why they are important.

A useful definition for competence is found in [12, p. 315], which states, “Competence requires technical or factual knowledge as well as soft skills... Competence enables individuals to analyze complex and new situations, to find creative possibilities of a solution, and to decide on the way of action under considerations of causes and consequences.” To help students pursue that competence, this thesis will offer examples of complex design situations, show how past students performed therein, and explain why they did or did not work.

While the focus of [12] was software and not electrical engineering, the authors present a system for categorizing competencies that will help define the scope of this thesis. They established concentric domains (Figure 1) and then listed the skills from each domain that automotive software graduates would be expected to have based on industry surveys. At the end of this chapter, a similar diagram will be presented for electrical students based on the author's experience from the EcoCAR competition and the following literature review.

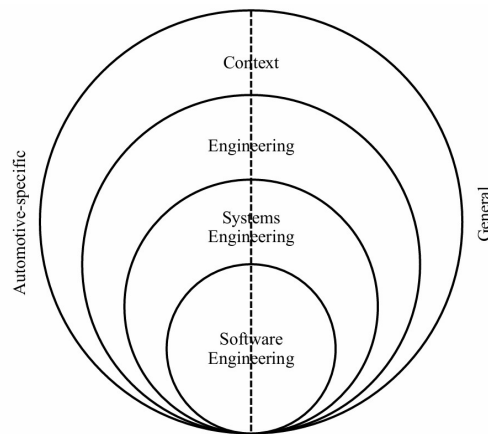


Figure 1: Schema for organizing competencies in engineering students [12]

2.1 What has already been done to identify and instill the electrical skills needed in a student design team?

Skill profiles that automotive companies find desirable are compiled in [13] and compared with what is taught in a traditional electrical engineering curriculum. The gaps discovered included automotive wiring, EV batteries, and HV engineering.

The authors of [14] surveyed mechanics, firefighters, and towing services seeking to identify the training they would need to work safely with EVs. These included HV safety, responding to battery fires, and emergency disconnect systems. Students building EVs will require similar training, as well as an understanding of how to construct emergency systems that comply with EV regulations and emergency responders' expectations.

The design reports of past student teams can offer insight, but these tend to be quite narrow in application. For instance, [15] describes the LV distribution and control system built by a Formula Student Electric Racing Car (FSERC) team. The PCBs the team made are described in complete detail and would offer valuable insights for anyone attempting to reproduce their project. The focus is more on what they made as opposed to how or why they made it. Experienced teams with the skills needed to replicate their work can gain much from such references when looking for ways to improve their designs. However, design reports tend to be dense, abundant with technical language and acronyms, and assume a high level of prior electrical knowledge, which new students likely lack.

Some institutions have courses teaching EV engineering principles, such as those presented in [16], [17], and [18]. These courses tend to concentrate on the science behind EV technologies or soft skills related to project-team management. Their lessons are valuable for individual students' careers, but competition teams may find them too theoretical to practically apply in their competitions.

Several universities have founded courses and even full degrees on the premise that hands-on experience is of equal or greater value to class-based theoretical instruction [19][20][21]. For example, Tecnológico de Monterrey ran a design course about building an EV and reported their approach in [22]. The core skills identified were detailed design, evaluation and validation, development of manufacturing processes, process simulation and product validation, electrical hardware, and reasoning for complexity. This example closely mirrors the experience of EV student teams: taking a pre-existing vehicle frame and integrating their own LV and serial networks in

addition to other mechanical and software goals. They also had to coordinate with an industry sponsor and present their work by a set deadline, like most competition teams do.

Where this example differs from student-led teams is the greater involvement of system-specific experts. For each project subsystem, the students were taught by master's or PhD graduates who specialized in that domain of automotive engineering. These instructors also acted as project managers for the team, though only students were allowed to do the hands-on work. The paper states that students spent at least 200 hours cumulatively, or 12.5 hours per week, with experts from academia and industry. In the author's experience, student-led competition teams get less than 4 hours a week if they push for that time and may get none if they do not understand the importance of expert advice.

A further difference is the short timeframe of a single semester, whereas teams like UWAFTE can have up to 4 years to complete their projects. Despite this short time frame, the students completed 83% of their objectives, and both the professors and industry partners were pleased with the students' progress at the end of the term.

When discussing the issues that prevented 100% project completion, the authors said, "The time required to perform some tasks was underestimated," and "Another relevant identified issue was the resource supply problems... Components should be selected and bought with more anticipation in future editions" [22, p.5]. From this, we see that even when expert advice is abundantly available, a collection of best practices for performing EV design tasks could help set realistic timeframes and identify what equipment is needed in advance.

Attempts have been made in UWAFTE's past to create such compilations. This thesis was written in part to build on one of these works: Singh's "Experiential Learning with Respect to Model Based Design Applied to Advanced Vehicle Development" [23]. The stated objective was "to discuss the resources, techniques and processes needed to design and construct a green research vehicle within a post-secondary institution" [23, p.4], which closely mirrors the objective of this thesis. The key differences lie in the case studies chosen and the depth of topics covered.

For the design case study, [23] recounts the UWAFTE efforts in the AVTC EcoCAR2 competition, where the goal was to convert a gas-powered vehicle to a hybrid and reduce its emissions. The case study in this thesis will revolve around UWAFTE's efforts in the EcoCAR5 competition to modify the powertrain of a fully electric vehicle while implementing autonomous features.

As for depth, [23] broadly covers the entirety of a green vehicle project, including all subsystems, project management considerations, and arguments for why universities and industry partners should invest in such a program. Because of this, deep dives into each subsystem would have made the work prohibitively long. This thesis seeks to cover the electrical subsystem in greater depth and leave other subsystems for future work.

UWAFST built an HV battery for EcoCAR2, and [23] makes this the focus of HV discussions. Battery safety, design, and connections to mechanical and thermal systems are covered in great enough depth that this thesis will focus on other HV subjects, such as junction boxes and safety testing procedures. The calculation for selecting fuses is given significant attention, which benefits both HV and LV systems. However, the topic can be confusing, and students would benefit from additional examples demonstrating the selection process from beginning to end.

The discussion on LV is relatively short, with recommendations for wire selection, connection styles, and documentation that lack nuance. For instance, soldering is suggested as a means to connect low-gauge wires, which can be appropriate in some situations but will lead to broken wires in others. Students must understand the strengths and weaknesses of these techniques so that they can choose the one best suited for their needs.

A brief explanation of CAN is given along with an example of a serial network. [23] walks through the process of identifying what devices/ports were needed in the EcoCAR2 network and justifies why certain devices were chosen. The walkthrough provides a good reference for students making their own serial design decisions. The corresponding section of this thesis will be patterned after the style found here while expanding on CAN theory, physical assembly, and debugging practices.

2.2 Case Study Context

The Advanced Vehicle Technology Challenge (AVTC) provides hands-on competitive experiences with the latest in automotive technology for university students [24]. They connect student teams with industry sponsors, hold training workshops, establish rules for team designs, and run annual competition events.

Since 2008, they have been running the EcoCAR Challenges, the present incarnation being the EcoCAR 5: EV Challenge. In this, teams are competing to tear down, redesign, and rebuild their donated 2023 Cadillac LYRIQs. The AVTC set broad objectives for teams to achieve in vehicle

functionality, energy conservation, and autonomous driving. The structured format of this competition provides many guardrails for what students can and cannot build into their vehicles, and the AVTC regularly updates the guidebooks defining those rules. This is significant because those rules were a major influence on the design case study of this thesis, holding teams to standards of safety and design that sometimes precluded options open to teams in other competitions or even professional auto manufacturers (e.g., banning zip ties).

Though that may sound restrictive, teams were free to choose between multiple industry sponsors or find their own sponsors for motors, sensors, compute units, etc. This enabled some teams to take the relatively low-effort path (mechanically speaking) of rear-wheel drive (RWD) designs so they could spend more effort developing their software. In contrast, others went all in mechanically with all-wheel drive (AWD) designs, accepting the trade-off of having less time/human resources to spend on software. Choices like this help to develop a generation of engineers with diverse skills within the automotive sector, as they prompt students to specialize based on their interests.

UWAFT decided to pursue an AWD design, which gave rise to numerous supporting objectives. Among those, the most relevant to this thesis were the powertrain and autonomous driving goals.

Powertrain objectives included replacing the stock rear motor with a larger electric drive unit (EDU) and adding a second EDU to the front. These changes dramatically reduced available space under the vehicle and in the engine bay, requiring the relocation and rewiring of the LV and HV distribution systems. UWAFT did not modify the HV battery and its charging modules, as this would have violated the competition rules.

Autonomous driving objectives required the addition of two large computing units (relative to stock units) and various sensors inside and outside the vehicle, further reducing available space and increasing the demand on the LV distribution system.

2.3 Conclusion

Based on the above literature and the author's EcoCAR experience, Figure 2 presents the subjects that electrical students working on an EV should be familiar with. While not exhaustive, it should give enough target skills to get students pointed in the right direction.

Context refers to knowledge of the broader societal influences that push the EV industry. General Engineering refers to other engineering fields that the electrical team would interact with, and the soft

skills needed to function in professional engineering environments. Systems Engineering narrows the scope further to the software, safety, and testing aspects that are closely tied to the electrical system, which electrical students may be called upon to support. At the core is the Electrical Engineering domain: the knowledge and skills that an electrical team would specialize in.

Some of these topics were common to find in new members, instilled by their academic classes or co-op jobs. Other topics were found to be lacking in new students or were the focus of lessons learned during the competition. These topics have been bolded and will be the focus of the following chapters.

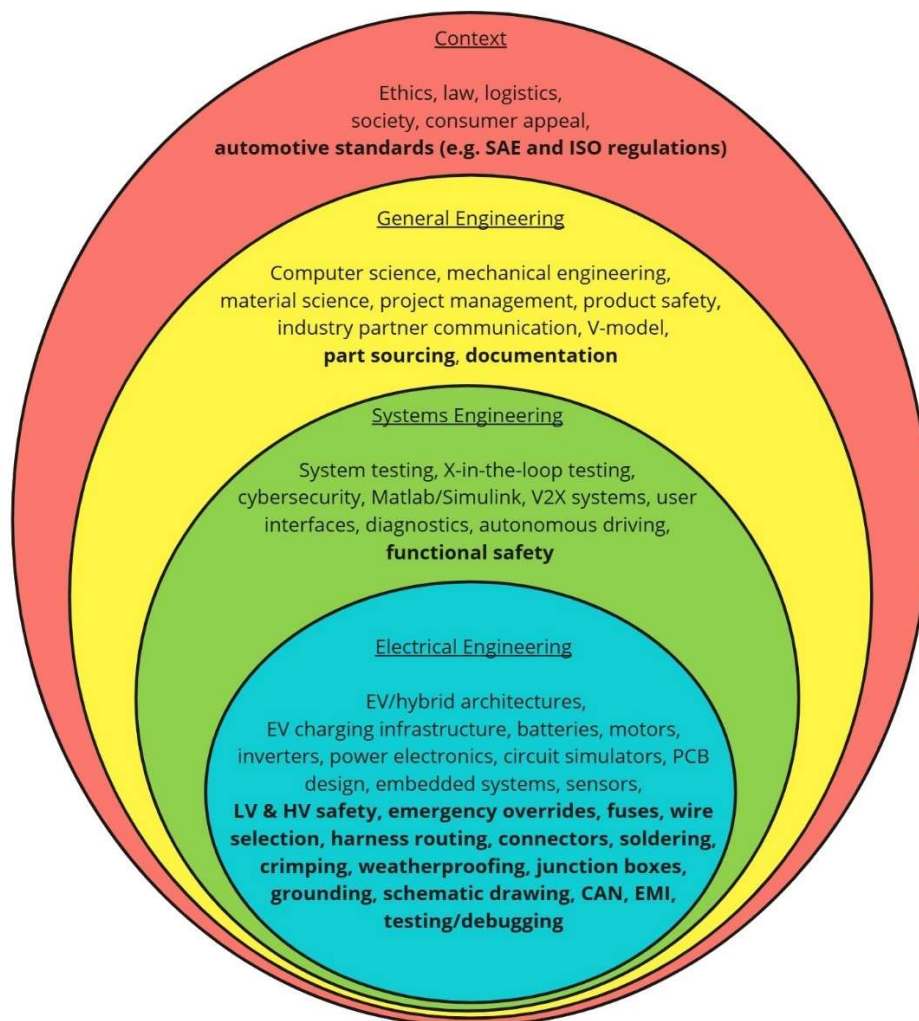


Figure 2: These are subjects electrical students working on an EV should be familiar with.

Bolded topics are the subject of this thesis.

Chapter 3

High Voltage Systems

3.1 Generalized Learnings

3.1.1 Background

High Voltage systems cover everything in the vehicle above 60 VDC, which in practical terms means the HV battery and all devices that interact with it electrically. Since the HV battery was left stock for the EcoCAR5 competition, the internal structure of HV batteries will not be discussed here.

On the input side, the HV battery requires charging, and multiple systems can be used in one vehicle to accomplish this. The UWAF case study employs both regenerative braking and plug-in charging to this end.

As for outputs, the primary purpose of the HV system is to power the vehicle's motors. However, EV motors are designed to run on AC power for greater efficiency, and HV batteries output DC power. Therefore, inverters are used between the battery and motors to convert the power from AC to DC. Recently, manufacturers have begun building the inverters and motors together into a single device referred to as an Electric Drive Unit (EDU), which has reduced HV system complexity and saved space in motor compartments.

Finally, the HV system can draw power from the HV battery to restore the LV system's 12V battery if the vehicle detects that the 12V battery is depleted.

Given the critical function of the HV system and the high-risk potential associated with HV power, the knowledge and procedures required for students to operate safely are far more intensive here than in other sections of the vehicle. Thus, the bulk of this chapter will focus on the safety aspects of HV design in an EV.

3.1.2 Safety Systems

3.1.2.1 Isolation

Unlike LV devices, which use the vehicle's chassis as a return path to the negative terminal of the 12V battery, HV devices must be isolated. Electrically speaking, the positive powering path and negative return path of the HV system must never touch each other, chassis ground, or any other

conductive material. These two pathways require robust insulation to isolate them from the surrounding environment.

Any break in the insulation of an HV wire, whether to insert a fuse, contactor, or branching paths, must occur within HV junction boxes. A single junction box may contain both positive and negative pathways, and often this is necessary due to space constraints.

All HV connectors, wires, and junction boxes must be sealed from water and dust (See the IP64 definition in Chapter 4). The pollution of water or dust particles in the air between HV conductors can increase the chances of dangerous arc flashes between them. Such events can destroy equipment and cause serious bodily harm.

Arc flashes occur when the voltage difference between two conductors is great enough to overcome the gap or insulating material between them. The minimum air gap between two points that safely prevents arcing is termed “**clearance**”. The minimum route along a surface is termed “**creepage**”.

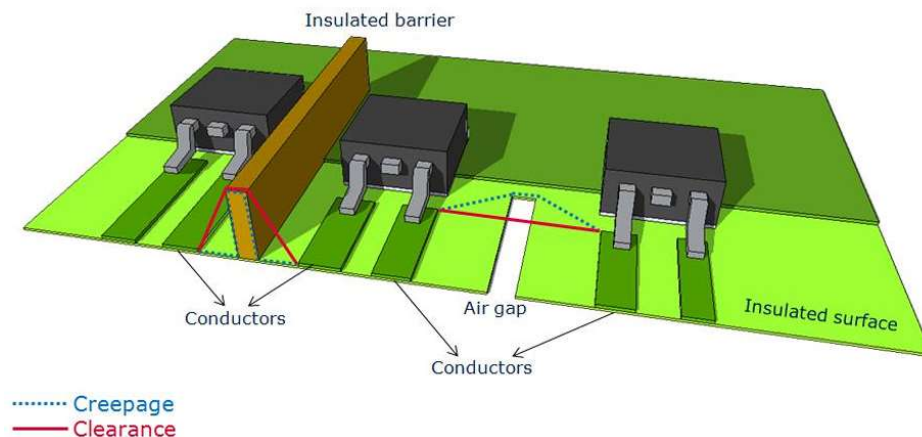


Figure 3: Definitions of creepage and clearance [25]

A student team must determine what clearance is acceptable for them based on expected voltage levels, water/dust pollution, insulating materials, and even altitude [26][27]. Based on the 400V battery they would be working with, UWAFI followed a minimum creepage and clearance of 12.7mm and 9.5mm, respectively.

Isolation monitoring devices (IMDs) are to be installed in any vehicle with HV. They measure the voltages on the positive and negative buses and compare them to the vehicle’s chassis ground voltage. If ever those voltages are not within expected values, the IMD alerts the system’s supervisory control

unit, which should then safely shut the system down and toggle high visibility warning lights until the IMD no longer detects an issue.

3.1.2.2 Emergency Disconnect Systems

The Emergency Disconnect System (EDS) is a safety measure that rapidly shuts down the HV bus when triggered to prevent live HV power from exacerbating emergencies. EDS buttons must be easily recognizable and accessible to both the driver and bystanders outside the vehicle, as depicted in Figure 4.



Figure 4: Locations of the EDS Buttons in the UWAFTEcoCAR 4 Vehicle

The disconnection of HV power is actuated by HV contactor switches that interrupt either the positive or negative HV line. A line from the HV battery bolts to the input of the contactor, and a line to the rest of the system is bolted to the output. Inside the contactor, a conductive bar connects the input and output points. An electromagnet is positioned to pull the bar against the points, and a spring pushes the bar away from them. When the electromagnet is supplied with 12V, it overpowers the spring, and the bar allows HV current to pass to the EDU. If the electromagnet's 12V is cut, the spring pushes the bar away, and the HV current stops. An example of an EDS circuit is described in the Design Case Study of this chapter.

3.1.3 Safety Practices

This section condenses the UWAFTHV Safety documents [28][29] into the main points that apply generally to EV student teams. These documents were themselves based on the UWAFTHV safety guides from past competitions as well as competition guides [30] and safety seminars taught by industry professionals [31].

3.1.3.1 HV Certification for Team Members

Student teams intending to work on HV components MUST create their own HV student training and test procedures. The number of students allowed to work with HV should be a small proportion of the whole team. Training this elite group must complete should include (but is not limited to):

- Education about the risks of working with HV
- Education about every aspect of the HV system installed in the vehicle and the components which utilize HV
- Training in the proper use of a multi-meter and how to perform a live-dead-live check
- Training in the proper use of HV rated gloves (including mandatory pre-use checking of the gloves)
- Training in the proper procedures for de-energizing and energizing the HV system
- Training on proper lockout/tagout procedures
- Emergency procedure training

A hierarchy of training levels is encouraged and would follow the industry paradigm. UWAFTHV's method for defining HV qualifications is provided for reference in Appendix A.

3.1.3.2 HV PPE

For any work performed on potentially live HV components, the following PPE is required:

- Certified high-voltage safety gloves*
- Closed-toe shoes
- 100% cotton clothing
- Face and neck protection to guard against sparks from molten metal
- HV-rated tools, typically orange and labeled with their rated voltage**



Figure 5: HV PPE and Tools

*The HV safety gloves will require certification and must be marked with the date they are opened for first use. Certifications may last for about 6-12 months, after which the gloves need to be re-certified. They must always be inspected before being worn. See [56] for more details on glove safety and testing.

**Performing mechanical work while the system is energized should never be attempted unless there is clear expectation to do so from the competition and live oversight of academic supervisors for the work.

In addition to the above PPE, the following safety equipment must be readily available while working on HV vehicle systems:

- Insulated rescue cane, which is to be hooked around the waist of anyone working on live HV and held by another member. If the worker is electrocuted, the cane-bearer must be strong enough to pull them out of harm's way.
- Fully charged Class D fire extinguisher
- First Aid Kit
- Automated External Defibrillator (AED)
- A functioning phone, which should be held by an observer who is not participating in the HV work.



Figure 6: UWAFT's rescue cane and Class D extinguisher

3.1.3.3 Methods to Minimize Exposed HV Risks

- Wear HV gloves and all other required PPE
- Remove only the covers that are required for the work being carried out
- Utilize insulated safety blankets to cover any exposed HV components
- If feasible and safe, work with one hand behind your back to minimize the path for current flow
- Work on HV slowly and carefully, never while tired, frustrated, or inebriated

3.1.3.4 Lock Out Tag Out (LOTO) Procedures

To ensure that any electrical hazards in the vehicle have been properly disconnected and shall remain so for the duration of the work session, the disconnects are physically locked OFF and tagged with the lead worker holding the key. Below is a summary of the LOTO procedure used by UWAFI.

Before starting work:

1. Only authorized members are permitted to perform lockout/tagout procedures.
2. Prior to commencing work, the electrical system shall be inspected to verify if it can be effectively isolated.
3. If an energy isolating device is capable of being locked out, then it must be locked and tagged.
4. If an energy isolating device is not capable of being locked out, then it must be tagged out.
5. Each person performing work on an HV system must apply their own lock. After the lock has been placed, the key must be retained by the person who applied the lock.
6. Advise all members of equipment being locked out, and cordon off the area that will contain exposed HV.
7. Put on appropriate personal protective equipment.
8. Obtain necessary locks, tags, lockout devices and other equipment to perform the work



Figure 7: Lockout Station and Corresponding Lockout/Tagout lockbox

Applying lockout/tagout

1. Apply LOCKS and TAGS to the vehicle's HV Service Lockout mechanism and any other relevant HV systems to ensure it cannot re-enable HV.
2. Write your name, the date and the purpose for the lockout/tagout on the tag.



Figure 8: Example tagout tag

3. Keep the corresponding key on your person so as to not have anyone else be able to unlock it whilst performing HV work.
4. After application of lockout devices, all stored or residual energy must be relieved, disconnected, blocked, bled, restrained or otherwise made safe. Student teams must have a clear set of written instructions for how to perform this on their unique vehicle.

5. In order to check if HV current is still flowing in HV components a three-point Live-Dead-Live test should be conducted on each device in the system under work.

Live-Dead-Live test

The live-dead-live-check test ensures that the digital multi-meter is accurate before measuring the component and it was not damaged after measuring the component.

- 1) Use the digital multi-meter to measure the voltage of a known source (ex. 12V battery).

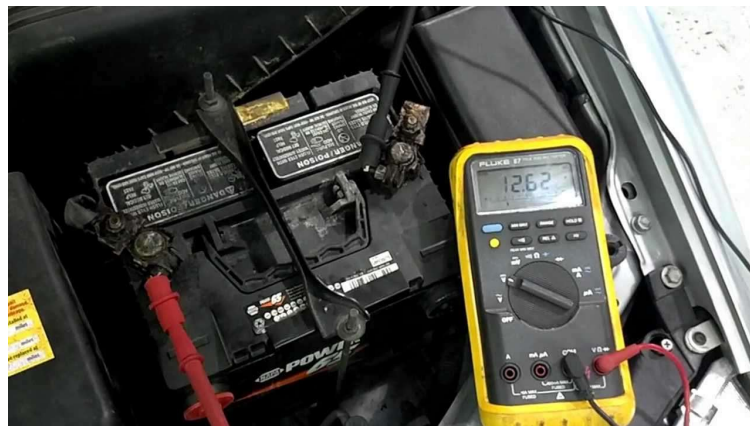


Figure 9: Live test on 12V battery

- 2) Use the same digital multi-meter to measure the voltage of the HV component to be de-energized
- 3) Use the same digital multi-meter to measure the voltage of the same known source again

Work Completed, Removing lockout/tagout

1. Ensure all non-essential equipment or parts have been removed from the vehicle and the vehicle is intact and safe to operate. This includes performing an isolation test.
2. Ensure all HV equipment has been properly installed and all HV wires are properly routed in the vehicle to prevent exposure hazards of people performing non-HV work in the future.
3. Clear away all personnel.
4. Each person who applied a lockout device and tag must remove their own equipment.
5. Notify all team members of the removal of the lockout/tagout equipment and that normal operations can resume

3.1.3.5 HV Test procedures

Teams will need to tailor HV testing to their unique vehicles, but anyone working with HV should have some form of the following tests. These are listed in the order they must be performed in and are dependent on the LOTO procedure being completed first. Each requires access to the HV pathways via junction boxes, and experts must be consulted on the design and implementation of both the tests and junction box infrastructure.

- 1. Insulation/Isolation Test** – determines if the insulation between chassis ground, HV positive, and HV negative are all acceptably high enough ($>1\text{M}\Omega$) to prevent unwanted current flow. This will require the use of an insulation tester (also known as a mega ohmmeter). If this test fails, something has gone extremely wrong. HV current may be coursing through unexpected areas, and no other work or testing should be done until the issue is resolved. General procedure is to plug the insulation tester leads into ports of an HV junction box designed specifically for this test. Resistance measurements are then taken between chassis ground, HV positive, and HV negative.
- 2. HV Bus Bleed-down Test** – determines that the HV system safely de-energizes when the EDS buttons are hit. The duration required for the HV system downstream of the EDS contactors to drop from operational voltage to below 50V is called its “bleed down time” and should be less than 60 seconds. General procedure is to start the car, plug multimeter probes into ports on an HV junction box designed specifically for this test, hit an EDS button, and time the voltage drop.
- 3. Ground Fault Insertion Test** – determines that isolation monitoring devices are functioning as expected. General procedure is to insert a known resistance (around $100\text{K}\Omega$ - $250\text{K}\Omega$) between chassis ground, HV positive, and HV negative one at a time via ports on an HV junction box designed specifically for this test. The isolation monitoring system should detect that isolation has been breached and the vehicle should respond with appropriate warning indicators within 60 seconds.

3.1.4 Best Practices for Assembly

3.1.4.1 Crimping HV Wires

Crimping thick gauges of wire is very different in practice from crimping lower gauges, requiring different tools and techniques. First, HV cables are shielded, which means that there are extra layers of insulation and meshed conductive material protecting the conductor. The tool in Figure 11 has blades circling one end that assist with cutting through those layers. Secondly, the force required to crimp a lug is more than can be applied by hand, so a hydraulic crimping tool must be used.

In LV crimping, most terminals can fit a small range of gauges, but here the match between wire and lug must be exact. The conductive material should be nearly the exact diameter of the lug's socket, or else the crimp will be insecure. This means that a few stray strands of copper usually stick out when fitting the lug, and these are acceptable to cut. However, if it seems the lug will not fit without cutting a sizeable chunk out of the strands, the wrong gauge of lug is being used.

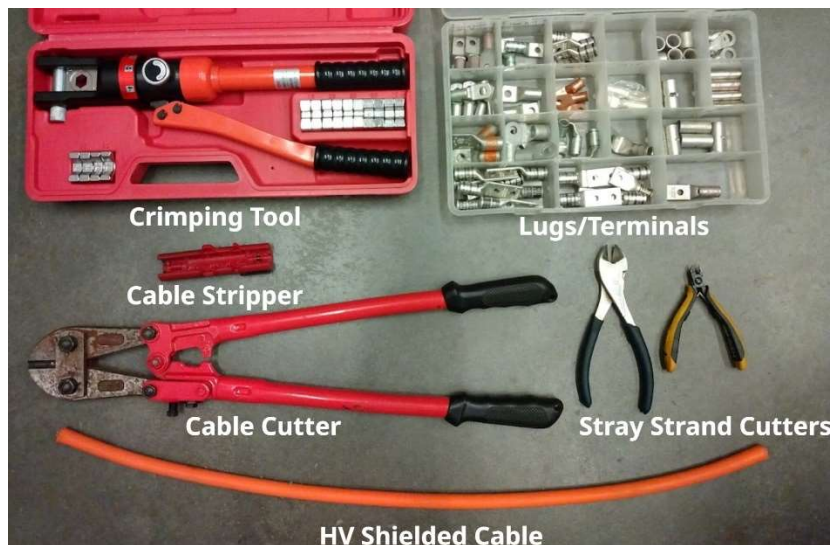


Figure 10: Tools and materials needed for crimping heavy gauges



Figure 11: Stripping insulation and shielding from an HV cable



Figure 12: HV cable ready for crimping with shielding and outer insulation stripped further back and taped



Figure 13: HV wire in a crimping tool

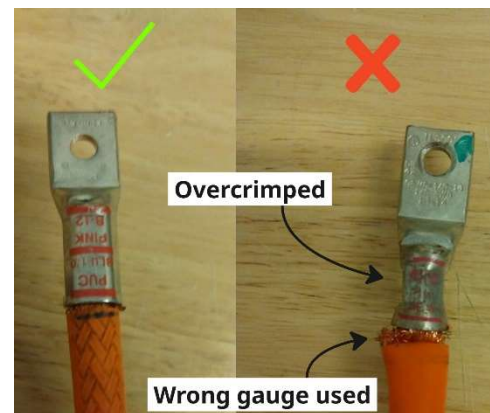


Figure 14: Good and bad crimping examples



Figure 15: Varieties of lugs

Heavy gauge terminals, also called lugs, come in many shapes and sizes to help adapt to the electrical and mechanical needs of the design, as depicted in Figure 15.

However, one type of terminal that should never be used in an automotive HV system is a barrel crimp (Figure 16), even though they come in most lug kits, as seen in Figure 10. In non-automotive sectors, these are used to connect the ends of two wires. For student teams working with donated parts, it is common for devices to come with pre-existing wires attached. If these wires are not long enough for the student's designs, it can be tempting to use barrel crimps to extend their length, especially since the similar butt splice crimps used in LV are acceptable.



**Figure 16: Do Not Use
HV Barrel Crimps**

Barrel crimps breach the wire's insulation, and if water enters that breach, the capillary action created by the many strands of the thick wire will pull water up, potentially into the HV battery pack. While tape and loom could greatly reduce the likelihood of this happening, they are not 100% guaranteed to keep water out. Given the enormous calamities that could occur should water reach the HV battery, this is not a viable solution. Furthermore, these joints can increase the resistance of the line and lead to inefficient power delivery.

The better alternative is to make an HV junction box in which the two wires being joined are crimped with regular lugs, then bolted together. This still increases resistance and reduces efficiency slightly but does solve the waterproofing issue. The best solution is to simply install an unbroken cable, but this is not always an option for student teams.

3.1.4.2 Fuses

Fuses protect both people and the vehicle from unexpected surges of current by opening the circuit and halting the flow of power. Under normal conditions, a fuse allows current to flow through it as if it were a wire. Designed to be the weakest link of the circuit, the conductor inside the fuse will break in a controlled manner if the current ever surges above expected levels. Since the fuse breaks first, other devices on the line are shielded from damage. Fuses are not instantaneous, and harm can be done in the brief time it takes the fuse to break. Even still, fuses significantly reduce the duration of exposure, limiting the extent of damage.

Some fuses make use of the time they take to blow. Slow-blow fuses are designed to withstand their breaking current for a specified duration without breaking the flow. They are applied to circuits that

may momentarily have a steep rise and fall in current, such as for a boost mode that lasts only a few seconds before the current returns to nominal levels.

Fuse selection depends on the circuit it is protecting. Choosing a fuse rated too low can lead to frequent/unnecessary blowing. Choosing a fuse rated too high can fail to protect the circuit and cause wires to melt and start fires. This topic is covered thoroughly in [32], and [23] extrapolates the same concepts to student teams working with HV.

As an example, a device rated for 180A with a max expected current draw of 45A is supplied by a wire rated for 130A. The upper bound for fuse rating will be determined by the rating of the weakest link in the circuit. In this case, it would be the wire's 130A.

While the device's data sheet may report a 45A max, practical implementation can see fluctuations in the current which are not dangerous but would blow a fuse rated exactly at 45A. To avoid this, the lower bound of the fuse rating range is 125% of the expected current, which will be $1.25 \times 45A = 56.25A$ in this instance.

Fuses are not usually made for currents as precise as 56.25A, so the next highest-rated fuse is chosen, so long as it is below the upper bound. Therefore, a 60A fuse would be viable for this example.

Fuses come in different shapes depending on their use case. A few examples are depicted in Figure 17.

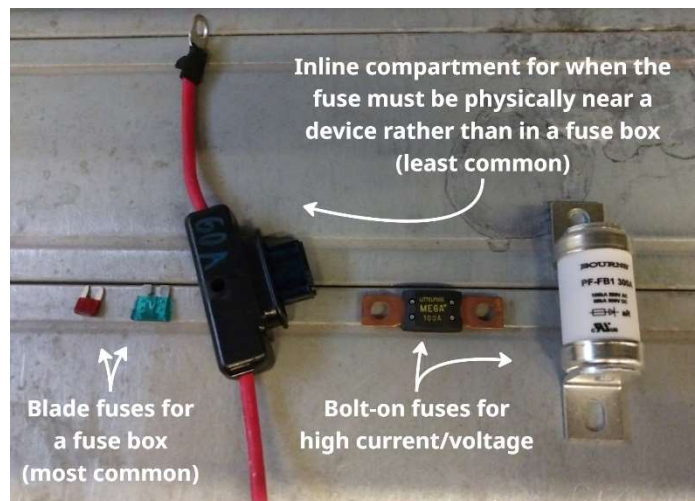


Figure 17: Fuse styles

3.1.4.3 HV Junction Boxes

High Voltage Junction Boxes (HVJBs) house all branching points, fuses, contactors, and testing infrastructure for the HV system. They can be made of either conductive or non-conductive material. However, conductive boxes must be grounded to the chassis and comply with the team's creepage and clearance rules to ensure the HV paths remain isolated. If an HVJB contains lines that are always energized, such as a contactor box, it must also pass a "wrench drop" test. That is, when the lid of the HVJB is off, a dropped wrench, screw, or other metal tool must not be able to connect the energized material to ground or the opposite voltage path.

Multiple HVJBs can be installed on a line (one to house a fuse, another to branch a path, etc.) if it makes more sense from a space claim perspective to keep the boxes small. The HVJBs that contain fuses, contactors, or testing infrastructure should be accessible without the need to remove other parts of the car. If space allows, every element can be housed in a single large box as in Figure 18. Note that the HVJB pictured is only 95% complete, missing a few LV connections and warning stickers.

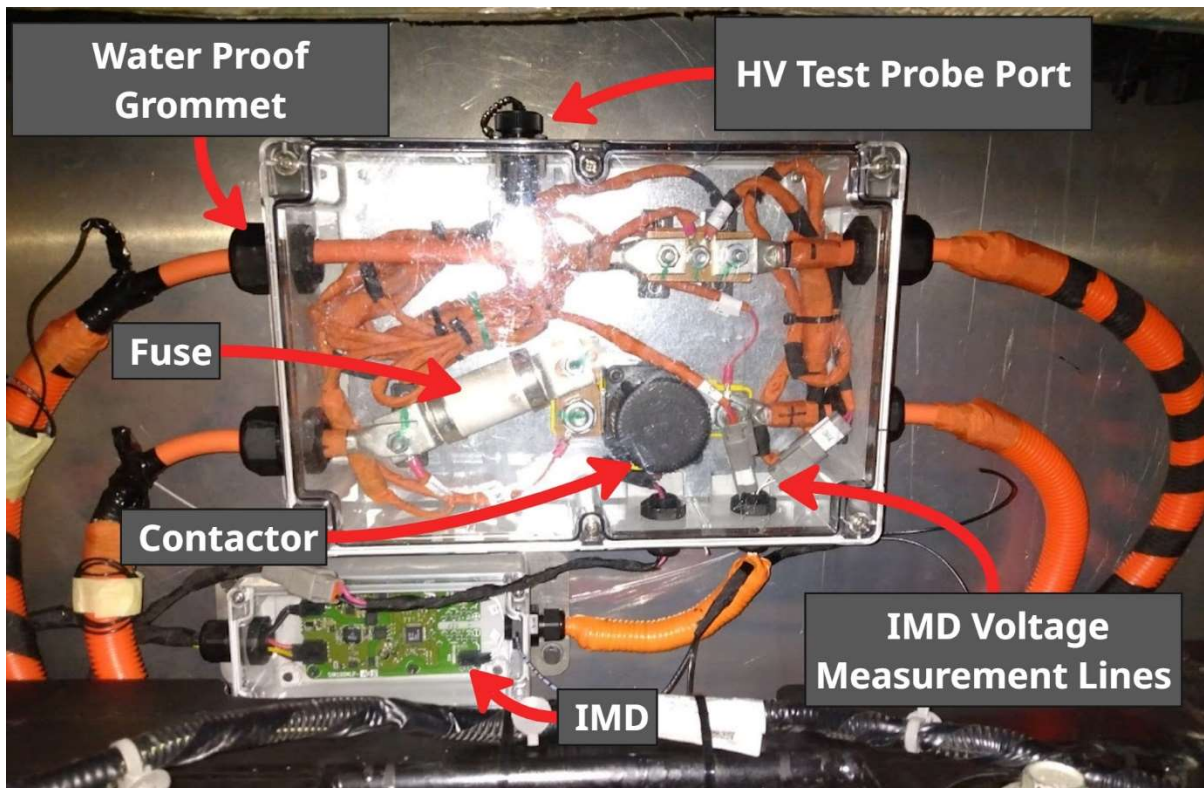


Figure 18: UWAF's Rear High Voltage Junction Boxes

An HVJB must not be opened accidentally while the system is energized. The first step to avoid this is to secure the lid with screws so that it can only be opened deliberately with tools. The second is to create a High Voltage Interlock Loop (HVIL).

HVIL operates on a similar basis as the EDS circuit, with a signal passing through each HVJB and ending at a supervisory controller. HVIL switches in each box are pressed ON by the presence of the box's lid, which means that any open box will break the HVIL circuit and alert the controller, which can then respond with a system shutdown and warning indicators. HVIL should also be extended to all connectors that plug into the HV battery, EDUs, and other HV devices. Many HV connectors have an HVIL switch built in and only need to be wired into the circuit. Otherwise, the team will need to add the switch themselves.

3.1.4.4 Routing and Labelling

Each wire has a certain degree to which it can bend with negligible risk of fracturing the conductor or tearing the insulation. This is represented by a wire's minimum bend radius: the smallest radius of a circle that the wire could wrap around, as depicted in Figure 19. Consult the manufacturer for a wire's minimum bend radius, especially for thick wires like battery cables. The minimum bend radius increases with wire thickness, so those cables need extra room to bend. This aspect caused UWAFST several redesigns as the team found themselves caught between the HV wire's bend radii and the tight spaces of their vehicle. It is recommended for teams that anticipate similar struggles to train or acquire a member with expertise specifically in wire routing CAD.

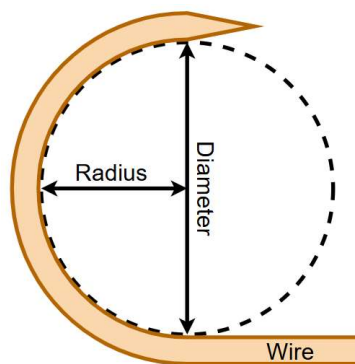


Figure 19: The minimum bend radius rating of a wire determines how tightly a wire can be bent safely

HV wires/devices should never be routed through the passenger compartment, nor should they be the lowest point in a vehicle. LV and HV wires should never run through the same conduit or junction box, except for HV safety infrastructure that depends on LV. Positive and negative HV lines should never be run through the same conduit. All HV wiring, both positive and negative, must be visibly orange. Large conductors or conduit housing HV wiring may also be marked with orange tape for identification. More is said on tape and loom selection in Chapter 4. All areas containing high voltage (HV) must be clearly labeled with the warning: **“Warning: High Voltage.”** Labels must use a sufficiently large font, be easily legible, and clearly visible. Additionally, any HV components that remain energized when HV Disconnect mechanisms are activated must be labeled: **“Warning: High Voltage – Always Energized.”**

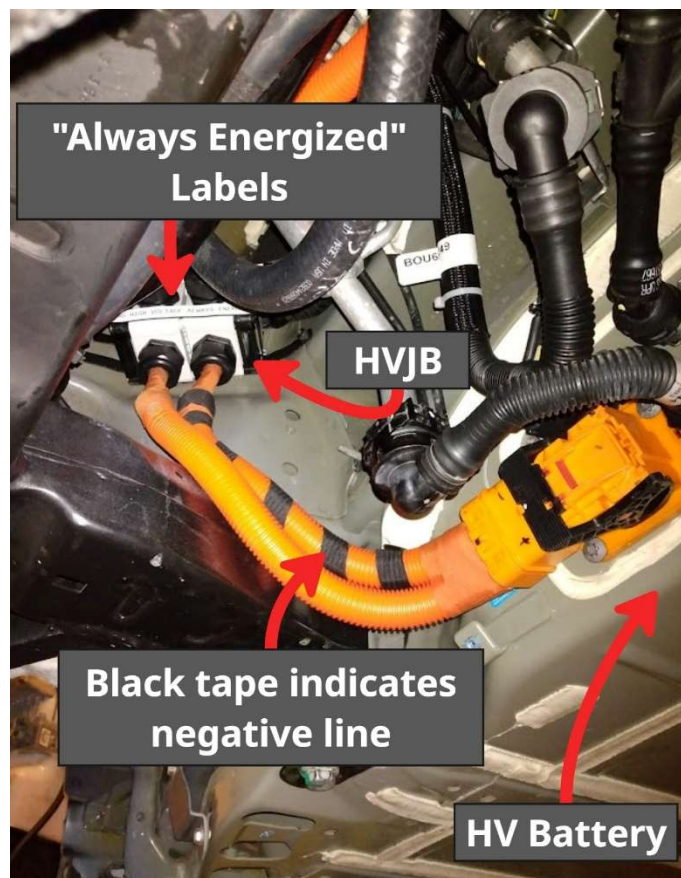


Figure 20: UWAF's HV lines between the HV Battery and a High Voltage Junction Box

3.1.5 Debugging EMI due to HV

The properties of an HV system can induce a charge to build up within any of its metal enclosures, like junction boxes and EDUs. This charge can generate an electric field if not allowed to disperse to the vehicle chassis ground. In EcoCar3 this problem created enough EMI to disrupt the CAN channels and prevent the car from turning on. The solution is to add grounding straps to all metal surfaces enclosing HV, including the shielding of HV wires, so they have a connection to the vehicle's chassis.

3.2 Design Case Study Schematics

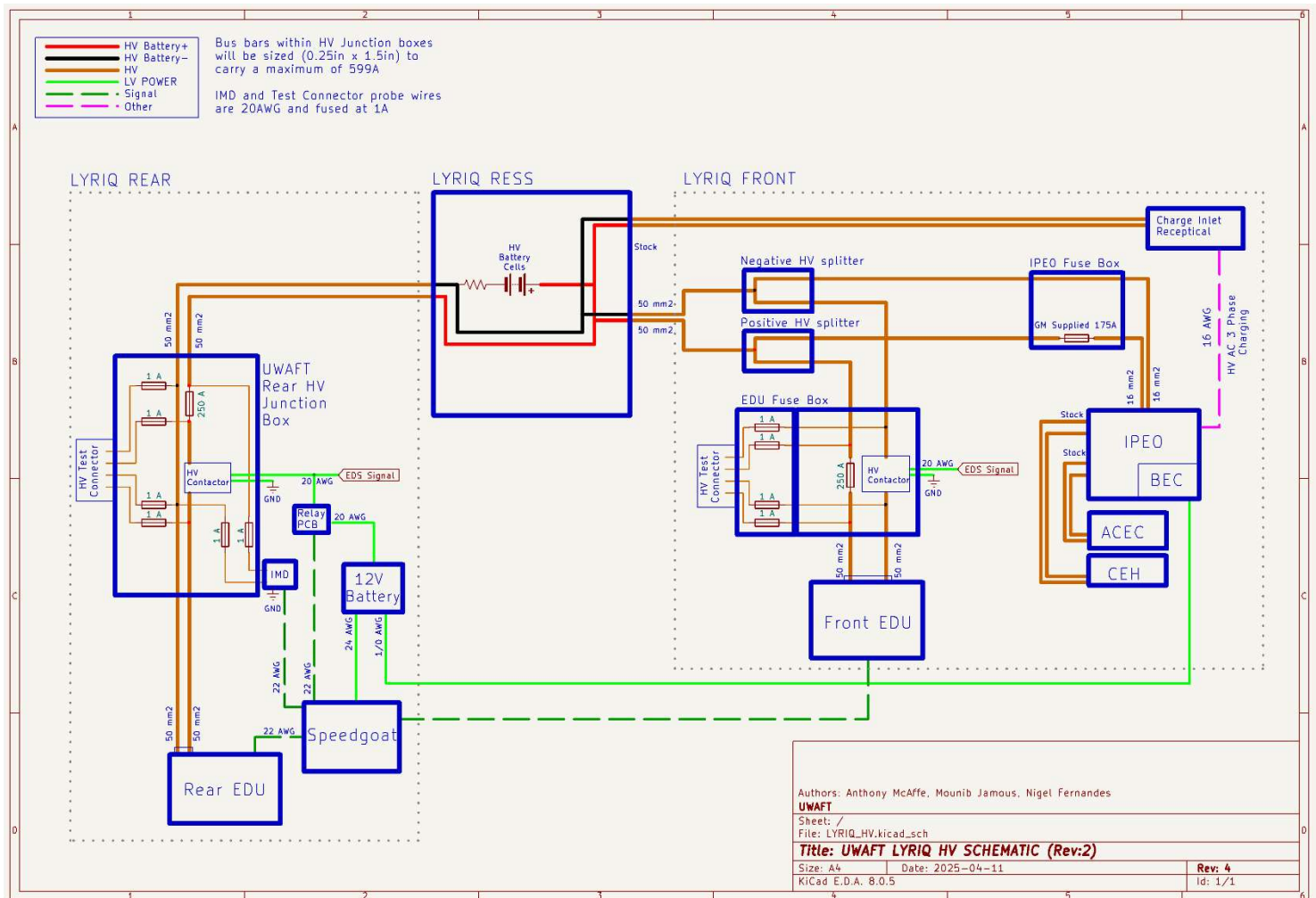


Figure 21: UWAF T HV Overview Schematic

The UWAF T HV system is divided into front and rear compartments with the HV battery between them. The purpose of this schematic is to show the flow of HV power through the vehicle, as well as the safety systems that control it.

While most of the internal structure of the HV battery is left to detailed schematics, it is important to show how the positive and negative pathways are connected so reviewers can understand what is and is not protected by fuses and contactors. The rear HVJB contains all the necessary breaks in the HV lines in its compartment, whereas the front had to be broken up into multiple smaller boxes for space claim purposes. A difference in line thickness between HV power and HV testing probe connections emphasises the change in gauge and purpose, though they are all colored in HV orange.

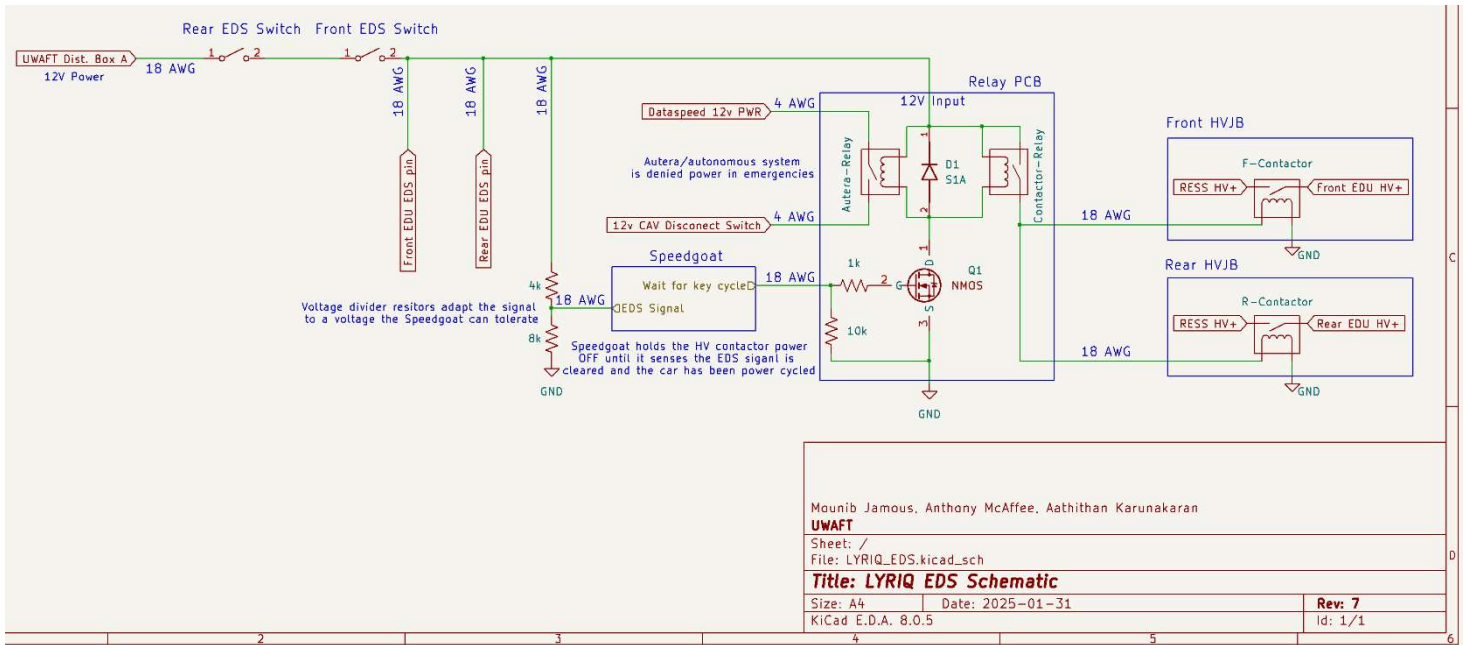


Figure 22: UWAF EDS Schematic

Figure 22 displays the UWAF EDS circuit, which cuts off HV power in emergencies. A 12V signal flows through EDS buttons in the front passenger’s compartment and rear bumper. If neither is pressed, the signal passes to the EDS signal receivers in the EDUs, the PCB that acts as a control for the HV contactors, and the Speedgoat supervisory control unit. If a button is pressed, the EDUs begin shutting themselves down, the Relay PCB cuts power to the contactors’ electromagnets, and the Speedgoat triggers a MOSFET switch to do the same until a full power cycle of the vehicle has occurred. The redundant MOSFET switch accounts for the EDS button accidentally being reset in the chaos of an emergency.

Chapter 4

Low Voltage Systems

4.1 Generalized Learnings

4.1.1 Background

Car manufacturers have powered automotive electrical systems with 12V batteries since the early 1950s [33]. Even with the introduction of HV batteries to hybrid and electric vehicles, the 12V battery remains standard across the industry for LV applications. Over the years, companies that make parts to sell to OEMs have adapted to this standard and designed their components to run directly off 12V. Nearly all sensors, pumps, displays, controllers, etc. meet this expectation. Therefore, compatibility is rarely an issue for student teams integrating new parts into their vehicles.

The challenge is to ensure the safe and reliable direction of power from the 12V battery through the car. Degrading factors like abrasion, heat, and vibration threaten to breach this containment. Anytime a device requires power outside the insulated cabin, like a motor controller under the hood, even more protection is needed to account for water, ice, dirt, etc. Finally, power can flow in damaging ways despite proper containment due to human error. The best-built wire in the world will still cause damage if plugged into the wrong port.

This chapter will discuss the tools and best practices commonly used to mitigate these risk factors, beginning with the safety precautions that protect those working on or driving in the vehicle.

4.1.2 Safety Considerations

In a hypothetical scenario, a student lies beneath the vehicle and feels along a wire with their bare hand trying to debug a power failure. They assume that because the voltages are low in this circuit, there is no risk. A break in the insulation is found by their thumb while the knuckle of the same hand is brushing against the vehicle's chassis. The current that rushes from the live wire to the chassis

ground point forces the muscles in their hand to grip the wire as severe burns spread between the two points of contact. They are lucky the current is not passing through their heart.

Table 1 details the effects of current on the human body. To put this table in perspective, most wires in the UWAFV LV harness carry more than 100 milliamps, and the maximum current predicted to flow through the wires directly connected to the LV battery is 300,000 milliamps.

Table 1: Consequences of increasing levels of current passing through the human body [34]

Current	Reaction
1 milliamp	Just a faint tingle.
5 milliamps	Slight shock felt. Disturbing, but not painful. Most people can “let go.” However, strong involuntary movements can cause injuries.
6-30 milliamps	Painful shock. Muscular control is lost. This is the range where “freezing currents” start. It may not be possible to “let go.”
50-150 milliamps	Extreme pain, respiratory arrest, severe muscular contractions. Individual cannot let go. Death is possible.
1,000-4,300 milliamps (1-4.3 amps)	Ventricular fibrillation (uneven uncoordinated pumping of the heart.) Muscular contraction and nerve damage begins to occur. Death is likely.
10,000 milliamps (10 amps)	Cardiac arrest and severe burns occur. Death is probable

The first rule of electrical safety is to never work on an energized system. “Work” refers to installing wires, unplugging connectors, or any action that may expose current-carrying material. Disconnect switches like Figure 23 can be added to control which portions of the vehicle are energized. Disconnect switches also serve to prevent “parasitic loads” that drain the battery when the car is not on. For example, compute units still draw small amounts of current when in sleep mode. Without a disconnect switch, these parasitic loads can dramatically shorten the battery’s lifespan.

The second rule of electrical protection is to always assume the system is energized. Disconnect switches can malfunction,



Figure 23: A Disconnect Switch cuts off power so work can be done safely.

students can forget to use them, and unwary teammates can turn the system back on while another is working. Protections like fuses (discussed in Chapter 3), safety covers, and PPE must be in place as secondary lines of defense.

Battery leads, bus bars and other conductive materials that lack insulation need to be protected by safety covers. Depending on the competition context, these may need to be finger and/or waterproof. At a minimum, these covers should be able to pass a “wrench-drop” test, meaning that there should be no possibility of dropping a wrench such that it connects two potential voltages, as happened in the case pictured in Figure 24.



Figure 24: Unprotected battery leads destroyed by dropped wrench [35]

To further minimize health risks, PPE requirements should be established in case all other safety measures fail. Wearing closed, rubber-soled shoes can prevent current from passing through the body into the floor, and rubberized working gloves can prevent current from entering the hand. It is also wise to remove all jewelry, including rings, and tie back loose hair.

4.1.3 Best Practices

The general design process for designing and building an EV LV system is laid out below. The rest of this section will elaborate on the best practices to employ in this process.

4.1.3.1 The LV Harness Design Process

Collect Information

1. Make a list of all devices that will need LV power
2. Collect the data sheets for each device in the system to determine their power requirements

3. Create a spreadsheet for each device listing its power inputs/outputs, pinouts, expected currents, compatible wire gauges, compatible connector part numbers

Draw Schematics

4. Draw a high-level schematic of the LV system. Start by placing each device from the list on the page, then drawing their powered connections as simple lines, creating a “rat’s nest”. Rearrange the devices until the rat’s nest becomes an orderly flow of power from top left to bottom right.
5. Decide where to place disconnect switches, fuse/distribution boxes, and any power electronics to step the voltage up or down for devices that cannot run on 12V.
6. Starting from the furthest points downstream of the 12V battery and working back towards it, calculate the maximum currents expected on each line. Then select wire gauges and fuses based on those currents.
7. Draw detailed schematics for each device.

Select and Order Parts

8. Order greater quantities of wires, connectors, fuses, etc. than what is described in the schematics. This frees the teams to spend materials on training and gives room for error when assembling the vehicle. Also order extras of plugs/ports already built into stock/donated devices, so students can practice on expendable materials.
9. Before assembling anything, **practice, practice, practice** with the spare parts, particularly the connectors. Assume the first 3 units a student builds will be thrown out as practice attempts.

Assemble

10. Arrange the devices in the vehicle. They do not need to be mechanically secure at this stage, though that helps.
11. Identify any points where wires will need to pass from one compartment of the vehicle to another and get mechanical students involved to find routing solutions that maintain structural integrity and weatherproofing.
12. Create “rib” break-out plugs (described in Chapter 5) where appropriate, such as on an EDU or compute unit to make it easier to connect/disconnect related pin groups. For instance, an

- EDU connector can have 50+ pins. Short breakout plugs can be used to separate the power pins from signal pins and make assembly much easier, since the power harness assembly will no longer be dependent on the signal system's harness also being ready to integrate.
13. Moving downstream from the 12V battery to the disconnect switches, then fuse boxes, then to each device:
 - a. Lay a string along the path each wire will be routed. This will be a best guess of the path since routing often changes as the system builds up.
 - b. Cut and strip the wires to the string lengths
 - c. Temporarily label each wire with its destination and source
 - d. Crimp or solder the wires into their connectors and attach them to the device
 - e. Test each new connection for continuity with a multimeter
 14. Once all points downstream of a disconnect switch are electrically continuous and safely insulated, the branch can be tested by turning the disconnect switch ON. Return to OFF position to debug or continue working.
 15. Remove temporary labels and add tape, loom, strain relief clamps/ties, and permanent labels to each harness bundle.

A word of caution: this process will not flow smoothly from step to step. There will be a lot of going back and forth, especially when trying to bring the first drafts of the schematics into the real world. In EcoCar5, trying to perfect the schematics before building anything cost UWAF time. Waiting for every device to be secured in place before assembling any cables cost even more time. A mindset of “we can't finish Y until X is 100% done” cost UWAF many points in their competition. A better mindset is: “I may not know what 90% of this circuit will look like, but I **can** build this part **now**.”

4.1.3.2 Best Practices: Schematics

Schematics primarily describe electrical connections within a system and only rarely do they represent the physical arrangement of devices as well. Building a LV harness without a schematic would be the same as building a house without a blueprint.

Just as blueprints for residential houses and skyscrapers will follow slightly different paradigms, schematics for EV harnesses and PCBs will be drawn differently. Most EV student teams will require a working knowledge of PCB design. However, that is a topic commonly covered in electrical

engineering programs, whereas EV harnesses are not. Therefore, and as a matter of scope, the advice given here will be specific to power harnesses.

4.1.3.2.1 High-Level and Detailed Schematics

Both high-level overview schematics and device-specific schematics are important for an EV harness. The high-level schematics fit the whole LV subsystem onto a single sheet, giving a big-picture view of power and/or signals flowing through the vehicle. This helps students follow and identify wires during debugging and informs them where new devices can be added in the future. However, sheet size and legibility preclude details like pinouts or connectors on overview schematics. Hence, numerous detailed schematics zoom in on specific devices or compartments. Device-specific schematics should also include any HV or serial communication connections to the device.

4.1.3.2.2 General Rules for Schematic Drawing

Power should flow from top-down and left to right.

The current rating of any fuses and the gauge of any wires shown should always be included.

For readability and accessibility, maintain legibility when printed monochromatically on an 8.5x11" piece of paper.

Student teams working with donated vehicles do not need to recreate the original schematics, though they should indicate clearly how their added systems connect into the stock system.

Fuse box schematics should be drawn to mimic the shape and layout of the real-world box so that reviewers can easily see where the power flow is branching. This also makes it harder to mix up which fuse goes where.

As shown in Figure 25, dots indicate nodes where two wires or harnesses connect electrically. An absence of a dot indicates the lines do not connect. The latter should be avoided by routing lines around each other instead of through, but sometimes the layout of a page makes this impractical.

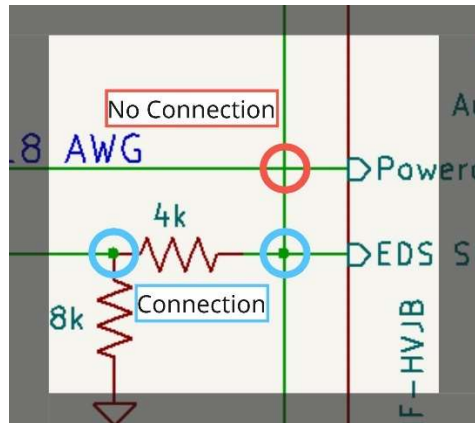


Figure 25: Dots represent nodes where lines connect electrically.

Regarding metadata: the revision number, date of revision, and the names of those who worked on it must be included. Additional info could include the names of relevant supervisors, part numbers, a project description, and the reason behind each revision. However, too much metadata can clutter a schematic, reduce readability, and create redundant work for the designer. A balance must be struck by each team between making the schematic practical for designers in the present and useful for those in the future.

4.1.3.3 Best Practices: Wires

Automotive-grade primary wires are often thicker than other grades and are made of hardier materials to resist a vehicle's vibration, heat, and environmental factors. As such, student teams that use non-automotive grade wires are at a higher risk of wire degradation, malfunctions, and safety hazards.

When browsing for wires online, the many acronyms and options can be overwhelming. This section aims to demystify the process so students can define what they want and possess the terminology to ask suppliers for it.

At its core, wire selection balances four requirements: it must **not overheat**, it must **bend** to fit in the space available, it must minimize **weight**, and it must minimize **cost**.

4.1.3.3.1 Prevent Overheating: Gauge Selection

When a wire overheats, the insulation melts and exposes the conductor, which could touch the vehicle's chassis or another wire and create a short circuit. Short circuits lead to runaway currents that

could harm people or the vehicle. In extreme overheating events, the copper at the hottest point of the wire melts, which can cause arc flashes. [36]

Heat is generated as the material of the wire resists current passing through it. The greater the resistance the greater the heat generated. Resistance (R) in a wire is affected by the conductor material's resistance to current (ρ), as well as the length (L), and cross-sectional area (A) of the wire as described below.

$$R = \frac{\rho L}{A}$$

To reduce resistance, and therefore heat generated, ρ is minimized by using low-resistivity materials like copper or aluminum. The length of the wire is determined by the vehicle's needs, leaving the cross-sectional area the easiest variable to control. Some countries define wires by their mm^2 measurement, while others use the American Wire Gauge (AWG) standard. In the AWG system, the cross-sectional area decreases as the gauge number increases, as shown in Figure 26. Basically, the higher the AWG, the thinner the wire. Another oddity of this system is that past 1 AWG the definitions become 0 AWG, 00AWG, etc., or alternatively as 1/0 AWG, 2/0 AWG, etc. Students have mistakenly confused 1 AWG (pronounced “one gauge”) with 1/0 (pronounced “one aught gauge”). This can be a costly mistake as spools of these gauges can cost hundreds of dollars.

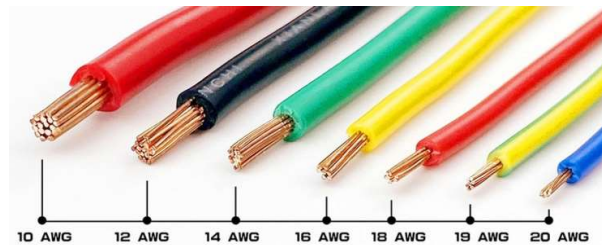


Figure 26: Illustration of wire thickness increasing inversely with wire gauge [37]

The rating for how much current a wire can safely carry without overheating is referred to as its ampacity. Wire manufacturers typically present their selection of gauges in an ampacity chart like Figure 27 below.

Total Approx. Circuit Amperes	Wire Gauge (For Length In Feet)												
	12VDC	3	5	7	10	15	20	25	30	40	50	75	100
1	18	18	18	18	18	18	18	18	18	18	18	18	18
1.5	18	18	18	18	18	18	18	18	18	18	18	18	18
2	18	18	18	18	18	18	18	18	18	18	18	16	16
3	18	18	18	18	18	18	18	18	18	18	18	14	14
4	18	18	18	18	18	18	18	18	18	16	16	12	12
5	18	18	18	18	18	18	18	18	18	16	14	12	12
6	18	18	18	18	18	18	18	16	16	16	14	12	10
7	18	18	18	18	18	18	18	16	16	14	14	10	10
8	18	18	18	18	18	18	16	16	16	14	12	10	10
10	18	18	18	18	18	16	16	16	14	12	12	10	10
11	18	18	18	18	18	16	16	14	14	12	12	10	8
12	18	18	18	18	18	16	16	14	14	12	12	10	8
15	18	18	18	18	18	14	14	12	12	12	10	8	8
18	16	16	16	16	16	14	14	12	12	10	10	8	8
20	16	16	16	16	16	14	12	10	10	10	10	8	6
22	14	16	14	14	14	12	12	10	10	10	8	6	6
24	14	14	14	14	14	12	12	10	10	10	8	6	6
30	12	12	12	12	12	10	10	10	10	10	6	4	4
40	10	8	8	8	8	8	8	8	8	6	6	4	2
50	8	8	8	8	8	8	8	8	8	6	6	2	2
100	4	4	4	4	4	4	4	4	4	4	2	1	1/0
150	2	2	2	2	2	2	2	2	2	2	1	2/0	2/0
200	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	4/0	4/0

Figure 27: Wire gauge chart [38]

The ampacity of a wire is affected by the conductive material used, how conductor strands are woven together, treatments manufacturers perform on the conductor, and the conditions assumed by the chart-maker. For instance, the site from which the above chart was taken states, “Chart is based on maximum 10% voltage drop @ 100° F (in free air).” [38]

A company that assumes different ambient temperature conditions or possesses unique treatments/strand weaving techniques might list different ampacities for their gauges. Additionally, companies may have different methods to calculate how changes in the ambient temperature will affect ampacity. From the chart above a 3’ wire carrying 15 A should be at least 18 AWG, but that is only at 100 °F. If the wire is expected to operate in temperatures over that, it may need to be a thicker gauge depending on manufacturer recommendations. Clear communication with the manufacturer is vital to ensure wires operate as expected.

As a final note on gauge selection, **know what gauges your connectors support**. In particular, student teams need to adapt to the connectors available on donated parts. For example, a donated

inverter that draws a nominal current of 10 A is fed by a 10ft wire. Referring to Figure 27, a student may order an 18 AWG wire based on that information alone. However, the terminal on the inverter was designed to accommodate only 16 AWG wires, and the student will be unable to attach the wire securely.

4.1.3.3.2 Preventing Overheating: Insulation Selection

Another factor that prevents overheating is the selection of the insulation. Automotive-grade wire insulation falls into two categories: Polyvinyl Chloride (PVC) and Cross-linked Polyethylene (XLPE).

Tables 2 and 3 are adapted from [39] and detail what each option is best suited for. PVC wires are highly resistant to oil, dirt, and acids and are used throughout the vehicle. XLPE wires are more heat and abrasion-resistant than PVC and are used when connecting to engines and motors. [40]

Table 2: Automotive PVC Insulation Options

Wire Type	Temperature Range	Gauge Size	Typical Applications	Notes
General Purpose Thermoplastic (GPT)	-40°C to 80°C	20 to 10 AWG	General wiring	The “Golden Standard” of PVC wires[40]
Thin Wall PVC (TWP)	-40°C to 105°C	24 to 10 AWG	Low-voltage applications	Small and light relative to GPT
Heavy Duty Thermoplastic (HPT)	-40°C to 80°C	20 to 8 AWG	Robust wiring needs	More abrasion resistant but less flexible relative to GPT

Table 3: Automotive XLPE Insulation Options

Wire Type	Temperature Range	Gauge Size	Typical Applications	Notes
General Cross-linked (GXL)	-40°C to 125°C	22 to 8 AWG	High-temperature conditions	-

Standard Cross-linked (SXL)	-40°C to 125°C	20 to 8 AWG	High-temperature, high abrasion conditions	Heavier but more flexible relative to GXL
Thin Cross-linked (TXL)	-40°C to 125°C	26 to 8 AWG	High-temperature, limited space conditions	Smallest and lightest of the three

4.1.3.3.3 Preventing Overheating: Wire Bundles

Another factor that prevents overheating is the wire's proximity to other wires. If multiple wires are bundled alongside each other, the air is less free to flow, and the heat of the bundle wires can compound together. This is an often negligible effect, but if most of the wires in the bundle are of the bare minimum spec, then the wires should be tested. [41]

For instance, one wire rated for max 10A might safely handle that current on its own, but if bound to 4 identical wires all running 10A, there is a risk that they could overheat. If that harness is routed near an engine block or the competition takes place somewhere hot like a desert proving ground, then the likelihood of overheating becomes significant.

Take the harness to a test bench and run it at the greatest expected current, ambient temperature, and length of time expected in your competition context. If the harness shows no signs of damage afterward, then it is fit to install.

4.1.3.3.4 Wire Stranding

The flexibility of a wire depends not only on its gauge and insulation but also on its internal structure, referred to as stranding. There are several classes of stranding, the most basic of which is Class A: solid-core wire. The other classes have many strands of conductive material laid or woven together and are more flexible than solid wires. Flexibility increases from Class B to Class M. Figure 28 presents the difference between solid and stranded wire.

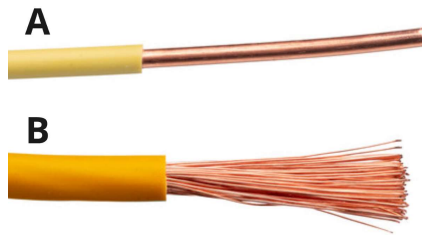


Figure 28: Stranded wire (A) vs. Solid-core wire (B)

Student teams should use “hook up” wire, which has a solid core with breadboards, embedded controller breakout boards, and screw terminals. Stranded wires could bend, split, and risk coming loose in these connections.

The classes of stranded wire are divided by how the strands are laid, woven, braided, or otherwise arranged in the wire. Generally, more flexible stranding classes require more intensive manufacturing processes and are more expensive. The bulk of an automotive wire harnesses will usually be stranded wire because of its greater flexibility to bend through confined spaces and because most crimping terminals are designed for stranded wire. The strands flare out on the other side of the crimp compression, preventing the wire from slipping out. Since solid core wire does not behave this way, it is unsuitable for crimping.

4.1.3.3.5 Wire Weight and Cost

Weight and cost are the primary restrictions on over-specifying wire gauges and insulation. For example, UWAFI installed approximately 30m of 16-20 AWG and 1.5m of 10 AWG wire in their LV power harness. It would have simplified the purchasing order and improved the wires’ protection against unexpected currents to replace all the smaller gauges with 10 AWG. However, this would add more than 6 times the weight and nearly quadruple the cost.

Teams that optimize energy efficiency or compete in racing events need to shed every unnecessary gram, and over-specified wires are one place they can cut back. Furthermore, student teams usually run on thin budgets, so knowing how to select the cheapest wire/insulation that meets the minimum current and temperature requirements can help reduce costs.

It never hurts to ask wire manufacturers to donate spools of wire, as many will gladly do so for student teams. However, charity cases are a lower priority than their normal customers, so “free

samples” can take weeks or months to manifest in the students' garages. Team managers must be proactive about requesting donations far before deadlines approach.

4.1.3.3.6 Wire Color

A red wire typically represents LV power, black is used for grounding wires, and orange indicates that the wire either carries high voltage or is critical to the HV system. Apart from these basics, color standards vary between vehicle manufacturers. Student teams modifying a vehicle are advised to find and stick to the stock color scheme to avoid confusion. When introducing new signal wires that have no pre-existing standard in the vehicle, consider how color choice can make a design more or less accessible to the colorblind.

Colorblindness affects 2/25 men and 1/200 women. A brighter hue of red for power wires will help those with red/green colorblindness tell those wires apart from the dark black ground wires. [42] When the options are available, choose wire colors from the palettes in Figure 29 which have been tested for color blind accessibility. [43]

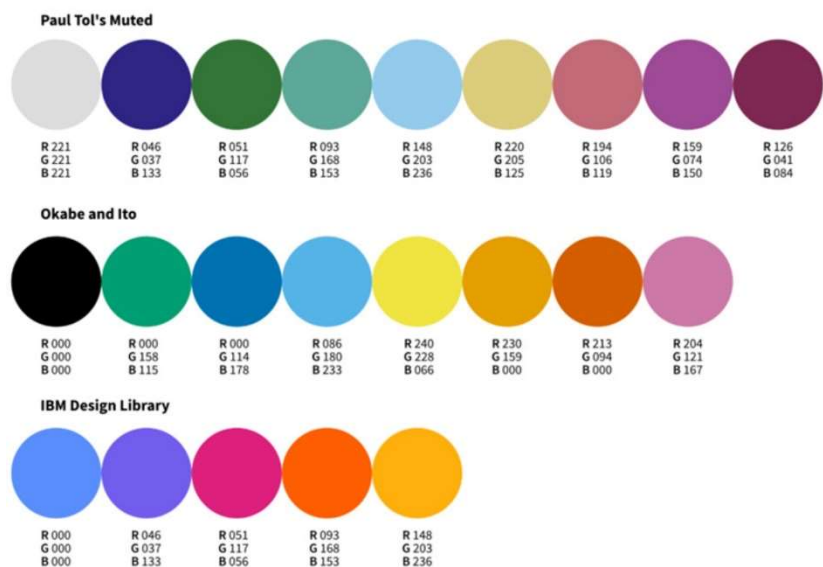


Figure 29: Colorblind-friendly palettes [43]

4.1.3.3.7 LV Battery Cables

Distinct from both primary wire and HV cables, automotive battery cables are heavy-gauge, single-conductor wires that link electrical automotive parts with the vehicle's battery. It's common for these to be 6 AWG, but they can be thicker depending on the needs of the vehicle. [44]

Battery cables should be used for the path between the positive terminal of a 12V battery, initial disconnect switches, and the first distribution-blocks/fuse boxes. Also use these when connecting the negative terminal of the 12V battery to chassis ground.

4.1.3.4 Assembly: Crimping Wire Terminals

Terminals are crimped onto the ends of a wire to connect it to a device or another wire. A few of the most common varieties of terminals are shown below in Figures 30-32. Red terminals denote a fitting for AWG 22-16, blue for AWG 16-14, and yellow fits AWG 14-12.

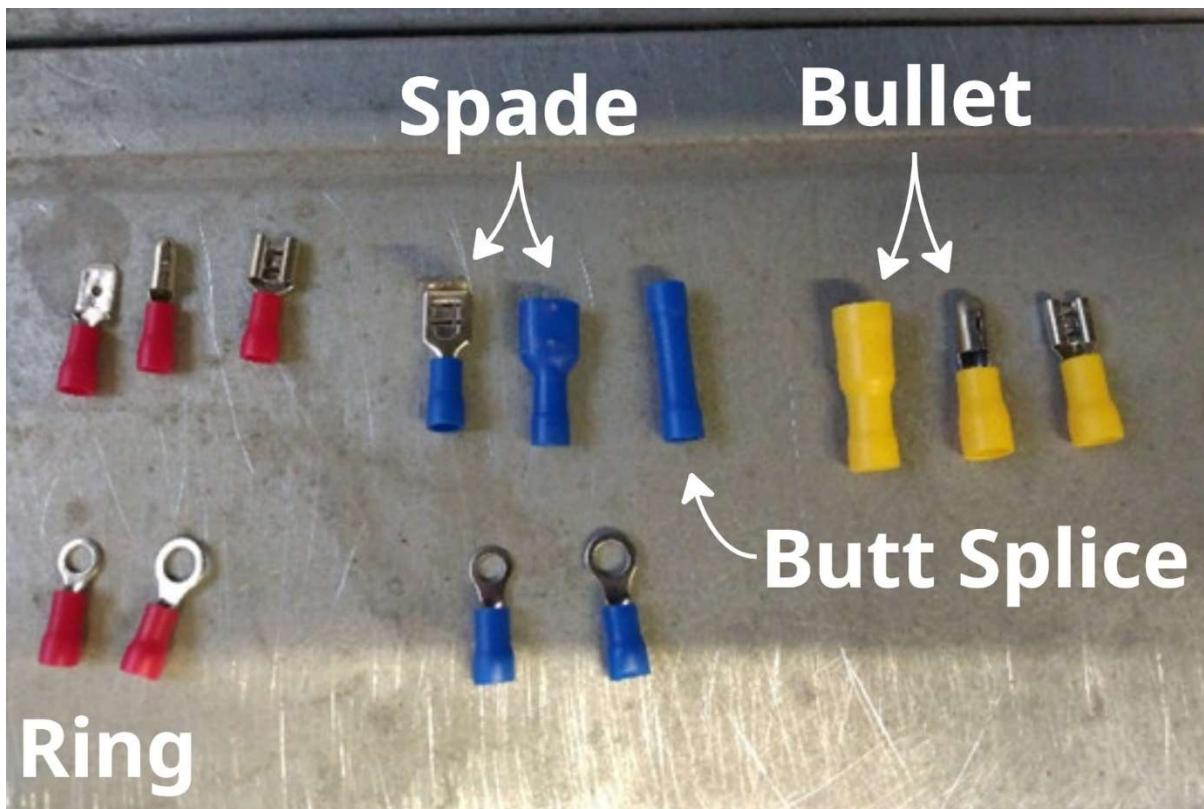


Figure 30: Ring terminals facilitate bolting wires to the chassis or fuse block posts. Spade terminals are used to reversibly connect the ends of two wires. Bullet terminals performed the same function as spades in older vehicles and are present in many terminal kits but are less reliable than spades. Butt splices crimp wires together that will not need to be disconnected.

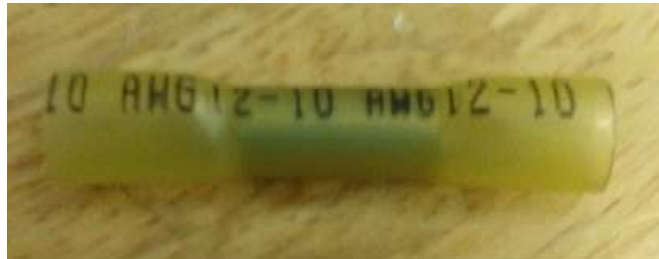


Figure 31: A butt splice terminal with transparent plastic, showing the metal that deforms when crimping to hold the wire in place. The flared ends on either side are heat shrink material, making this splice water resistant once shrunk.

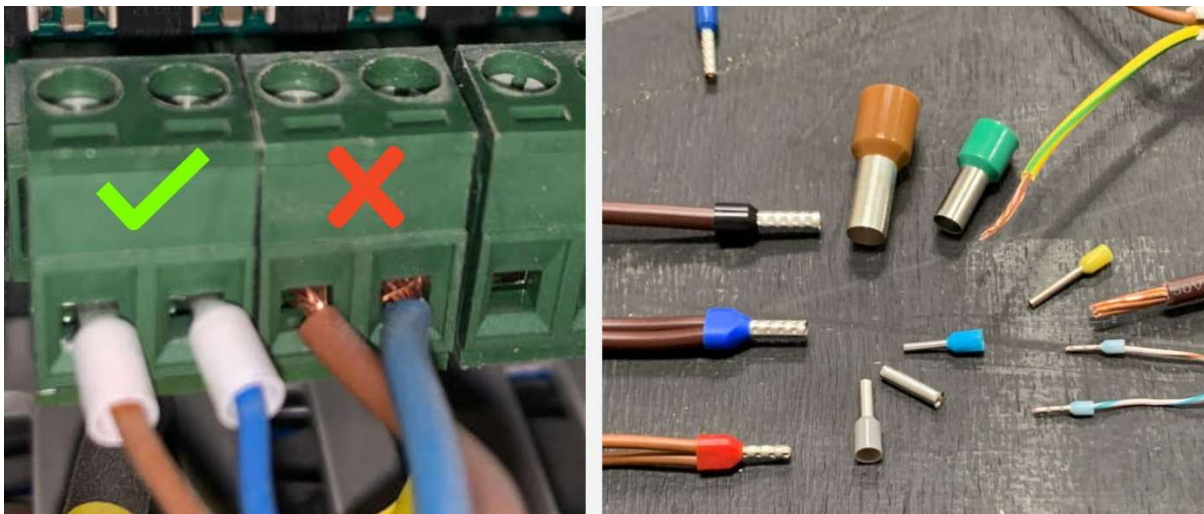


Figure 32: Ferrule terminals adapt stranded wires for screw down terminals, creating a solid connection. The color/gauge schemes of ferules differ from other terminals and vary between manufacturers. [45]

Most connectors will require wires to be crimped with terminal pins before insertion, similar to the EDU LV connector in Figure 33 that UWAFU used.

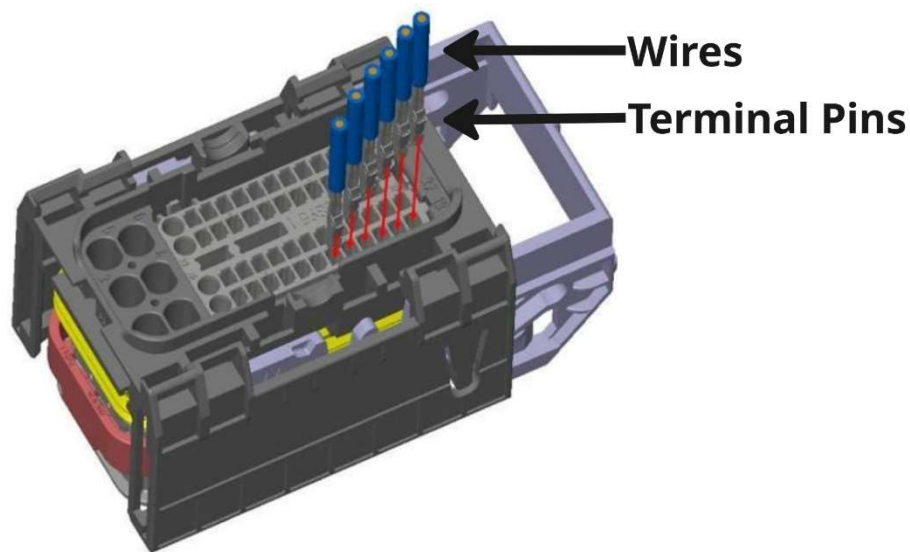


Figure 33: Datasheet instruction diagram for assembling an inverter's LV connector. [46]

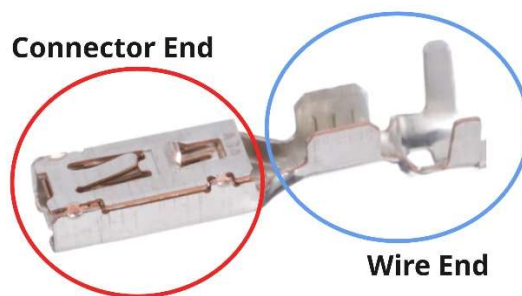


Figure 34: Terminal pin ends

It is important to consider both ends of a terminal pin when ordering. The connector end will be specified by the connector's data sheet, but the wire end may be left open to a range of gauges. UWAFT has ordered the correct connector-ends without specifying the wire-ends, which ended up not fitting the wires when crimping.

Common errors in crimping technique are shown in Figure 35. Example A has been stripped back too far, and the pin's grip on the wire is insufficient. B features an oversized gauge of wire, and the pin cannot properly contain it. C has pin arms that were not properly compressed because the wrong crimper dies were used. D shows a solid core wire crimped into a terminal that was designed for stranded core wire. E presents a properly crimped wire complete with a weather-proofing rubber seal ready for its connector.

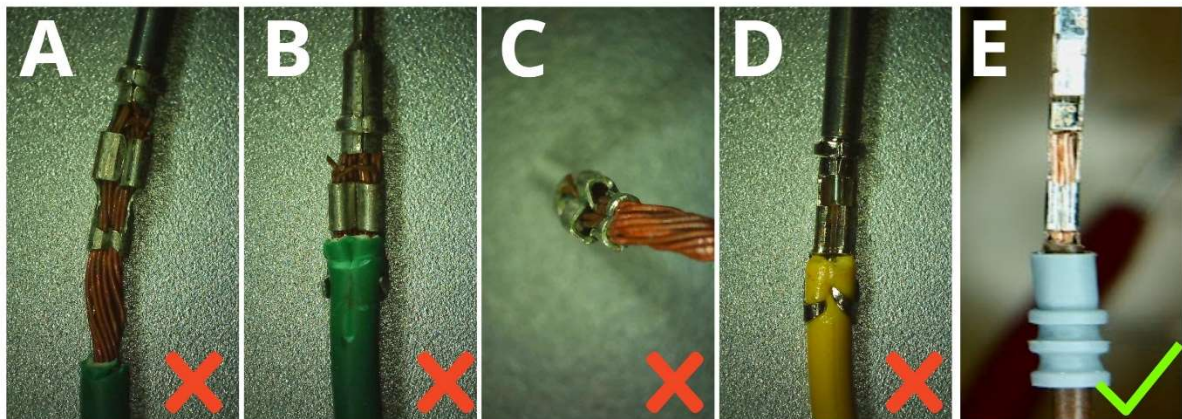


Figure 35: Crimping examples

4.1.3.5 Best Practices: Tape and Loom

Tape and loom (a plastic or metal tube that encases wire bundles, AKA conduit) both hold harnesses together and offer protection from the surrounding environment. Tape does more to bundle the wires and make them manageable, while loom provides better abrasion protection. Depending on competition standards, it may be required to overlap tape and loom on all bundles, or it may be fine to loom wires together without tape underneath. Both overlapping and loom-alone can be found in production vehicles. Teams should be aware of the tape/loom varieties so they can choose those best suited to their projects.

Table 4: Automotive Tape Varieties and their Benefits

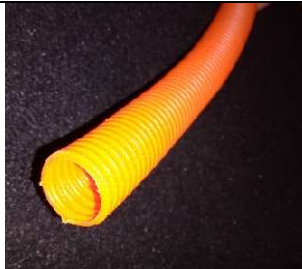
Type	Description	Example
Cloth-backed	Abrasion-resistant, used to wrap wire bundles together	

Rubber-backed*	Less abrasion-resistant but can bundle wires in places where no chaffing is expected, or wrap around split loom to hold it together and bind the ends	
Sleeve tape	- Has adhesive only on the top and bottom edges - Useful for long, unbroken stretches of harness - Reduces the stiffness seen when spiraling other tapes - Less total material used	
Fleece-backed	- Useful where the harness may knock against other objects - Fleece dampens any knocking and absorbs sound	
Thermal	- Reflects radiant heat from the environment - Raises the temperature that the wire can safely withstand	

*While closely resembling automotive rubber-backed tape, **common electrical tape will degrade quickly in an automotive environment, especially in high temperatures, so do not use it.**

Table 5: Loom Varieties and their Benefits*

Type	Description	Example
------	-------------	---------

Split corrugated plastic	• Cheap and widely used for basic abrasion protection • Makes installation and future changes easier for multiple small wires in a bundle • When debugging, the split can be opened to examine the wires for breaks.	
Non-split corrugated plastic	• Greater protection and possibly waterproofing depending on the brand • Used for thick battery cables, with just one wire passing through the tube	
Braided nylon	• High flexibility • Easy to apply heat shrink to the ends	

*Temperature resistance can vary for all types of loom depending on brand. A braided nylon tube from one brand may be extremely heat resistant, whereas a similar-looking tube from another brand may not.

Tape and loom can be ordered in various colors, but maintaining black for LV and orange for HV is consistent with industry practice. While black looms in most sizes are common and unlikely to ever be out of stock, more specific loom requests can take time. UWAFB did not begin looking for loom until a few months prior to their competition and were surprised to find that the thick, orange loom required for their HV system could not be shipped in time they had left.

Strip-style tapes (Cloth, rubber, etc.) are applied by spiraling the tape around the wire bundle so that the wrappings overlap. Companies recommend different ratios of overlap when spiraling, but $\frac{1}{4}$ to $\frac{1}{2}$ are common.

For **sleeve tape**, run the tape lengthwise down the wires to be bundled, then stick the bottom-edge adhesive to the wires. Wrap the tape widthwise around the bundle until the top adhesive can adhere to the backside of the tape.

A wrench can be used to make installing **split loom** on a harness easier. Place the wires in the mouth of the wrench, then press them into the split of the loom and run the wrench down the length of the harness. Once the wires are in, tape or heat shrink the ends of the loom to the harness to prevent slipping. Tape can also be spiraled around the split loom with a generous gap between wrappings to ensure no wires escape through the split.



Figure 36: Looming wires with a wrench

Non-split loom requires the wire(s) to be pushed through from one end before connecting both ends to terminals. A common mistake is to build and test the harness first and only then think about looming, leading to redundant reworking of the harness. As with split loom, secure the ends of the loom with tape or heat shrink.

Loom and tape can cover more than wires, such as the braided nylon loom protecting a coolant line from abrasion in Figure 37.



Figure 37: Braided loom protecting a coolant line from abrasion

4.1.3.6 Best Practices: Water and Dust Protection

The power and signal distribution systems need to be protected from water and dust. Besides the obvious dangers of water entering an electrical system, dust accumulation in LV circuitry can degrade equipment, reduce thermal ratings, or catch fire itself. [47] Ingress Protection (IP) ratings [48] define junction boxes, terminals, connectors, etc., by two numbers. The first number indicates protection from solid objects on a scale between IP0X (no protection) and IP6X (no dust can enter). The second number indicates protection from water between IPX0 (no protection) and IPX9 (safe from high-pressure/temperature jets of water). All electrical enclosures outside the vehicle's cabin should be rated at least IP64 for protection from dust and splashing water.

Some connectors are designed for a rubber seal to fit between the inserted wire and the connector's housing. Students often forget to place these seals onto the wire before stripping/crimping the wire, then attempt to slide the seal over the crimped pin. This can cut the seal and ruin its waterproofing.

If connectors are left open between work sessions, and especially if the vehicle will be transported during that time, cover the open connections with tape to prevent dust and fluids from entering.

4.1.3.7 Best Practices: Routing

To pass a wire between compartments such as the cabin and engine bay, it is not sufficient to just cut a hole in the vehicle's frame and feed the wire through. This breaks the environmental containment of the cabin and will lead to wire chafing/cutting even with tape and loom. Instead, a grommet must be used to seal the hole and protect the wire as depicted in Figure 38.

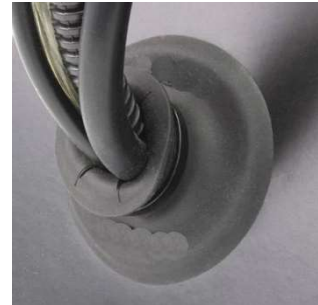


Figure 38: Grommet used to safely pass wires through a firewall

Zip ties are used by many competition teams and auto manufacturers to secure harnesses to solid points in the vehicle so that the wires do not move when the car turns or hits a bump. Such movement can create knocking noises and damage the wires over time. However, if zip ties are deemed unprofessional or lacking in robustness, as in EcoCAR 5, P clamps can be used as depicted below for a higher quality solution.



Figure 39: P Clamps can be used to restrain wire harnesses

When deciding how often along the line to add restraints, strike a balance between reducing knocking/chaffing and giving the wires enough slack. They should be secured in place but not taut, because if the routing pulls the wires against their terminals, they could pop out or break while the vehicle is in motion. Also avoid tight bends in the harness, keeping in mind the minimum bend radius of any wires therein.

The lowest component in the vehicle should never be a wire, tube, or electronic device. If such components need to be so near to the ground, they must have a skid plate or similar protection beneath them. Electrical devices should never be mounted directly beneath liquid-carrying equipment such as coolant pumps or reservoirs.

4.1.3.7.1 Best Practices for Grounding

Proper electrical grounding in a vehicle enhances efficiency, safety, and performance by stabilizing voltage, reducing noise, and preventing faults.

The grounding wire must be rated for the expected current, though it is better to err on the side of oversizing ground lines.

When choosing a point to ground to, look for mechanical integrity, ease of access, and a resistance of less than 100 mΩ between the device's ground output and the negative terminal of the 12V battery. [49] A milliohm meter can be used to verify the latter, though they can be rather expensive.

Remove any paint, coatings, or rust between the grounding line and its point of connection to the chassis with a wire brush or rotary tool. Make certain that the grounding line is securely bolted to the chassis and will not come loose with vibration. These factors can choke the current flow or cause it to flicker, leading to malfunctions in the improperly grounded device.

Keep grounding cables as short as possible to reduce resistance and EMI, improving efficiency and maintaining signal integrity. More than one device can be grounded to a single chassis stud, and for sensitive equipment like audio, video display, or sensors it may improve signal quality. [50]

However, it is not recommended to have more than 4 connections per stud. [49]

4.1.4 Debugging

If a device will not turn on as expected, it is likely that a connection was forgotten, or a wire was broken. To quickly find it perform a continuity check with a digital multimeter (DMM). Most multimeters will have a beeper mode, which will sound whenever the DMM detects a continuous electrical connection between its two terminals. If the DMM does not have a beeper mode, the ohmmeter mode will give a small, non-zero reading between two measured points if they are electrically connected.

After de-energizing the system, perform connectivity checks between the malfunctioning device and its power source, as well as from the device to chassis ground. It may be necessary to disconnect and open the terminal connectors to access the power pins. Alligator clips to secure probes conductors and thin probe tips for small terminal slots make this work much easier.

If a device turns on but experiences flickering, there are two likely possibilities. The first is a loose connection. Tug test all the connectors and check for rust/degradation, especially around the chassis ground point and any other bolted or screwed connections. The second likely explanation is that the device requires a different power level than what is being fed. Check the relevant datasheets and use a DMM to confirm the voltage and current. Since this test requires the system to be energized, it is important to wear the PPE and follow the safety protocols mentioned previously.

Finally, Appendix B is offered as a checklist to go through when debugging or reviewing the quality of a student's wire installation.

4.2 Design Case Study Implementation

4.2.1 High Level Overview Schematic

The UWAFTH LV overview schematic is displayed in Figure 40. It begins with the 12V battery and its ground connection in the top left corner and proceeds to show the distribution of 12V power through the devices added to the stock vehicle. Around the edges of the page are reference diagrams for the fuse blocks, placed for quick reference when debugging. Such diagrams do not replace detailed schematics of the fuse blocks. The following discussion breaks the distribution system down into 4 sections and points out how some of the best practices mentioned previously were put to use.

4.2.1.1 Section 1: Initial Power Branches

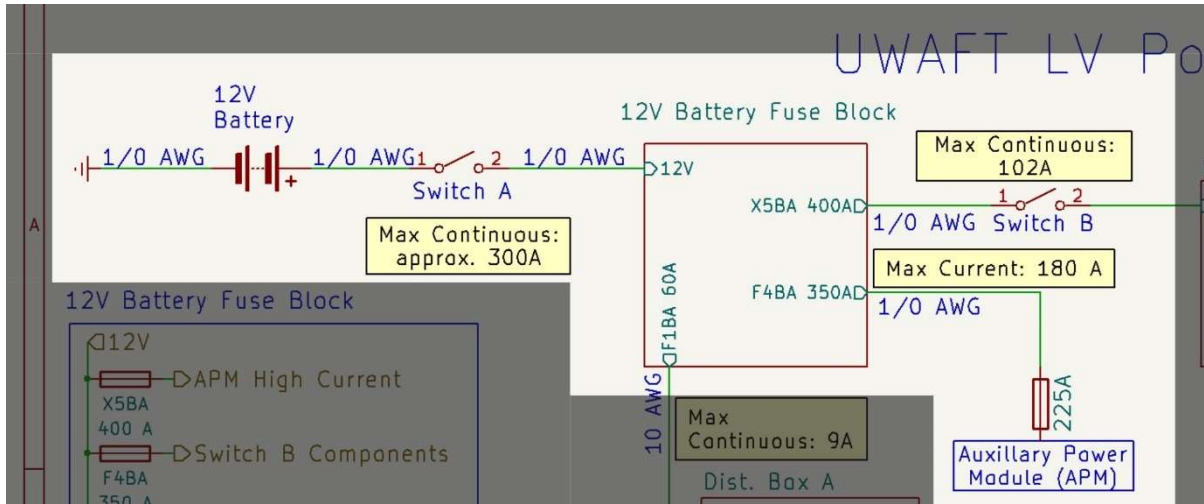


Figure 41: UWAFT LV Overview Schematic - Section 1

Figure 41 highlights the first section of the LV system. The first component following the 12V battery is Switch A, serving as a disconnect for all LV systems. Following that is the first fuse block, which divides the circuit into devices powered straight from Switch A, and those disconnected by Switch B. The purpose of dividing the devices was to allow the Speedgoat computer time to boot up. The Speedgoat acts as a supervisory controller and manages safety-critical functions, so it needs to be active before the devices it controls are turned on with Switch B.

There is also the stock Auxiliary Power Module (APM), which charges the LV system from the HV Battery and requires a high-current power line upstream of the other stock components. The 225A fuse is drawn closer to the APM than it is to the 12V Battery Fuse Block to indicate that this fuse is physically next to the APM. This is significant for inspectors since the APM is in the front motor bay and the 12V Battery Fuse Block is in the trunk.

4.2.1.2 Section 2: Supervisory Controller, Safety, and Diagnostic Devices

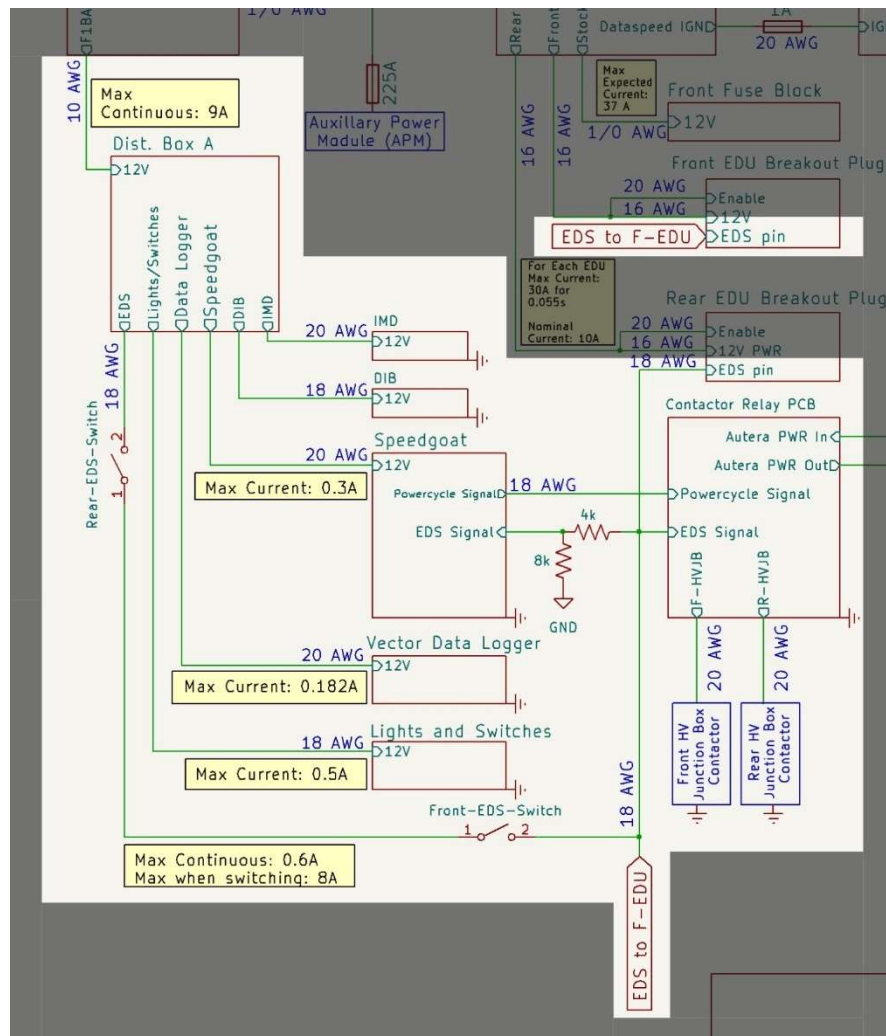


Figure 42: UWaFT LV Overview Schematic - Section 2

Figure 42 highlights the second section, corresponding to the added devices that receive power whenever Switch A is ON. Distribution Box A branches the power to the following:

- Emergency Disconnect System (EDS): Shuts off HV in emergencies via the HV Contactor Relay PCB
- Lights/Switches: Indicator lights and toggle switches pertaining to vehicle status
- Data Logger: Diagnostic recording module
- Speedgoat: Propulsion supervisory controller

- Data Interface Board (DIB): Diagnostic interface
- Isolation Monitoring Device (IMD): HV safety component

This section provides an example of using labels instead of lines to represent wired connections on a schematic. The “EDS to F-EDU” labels connect two points that would have been difficult/ugly to draw as a line. Labels can also be used to connect points across different detailed schematics.

4.2.1.3 Section 3: Propulsion Devices and Stock LV

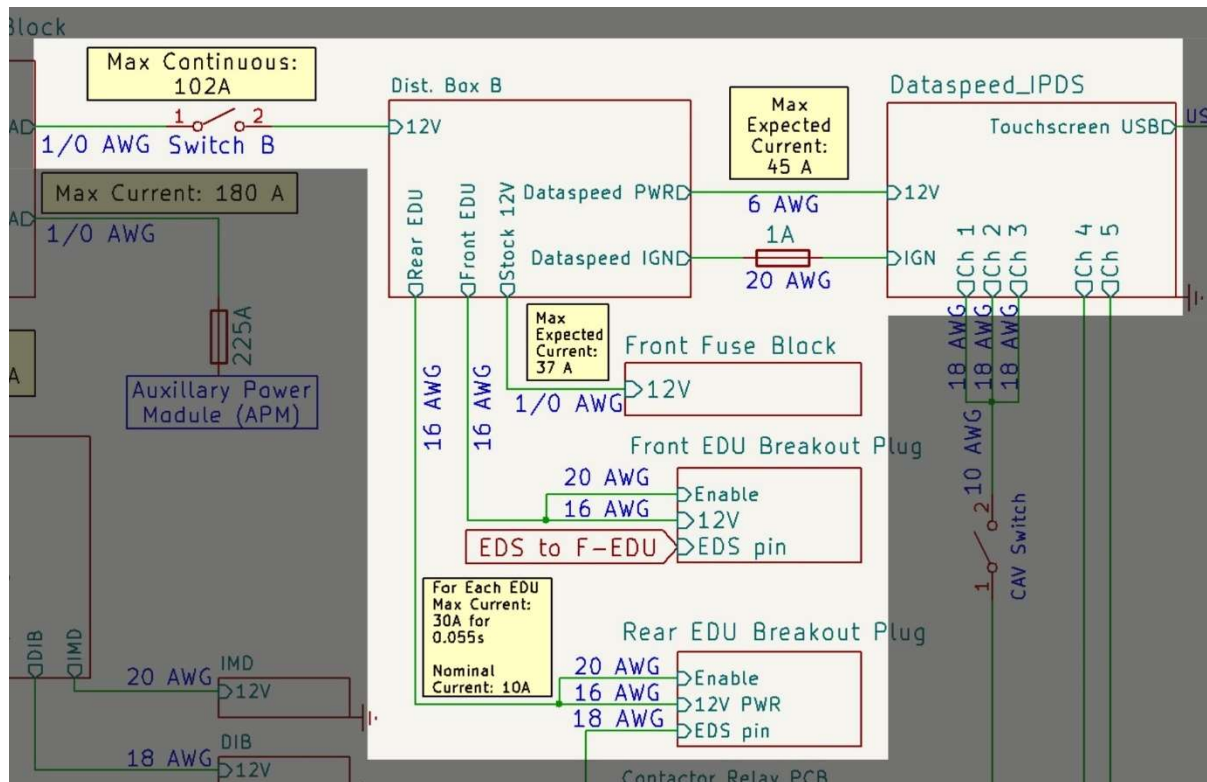


Figure 43: UWAF T LV Overview Schematic - Section 3

Section 3 in Figure 43 highlights the distribution of 12V power to the EDUs, the Front Fuse Box, and the Dataspeed whenever Switch B is ON.

In the stock vehicle, the Front Fuse Block connected the 12V battery to the rest of the vehicle. By relocating the battery and inserting the team’s distribution network between it and the Front Fuse Block, the majority of the stock LV system could be left electrically unmodified, which simplified the design and made integration easier.

4.2.1.4 Section 4: Autonomous Driving Devices

Section 4 in Figure 44 highlights power distribution to the autonomous system's devices via the Dataspeed, which will be explained further in the detailed schematic example below.

The Autera compute unit carries out the team's experimental autonomous control programs, and it can draw up to 45A. The Dataspeed can only output 15A on each channel but is designed to allow up to 3 channels to be combined for an output of 45A. Channeling 3 smaller wires into 1 like this is very unusual and only allowed under specific circumstances.

Typical best practice is that power should never be spliced from small wires into a larger one. Unless a device like the Dataspeed is built to manage current flow, and explicitly states that this arrangement is

feasible, the current may not be drawn evenly across each small wire. A majority of the power may inadvertently flow through one of them, exceed its ampacity, and melt the wire.

The CAV (Connected and Automated Vehicle) Switch facilitates testing the base functionality of the vehicle without autonomous features. The break just after the CAV switch diverts Autera power through the emergency disconnect system. This will cut the Autera's power and cease all autonomous functions in an emergency.

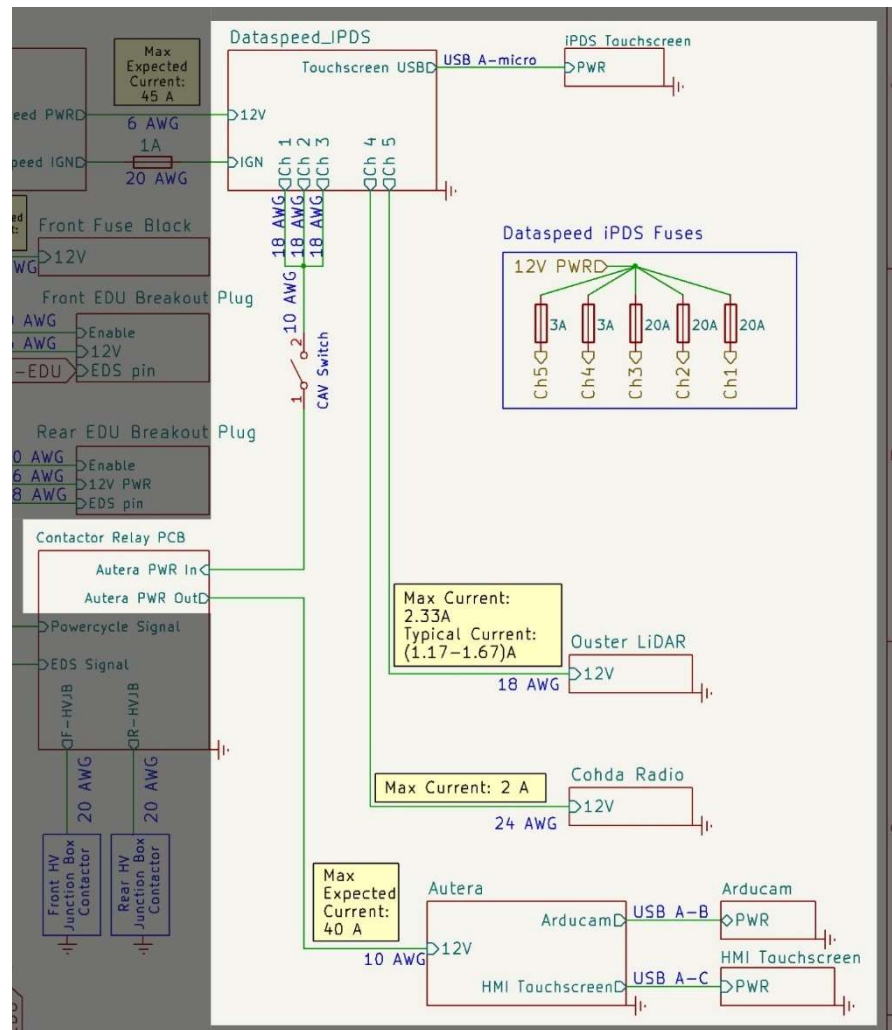


Figure 44: UWFT LV Overview Schematic - Section 4

4.2.2 Design Case Study: Detailed Schematic Example

The schematic in Figure 45 explains UWAF T’s integration of an intelligent Power Distribution System (iPDS) donated by Dataspeed. In addition to distributing power to CAV devices, it also measures their power draw and reports the measurements to the team’s diagnostic system via CAN.

As opposed to a high-level schematic, Figure 45 shows the exact pin numbers of the iPDS and closely resembles the physical position of those pins relative to each other. Inputs and outputs from the rest of the LV system are labeled to match the overview and other detailed schematics. A significant difference between overview and detailed schematics is that communication lines are included here, as would be any HV connections if they were necessary. The CAN line also demonstrates how to represent twisted pairs of wires in a schematic.

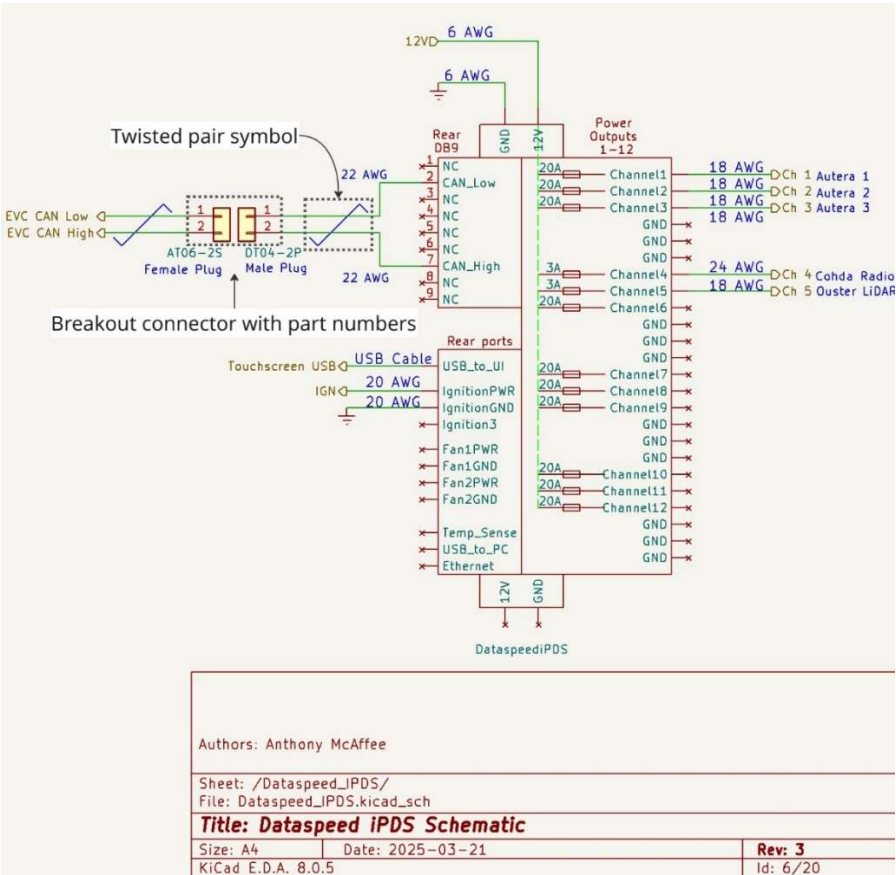


Figure 45: Example of a Detailed Schematic

Chapter 5

Serial Communication Systems

Literature exists in abundance concerning what serial communication is [51], how to build the physical harnesses that support it [52], and how to debug it [53]. However, for the niche case of student design teams, these resources have yet to be collected and applied to their unique needs in one comprehensive discussion. While UWAFB has some documentation about using relevant tools (such as soldering, crimping, or probing with an oscilloscope), these are mostly safety procedures and lack instruction on how to avoid many common mistakes. This chapter aims to gather knowledge and provide step-by-step instructions so that any student will be able to build and maintain their own serial communications systems.

5.1 Generalized Learnings

5.1.1 Background

Modern vehicles contain numerous electronic control units (ECUs) that need to communicate with each other to relay sensor data, command actuation, confirm safety conditions, etc. They do so serially, meaning a single bit (1 or 0) is sent at a time. Unfortunately, common automotive parts like motors, inverters, and power cables generate electromagnetic interference (EMI) which threatens to distort the signals passing between the ECUs. The Controller Area Network (CAN) system is a serial communication method designed to reduce the impact of EMI and is used widely in the automotive industry. An example of three ECUs connected by a CAN bus is provided in Figure 46. The words bus and harness will be used in this chapter interchangeably to refer to the physical layer connecting ECUs together.

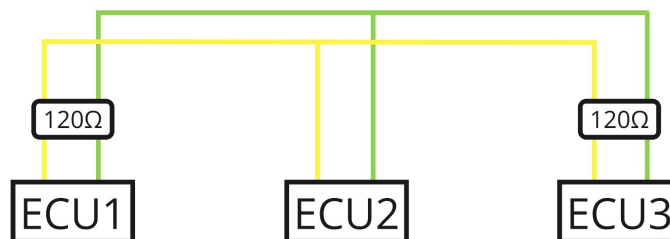


Figure 46: ECUs connected by a CAN bus

Each ECU is connected by two wires, usually yellow and green. The ECUs hold both wires at 2.5V when they are not transmitting. When an ECU wants to send a message, it signals a 0 by pulling the green line down to 1.25V and the yellow line to 3.75V. Hence, the yellow line is called CAN-high, and the green is CAN-low. It signals a 1 by letting both lines return to 2.5V. If you were to read the signals on a CAN bus, it would look like Figure 47.

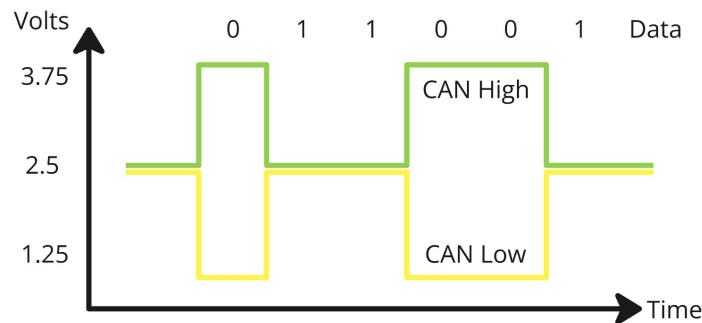


Figure 47: CAN differential signal

Splitting the signal into mirrored lines like this is called differential signaling. Differential signals help reduce EMI distortion by making 1s and 0s very distinct and requiring both lines be in agreement. Any distortion from the environment that affect both lines equally will not change the nature of “high/low = 0” vs. “identical voltage = 1” so an ECU can still read it. Any distortion that affects only one wire will throw off the mirroring effect, and an ECU will be able to recognize it and throw out the faulty message.

The 120Ω blocks in Figure 46 represent terminating resistors that sit on the two farthest ends of the CAN bus, bridging between the high and low wires. These resistors filter any messages that may hit the ends of the line and bounce back, causing an echo distortion.

Another way to reduce EMI interference is to twist the high and low wires together. This changes the electromagnetic fields of the wires such that the fields they each generate cancel out rather than amplify together. This effect can be related to the way two magnets work with each other or against each other based on their physical angle to each other.

While a thorough exploration of CAN transmission protocols is beyond the scope of this thesis (which focuses on physical implementation rather than software), the basic premise behind multiple ECUs communicating over a CAN bus can be explained with the following example of three ECUs connected by a CAN bus.

If ECU-1 sends out its message with the address of ECU-3 attached to the front of the string of bits, every ECU on the bus will see the message. ECU-2 will not read it because it does not see its address in the message. ECU-3 recognizes the address and reads the message. This is relevant for the harness designer as, according to ISO 11898 standards, it allows a single CAN bus to have up to 32 devices on it at a time.

It is possible to build a CAN bus with unbroken lengths of wire extending from one ECU to another, as depicted above in Figure 46 and seen in commercial vehicles. However, it is recommended that designers of prototype vehicles (i.e. student design teams) employ extra connectors breaking up the harness near each device as displayed in Figure 48. The red box outlines the connector that plugs directly into one of the UWFT motors and the green box outlines a connector breaking up the harness. The harness running between devices can be thought of as a spine, with the device→connector wires branching out of it like ribs. These ribs are commonly referred to as stubs.

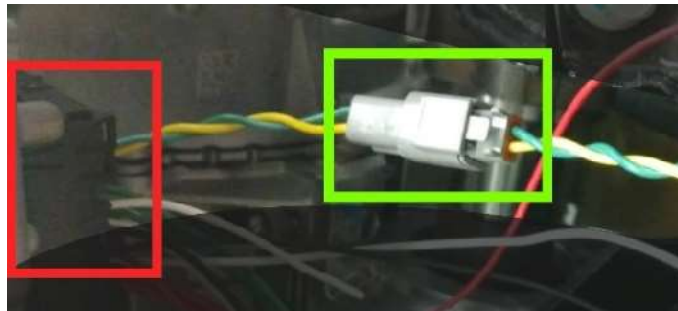


Figure 48: A motor port highlighted in red can access a CAN bus through the connector highlighted in green

Prototype vehicles often require components to be shifted around as the design improves. Modularizing the CAN harness makes it easy to take out a device with its stub and plug them in at another point on the spine. This also makes debugging easier, as the connector can be opened up to get readings with a multimeter or oscilloscope. Adding modularity also benefits harnesses that pass between compartments like the engine-bay and the cabin. By adding a connector near the gusset where the wire passes through, any changes or debugging to be done in just one compartment can be facilitated by disconnecting that connector rather than extracting the cable from the gusset, which can be a tedious and difficult process.

5.1.2 Making a standard CAN harness:

This section serves as a step-by-step guide for the fabrication of a CAN harness. Common mistakes noticed over the development of UWFAFT's harnesses are noted so that future students do not repeat them.

5.1.2.1 CAN Harness Fabrication Step 1: Planning

First, determine the harness's requirements. The Serial Network Diagram (refer to Section 5.2) informs which devices are on the bus. Each device's datasheet will indicate which of its connectors and pins the harness will need to interface with. Finally, the physical location of each device in the car will determine wire lengths and the placement of termination resistors.

5.1.2.2 CAN Harness Fabrication Step 2: Make the stubs

Second, manufacture the stub wires using the tools and steps laid out below. Refer to Appendix C for a description of the tools used in this process.

1. Cut and strip both ends of the wire.
 - Stub lengths should be 30cm or less from the device to the main CAN bus line. [52] Stubs longer than that have given UWFAFT problems with noisy signals in the past.
 - Stripping ~1cm will suffice for the DB9 end. The other end is dependent on the type of crimp pins used.
 - If stripping a 22 AWG wire, start with an 18 or 20 AWG setting and increase the setting if it does not work. The lower setting will often do the job, and the 22 AWG setting may cut a few strands depending on the tool, its wear over time, and the skill of the user.
2. Twist the wires together by securing one end of the pair in a clamp and the other end in a power drill. Spin the drill until the wires are firmly wound and will not come loose. Try to leave 4-5cm on each end untwisted so they are easier to work with in later steps.
3. Sleeve the wire in enough heat shrink to cover any exposed wire and the DB9 pin, but do not apply heat yet. Rather, slide it up the wire so it can be pulled into place later.



Figure 49: CAN Wire Building Steps 1-3

4. Solder a DB9 on one end
 - 4.1. Identify the 2-low-green/7-high-yellow pins. This is the most common mistake students make, so a diagram is provided in Figure 50. For a mnemonic, consider “High and yellow like the sun, green and low like the grass.”

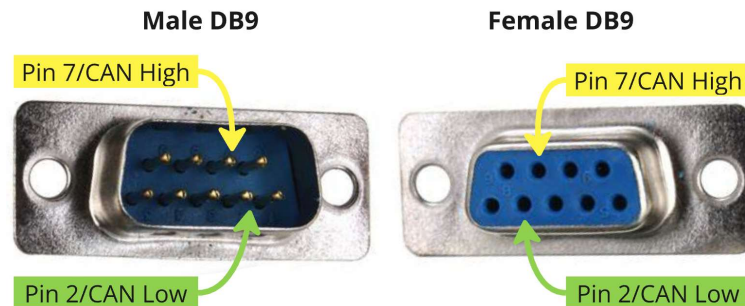


Figure 50: DB9 CAN pins

- 4.2. Set the soldering iron to ~750 F.
- 4.3. Line up one wire to the pin with helping hands, pushing the other out of the way.
- 4.4. Apply flux to the wire/pin. Heat up the wire/pin from underneath to melt the flux into the pin.
- 4.5. Tip the iron with a small drop of solder and apply it to the wire/pin. Finding the right amount of solder for a secure, good-looking connection takes practice. Be careful

not to let the iron get close to the heat shrink tubing, as the heat could seal the tube in place.

4.6. Let cool, then test the connection by tugging on it firmly. If you can break it by pulling, the car will break it by vibration over time.

4.7. Repeat for the other wire.

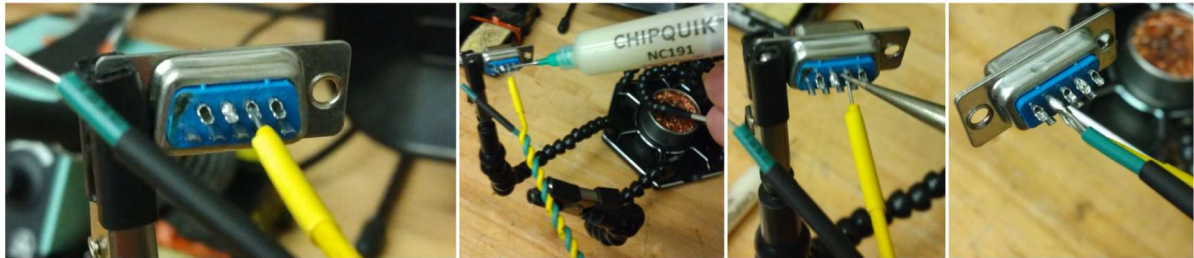


Figure 51: Left to right: Lining up the wire. Applying flux. Applying solder. Finished solder on both wires.

Figure 52 has three imperfect soldering examples. On the left too much solder was applied and it spilled over to another pin. The center example has an ideal amount of solder, but both it and the leftmost example show evidence of wire strands being cut back. Commonly, students will cut strands back because the wire seems too thick to fit in the DB9 pin. This is a sign that the wrong gauge of wire was used. The example on the right could be acceptable, but the excess of solder is balling up and may hide a gap between the wire and the pin which could expand into cracks over time with vibration.

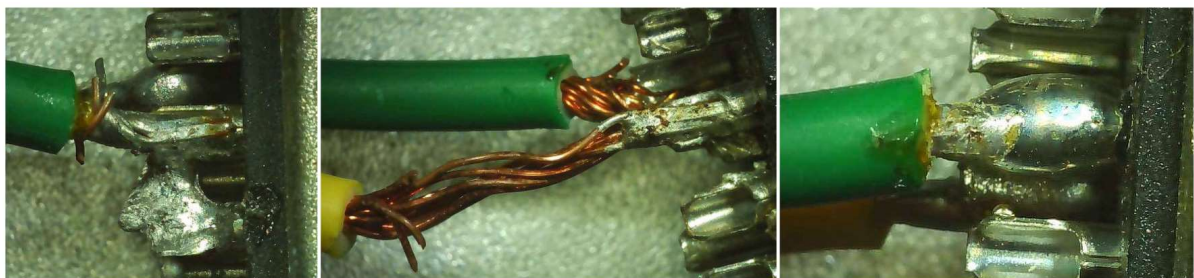


Figure 52: Soldering examples of what not to do

5. Slide the heat shrink up to cover the solder connections and apply heat to shrink with the heat-gun. You should be able to see the plastic tube conform around the wire. Use

caution with the heat gun, as it can get hot enough to melt plastic in the DB9 or the helping hands.



Figure 53: Heat shrink before and after applying heat

6. A good solder connection with heat shrink should not break easily but is still the point of the wire most likely to break. It is recommended to protect it from strain by adding a strain-relief case like in Figure 54.

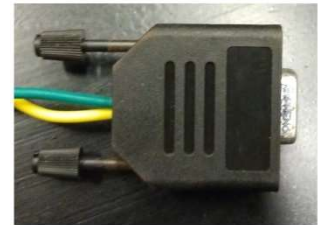


Figure 54: DB9 strain relief case

7. Crimp a connector onto the other end of the rib.
 - 7.1. Identify the right kind of pin for your housing. Figure 55 shows which pins and wedges are designed to go with their respective housings. A common mistake is to put male pins in the male housing. While the two housings may connect and appear functional with male pins used in both, this damages the wedges and does not create a secure electrical connection. This advice is specific to the Deutsch connectors chosen but should alert readers to the unintuitive ways connectors are often designed.

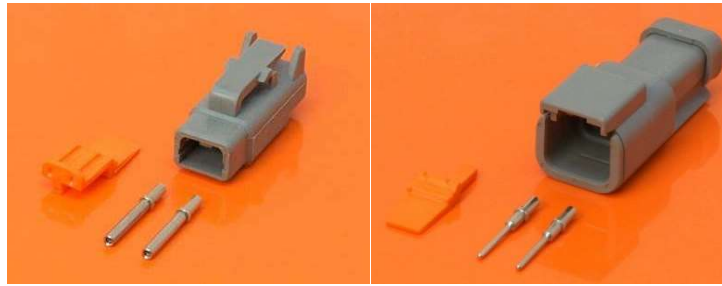


Figure 55: Left: Male housing with its female pins and wedge. Right: Female housing with its male pins and wedge [54]

- 7.2. Shape the pin's arms with tweezers if using a generic crimp tool. There are specific crimpers you can purchase for a particular pin, but these cost thousands of dollars. Instead, a generic crimper can be used for most pins if their arms are pinched slightly with pliers so they fit in the tool.
- 7.3. Place the pin in the crimper and squeeze until it holds the pin but has not yet compressed it. Crimpers are designed to not let go until fully compressed, but most will have a latch that you can release to open the jaws if you make a mistake.
- 7.4. Slide the wire into the pin so that the rear arms close on the insulation and the fore arms close on exposed copper.
- 7.5. Squeeze the crimper until fully compressed.
- 7.6. Insert the rubber seal into the connector.
- 7.7. Insert pinned wires into the connector until hearing them click. The entire pin should be buried past the rubber seal, as in Figure 56.

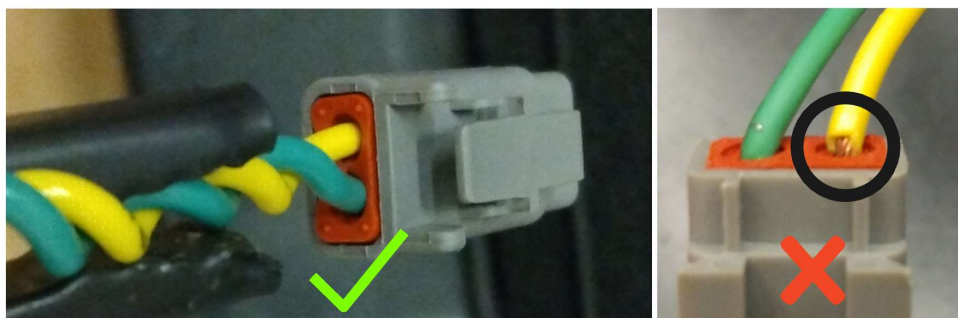


Figure 56: Left: Wires properly inserted into the rubber seal. Right: exposed copper extending past a seal that defeats the weatherproofing and could cause short circuits.

- 7.8. Insert the wedge lock into the connector. This lines up the pins so they will mate with their counterparts in the female housing.
- 7.9. Tug to test if the pins have locked into the housing securely.

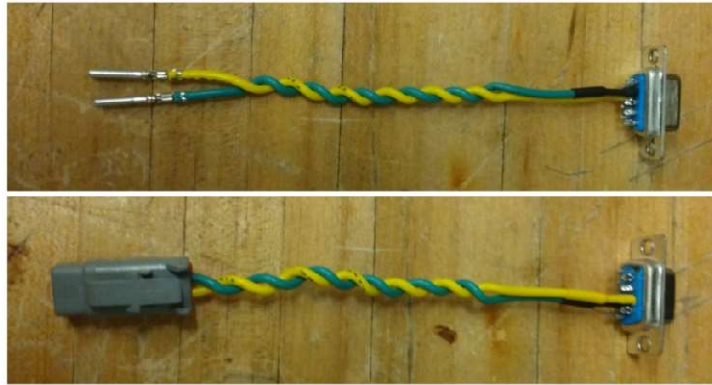


Figure 57: Before and after the addition of a connector.

8. If a device is on a far end of the harness, it will also need a termination resistor.
 - 8.1. Check the resistance between the device's CAN-high and low pins with a multimeter, as it is rare but not unheard of for a device to house terminators internally.
 - 8.2. If that is not the case, termination resistors can be added to the ends of a bus by using DB9 connectors with resistors built in, as depicted to the left in Figure 58. If the device at the end of the bus is not DB9 compatible, the resistor can be spliced into the wires using barrel crimps, as shown to the right in Figure 58. Note that the protective tape/loom has been pulled back to expose the resistor for the photo.



Figure 58: Termination Resistors (DB9 on the left, spliced with barrel crimps on the right)

9. Use a multimeter to confirm that there is a continuous electrical connection from one end of the rib to the other for both high and low wires.

5.1.2.3 CAN Harness Fabrication Step 3: Make the spine

To fabricate the “spine” of a CAN harness, begin by placing all devices with their ribs where they are expected to remain in the vehicle. Then determine the length of the spine by routing twine through the car and marking on the twine where the ribs would connect to the harness. Then cut and twist the spine’s wires to match the length of the twine. In alignment with the marks on the twine, cut the wire and rejoin it together with Y-splitting connectors like Figure 59 on both CAN high and low lines. Add female connectors to the ends of each branch of the spine and connect to the male counterparts on the ribs. Then the process for taping and looming from the LV chapter of this thesis can be applied to the CAN wire.



Figure 59: Y-split junction [57]

When planning the route of the wire with twine, EMI can be minimized by keeping the length of wire between devices as short as possible. Also, avoid routing near LV or HV power lines, especially if they carry high currents. If available space constrains the CAN line to pass near a power line, try to have them cross at 90 degrees to each other. The worst possible route for CAN lines is parallel with high current power lines along the length of the car, which is often the most straightforward routing solution that students default to if not EMI-conscious.

5.1.3 Debugging CAN Harnesses

When an ECU is not communicating with other devices in a prototype system the first point of investigation is the physical CAN harness. The purpose of this section is to provide solutions to common symptoms and save hours wasted by improperly tuned debugging equipment.

The best tool for debugging CAN harnesses is an oscilloscope; however, there are a few quick checks to make before setting one up:

1. Make sure everything is plugged in, then turn it all off and on again.
2. Give the device's CAN wires a tug to see if they are loose.
3. Perform a continuity check along the harness
4. Check for absent termination resistors on the ends of the CAN line. It can be easy to forget them if they are frequently swapped out during testing. If you cannot easily see the resistors, use a multimeter to find the resistance between any point on the CAN-low wire and another point on the CAN-high wire. If the termination resistors are present, the resistance between the lines at any point in the bus should be $120\Omega/2 = 60\Omega$.
5. If you were receiving CAN messages but it suddenly stopped, check the devices under test. Some systems, like a car when the start button is hit but no keys are present, shut themselves off after a period of inactivity.

5.1.3.1 Setting up the oscilloscope

To check if a device is sending and receiving CAN, plug in two scope probes to an oscilloscope and connect each to a CAN-high or CAN-low line of the device you are debugging. Many scope probes have a switch that amplifies the signal by 10X or leaves the signal at 1X. If the signal read by the oscilloscope appears to be the right shape but the voltage levels are off by a factor of 10X, this switch is likely in the wrong position.

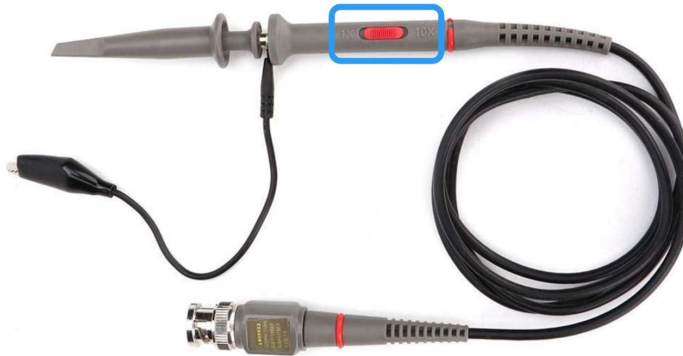


Figure 60: Oscilloscope wire with 10X amplifying switch highlighted

Oscilloscopes will have an eyelet or port that a ground wire must be tied to in addition to the probe ports. Grounding everything, including the oscilloscope and the chassis of high-current devices like motors, to the power supply's negative jack is necessary for accurate voltage readings. Proper grounding also helps reduce ambient noise from sources like wall outlets, HVAC systems, and other test setups.

Figure 61 is an example of a power supply with separate negative and GND jacks. A common mistake students make is to ground their systems to the GND jack. The negative jack is the voltage that the power supply sets as ground for whatever it is powering. The GND jack is earth-ground, and not necessarily the same ground as the rest of the system.



Figure 61: Power supply jacks

If only one device is being debugged, it is useful to make a connector with pig-tail wires sticking out to hold the probes in place. Decouple the harness from the device and insert the pigtail as shown in Figure 62.

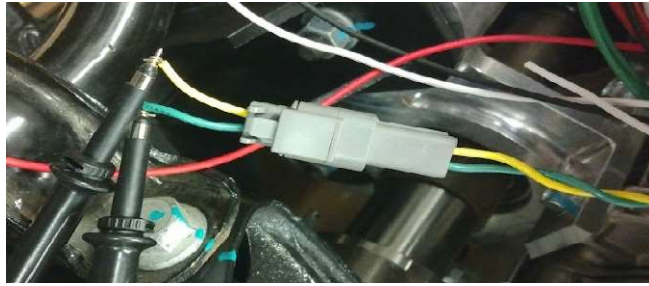


Figure 62: Pigtail connector and scope probes used in debugging UWAFt's motors

To read the CAN harness with all devices connected, it is recommended to fabricate a small testing CAN harness with three nodes as in Figure 63. The first node terminates in a connection the oscilloscope can read, the second in a male DB9, and the last in a female DB9. One DB9 can be plugged into a device's CAN port and the other plugs into the harness.

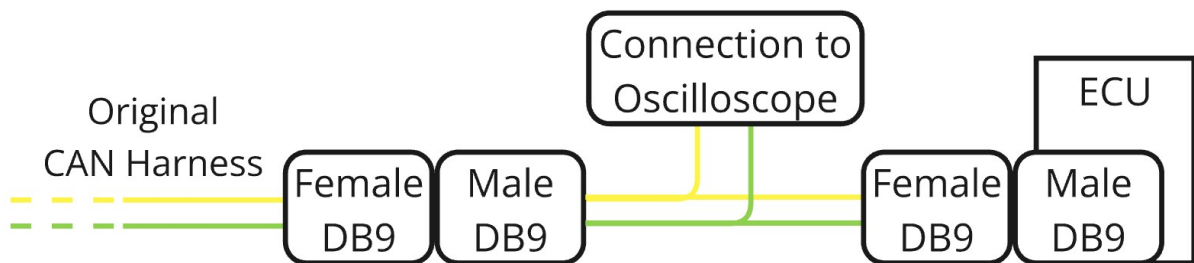


Figure 63: Splicing into a CAN harness with a three-node test harness

Depending on their needs and funds, student teams may use an oscilloscope like the one shown below, a device that connects to a desktop for processing power and display like [55], or another variant of scope. Regardless of scope type, there are typically 4 settings to consider, as outlined in Figure 64: **signal trigger**, **voltage/vertical axis**, **time/horizontal axis**, and **measurement display**. Once these settings are tuned, a CAN signal detected by the oscilloscope should appear similar to the display in Figure 64. Students who are unfamiliar with these tuning settings can spend hours trying to fix a proper signal that looks wrong on the scope. The following discussion is specific to the UWAFt case study but should help students make inferences about what to look for in their own scopes.

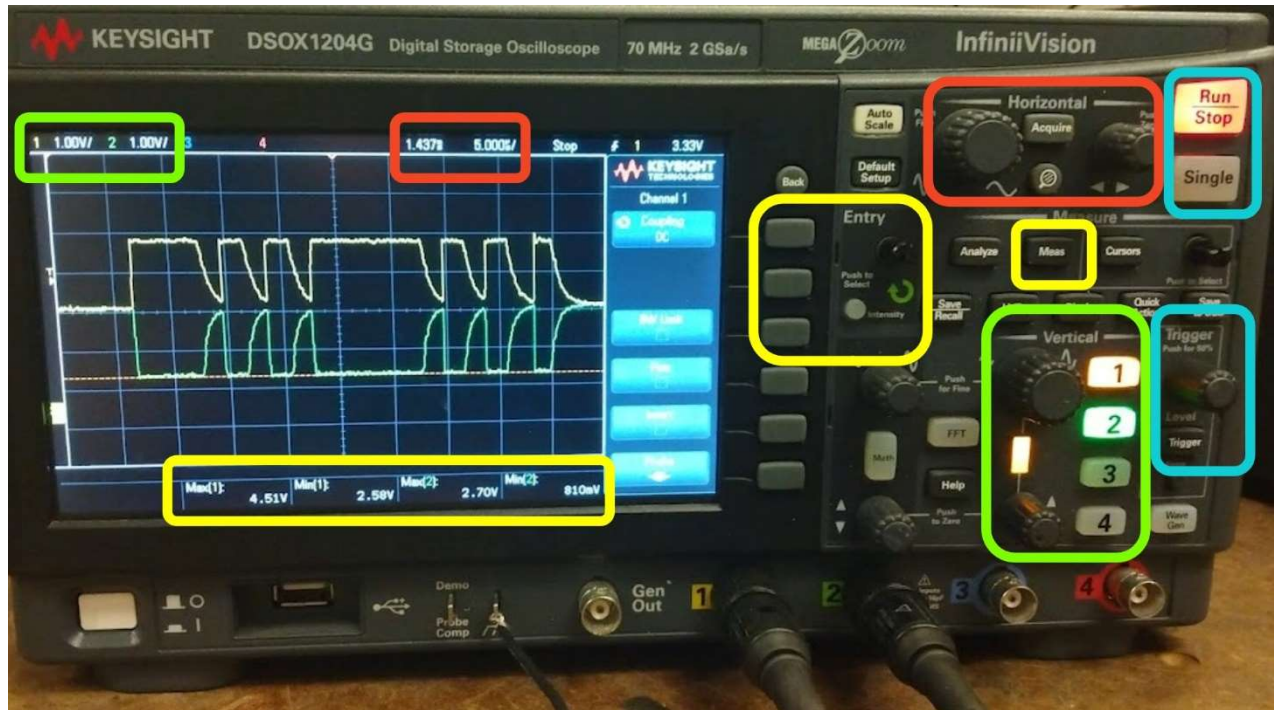


Figure 64: Relevant oscilloscope elements for CAN debugging

Signal triggering is off by default and the scope will display whatever it reads in real time, which is too fast for a human eye to track. Hitting the Run/Stop button will pause the feed, but to ensure it pauses on relevant signals we use the trigger function. If the Level Trigger button in the lower blue box is hit, a line will appear horizontally across the screen and the scope will only display readings when a signal is detected at that voltage level on channel 1. Hitting the button again makes the trigger detect signals on channel 2. This line can be moved up and down with the trigger knob. Set the trigger level to between 2.5V and 3.75V on channel 1. Then hit the Single button in the top blue box, which will cause the feed to pause when the trigger voltage is detected.

Voltage/vertical axis scaling is displayed for each channel in the top left corner of the screen. For CAN debugging, each should be set to 1V/ using the larger knob and the channel selection buttons next to it in the lower green box. The smaller knob adjusts the vertical offset of the signal relative to the 0V line in the middle of the display. Since CAN signals fluctuate around 2.5V, giving each channel an offset of -2.5V will make the signal appear in the middle of the screen.

Time/horizontal axis scaling and offset are displayed in the left red box and can be adjusted with the knobs in the right red box similar to those of the vertical axis.

The **measurement display** can show the maximum and minimum voltages on each channel for the present reading, among other features. Figure 64 displays a signal with a max of 4.51V on CAN-high and a min of 0.81V on CAN-low, which is an acceptable range since it represents the CAN signal added with the greatest peak of any noise on the line. The Meas button in the right yellow box can activate the measurement display, and the min/max data can be selected with the buttons and knob in the middle yellow box.

With the oscilloscope grounded, tapped in, and tuned, the signal can now be assessed.

5.1.3.2 Common CAN issues found via oscilloscope

If all that can be read is noise, the devices are not properly connected to the CAN harness. So long as the oscilloscope is tapped into a CAN line and a device on that line is powered, you should receive at least a 2.5V signal. Check thoroughly for faulty wiring. Opening connectors may be necessary to check the crimps, which can come loose if not correctly inserted. Another common mistake is to solder the wires to the wrong pins of a DB9.

If the low and high signals appear swapped, the low/high wires were likely inserted into a connector in reverse order.

If the oscilloscope is reading proper CAN signals, but your device is still not responding, it may be that a connector on the harness meant for one CAN network was accidentally plugged into another. The device is not responding because it does not recognize any signals from that network. Label both male and female sides of a coupling with their designated CAN bus to avoid this.

If the device is still unresponsive after checking all the above, the bug is probably software related.

5.2 Design Case Study

5.2.1 Serial Network Diagrams

UWAFT added various sensors and controllers to their competition vehicle, which needed to communicate with each other and the stock devices already in the car. Due to the ports available on the chosen devices, multiple communication protocols (CAN, USB, and Ethernet) had to be used. To keep track of what devices needed to be connected and with which type of protocol, UWAFT made a map or serial network diagram (SND) of the network, which is displayed in Figure 65. This is not the only format that an SND could follow. A simpler example from UWAFT's past can be found in [23].

This section aims to demonstrate that an SND is vital for understanding the system students will build. To underscore this importance with an example, the UWAFB team had not been updating their SND leading up to the May 2024 EcoCAR event. When it was discovered that the onboard computers were not properly communicating, debugging the issue was not completed in time to score points in the event. Later that year, after taking the time to redraw the SND from scratch, it became obvious that different subteams had been operating with different assumptions about what lines were needed. As a result, some lines were eliminated, missing lines were added, erroneous connections were fixed, and the CAN issues from the competition were resolved.

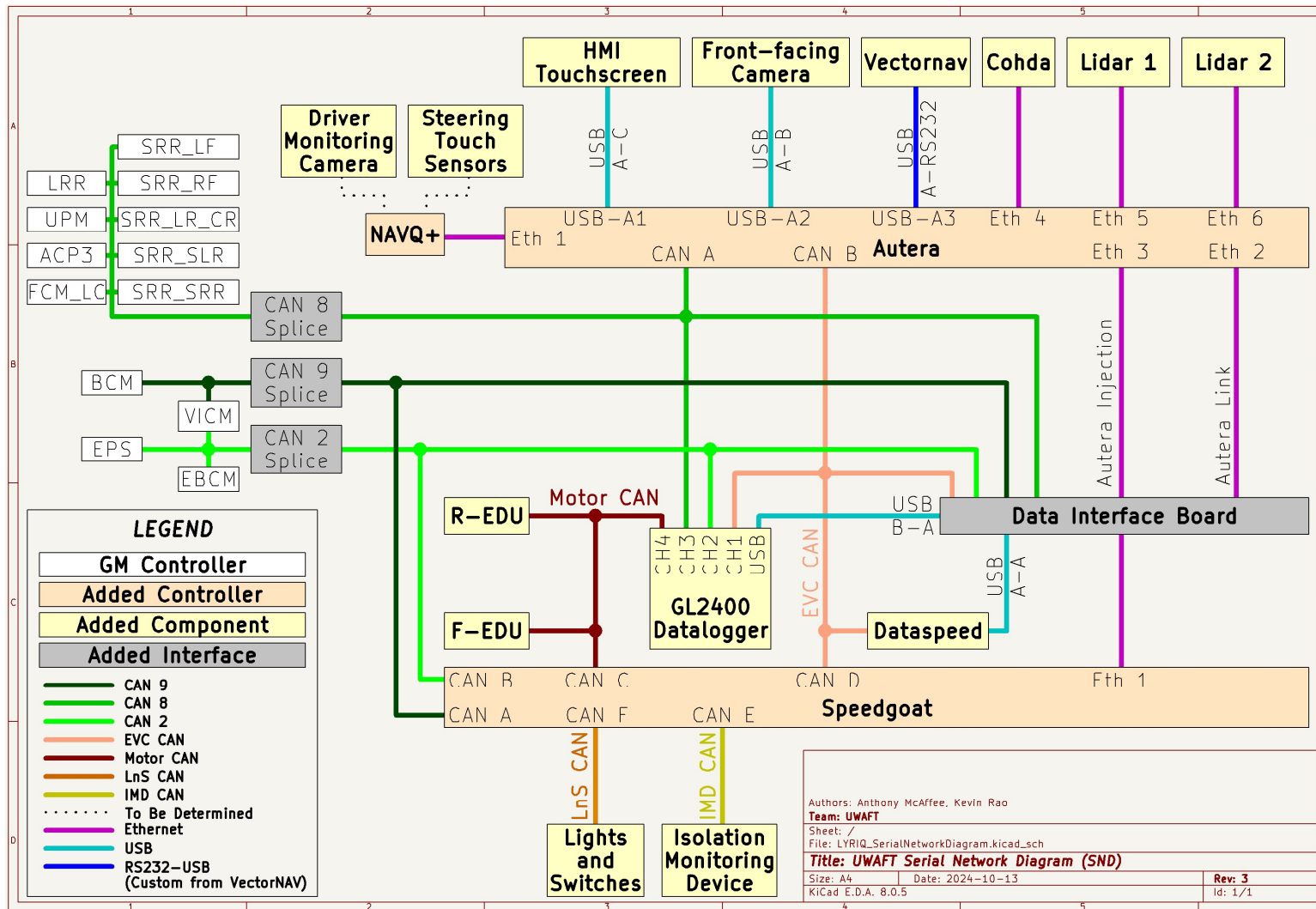


Figure 65: UWAFT Serial Network Diagram

5.2.2 Diagram Definitions

The following definitions describe the SND in Figure 65 and are included for clarity as well as providing language that students may find useful in making their own.

- **Controller**: a computer that takes in data from the serial network, makes decisions, and sends commands to other devices in the network
- **GM Controller**: Controller in the stock vehicle, not modified by UWAFIT
- **Added Controller**: Controller that UWAFIT added to the vehicle
- **Component**: devices that send data (ex. sensors) or receive commands (ex. motors) on the serial network but do not make decisions
- **Interface**: a point where the UWAFIT network taps into the stock network, or where an external device like a laptop can tap into the network for diagnostic purposes
- **USB X-Y**: USB wire that has X-type of plug on one end and Y-type on the other

5.2.3 Walking through the diagram

The following descriptions break the example SND into subsystems that other student teams building EVs will likely have, though the specific devices will vary. Each device in the diagram is mentioned in bold in the text for reference. The purpose of each device is described so that students can compare it with the needs of their own EV projects.

5.2.3.1 Autonomous Driving Systems

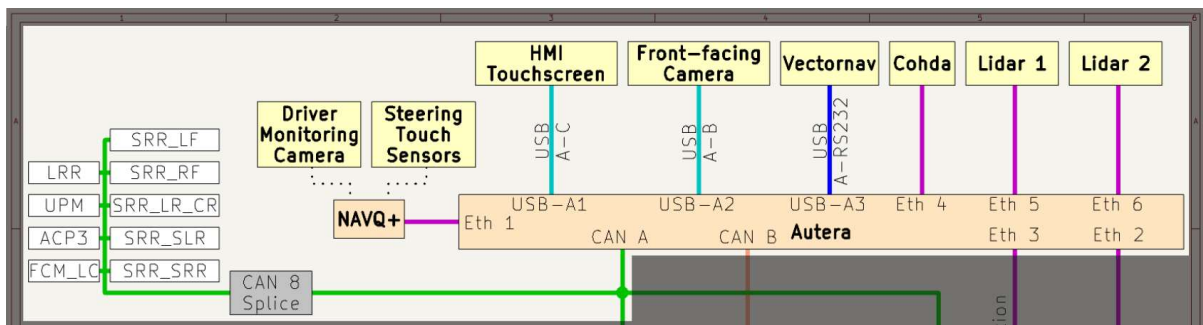


Figure 66: UWAFIT SND (autonomous driving system highlighted)

The **Autera** is responsible for controlling the autonomous features of the vehicle. It “sees” the world through the stock sensors, which relay their data on the **CAN 8 bus**, as well as the team-added

front-facing camera and a pair of **LiDAR** sensors. It “hears” through the **Cohda** radio, which communicates with street infrastructure and other vehicles to know when cars will turn or when stop lights will change. Its sense of position comes from the **Vectornav**: a GPS unit that determines the vehicle’s coordinates down to the meter as well as its heading. The raw data from all these sensors is processed by the Autera into discrete obstacles and merged into a complete map of spaces the car can move in.

The Autera is also responsible for the Driver Monitoring System (DMS), though it shares this task with the **NAVQ+**. The **driver monitoring camera** and **steering touch sensors** will eventually convey data to the NAVQ+, though the method of data relay has not been determined at the time of writing. The NAVQ+ will process the raw data, determine the state of the driver, and pass this state to the Autera. The Autera will then decide on an action to take, such as disabling autonomous features because the driver is not paying attention and inform the driver of this through the **HMI touchscreen**.

Once the Autera has a map of its surroundings and knows the driver is alert, it can plan a path through the environment with an algorithm programmed by the team. However, it does not command any of the vehicle’s actions. That function is the domain of the Speedgoat and the propulsion systems.

5.2.3.2 Propulsion Systems

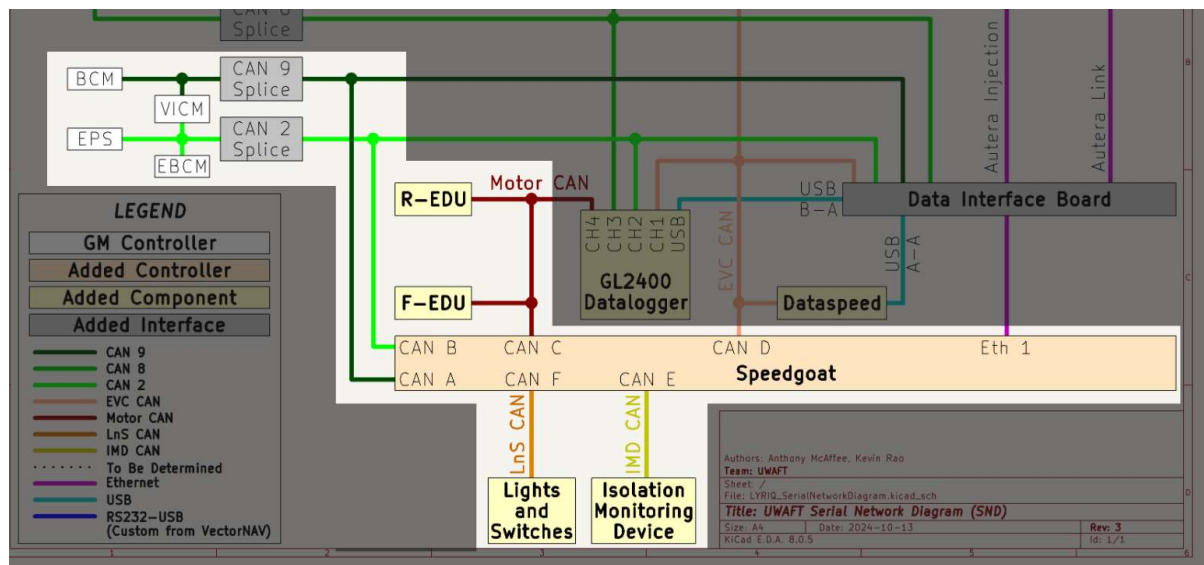


Figure 67: UWAFT SND (propulsion system highlighted)

The **Speedgoat** receives driver input from the steering wheel, pedals, gear shift, etc. via the stock CAN 2 and CAN 9 buses. When in autonomous driving mode it listens for acceleration, braking, and direction commands sent by the Autera over the **EVC CAN** bus. It is programmed to convert these commands into torque signals and relay them to the EDUs over the **Motor CAN** bus.

The Speedgoat also monitors two critical safety systems installed by UWAF: HV isolation monitoring and the emergency disconnect system. These are discussed in more depth in the chapter on high voltage systems, but both require the Speedgoat to send requests to open or close the HV battery's contactors through the stock CAN buses. The HV **isolation monitoring device** (a Sensata SIM100 MLP) directly communicates with the Speedgoat over a dedicated CAN channel.

When the driver wishes to enable regenerative braking or autonomous features, they toggle a switch that sends a signal over the **Lights and Switches (LnS) CAN** bus to the Speedgoat. The Speedgoat sends signals back to the switchboard toggling lights that indicate the state of propulsion, HV, and autonomous systems.

5.2.3.3 Diagnostic System

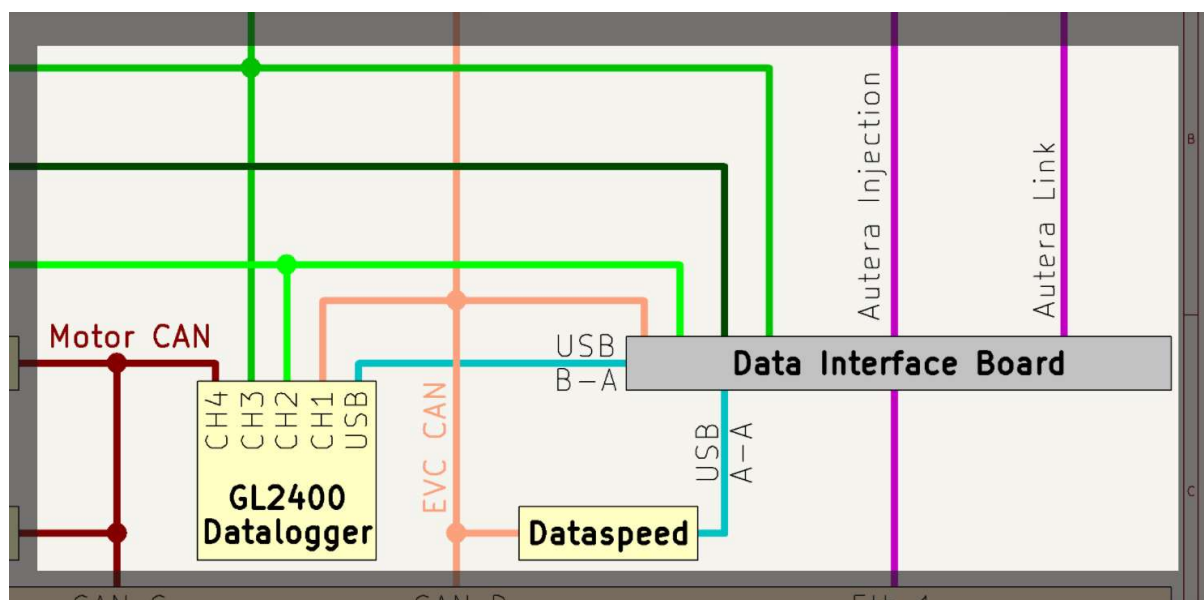


Figure 68: UWAF SND (diagnostic system highlighted)

As required by the competition rules, the **GL2400 Datalogger** records all traffic being sent on:

- Motor CAN: a UWAF-T-only bus dedicated to commands and warnings related to motor function
- EVC CAN: a UWAF-T-only bus dedicated to communication between the Speedgoat and Autera, plus reports from the **Dataspeed** (a power distribution device) on how much power the UWAF-T autonomous system devices are consuming.
- CAN 2: A stock bus that UWAF-T taps into for propulsion system messages
- CAN 8: A stock bus that UWAF-T taps into for autonomous system messages

As also required by competition rules, the **Data Interface Board (DIB)** is a collection of ports accessible from the passenger's seat where competition judges can tap into the serial network. The judges can read the power consumption reports from the Dataspeed, download the recordings of the GL2400, listen to traffic on the CAN buses in real-time, and communicate with the Autera and Speedgoat.

5.2.3.4 Stock ECUs

UWAF-T taps into the stock CAN buses by splicing UWAF-T CAN wires into the pre-existing CAN wires. The stock ECUs that the team communicates with are defined below.

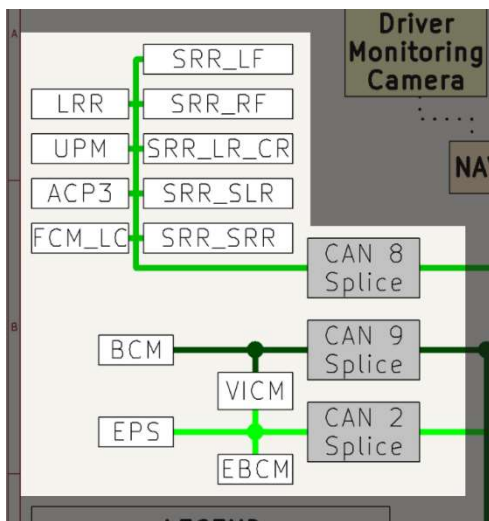


Figure 69: UWAF-T SND (stock CAN busses highlighted)

Device	Description
ACP3	ADAS Compute Platform
BCM	Body Control Module
EBCM	Electronic Brake Control Module
EPS	Electronic Power Steering
FCM_LC	Front Camera Module Low Content
LRR	Long Range Radar
SRR_LF	Short Range Radar Left Front
SRR_LR_CR	Short Range Radar Left Rear/Center
SRR_RF	Short Range Radar Right Front
SRR_SLR	Short Range Radar Side Left Rear
SRR_SRR	Short Range Radar Side Right Rear
UPM	Park Assist
VICM	Vehicle Integration Control Module

5.2.4 Suggestions for Drawing Serial Network Diagrams

Students sometimes have difficulty knowing where to start when drawing an SND, so this section aims to give some relevant pointers. SNDs exist in a grey zone between schematic and flowchart, so the choice of drawing tool is subjective to personal preference. While digital whiteboards like Draw.io or Miro.com would have been more convenient for making flowcharts, UWAFST decided to create their SND in KiCAD to give it a consistent appearance and storage location with their LV and HV schematics.

The process taken for creating UWAFST's SND is laid out below:

1. Created a list of all the devices that needed to be networked
2. For each device:
 - a. Listed all available communication ports on the device
 - b. Listed all devices or buses the device needs to connect to
3. Created a list of each bus and the devices on it
4. Placed color-coded blocks in KiCAD to represent each device.
5. Identified the devices with the most connections: the Autera, Data Interface Board (DIB), Datalogger, and Speedgoat. These serve as anchor points on the page.
6. Let the connections between the anchors determine where they should fit on the page.
 - a. The Autera and Speedgoat had many devices that connected only to them, so it made sense to give each a side of the page, whereas the Datalogger and DIB were primarily connected to multi-device buses and as such made most sense in the middle.
7. Fill in the rest of the devices around those anchor points.
8. Once all devices are represented on the page, begin adding communication buses from most complex to least based on the list of buses made in Step 3
9. Edit fonts, colors, line styles, and thicknesses until the entire diagram is legible when printed in greyscale on 8.5/11 paper.

Chapter 6

Conclusions and Recommendations

6.1 Summary of Knowledge Compiled

This thesis focuses on the key electrical systems in EVs that student teams must understand to build safe and competitive designs: High Voltage, Low Voltage, and Serial Communications.

HV systems power the electric drivetrain and can be extremely dangerous if mishandled. Therefore, HV designers must be knowledgeable in isolation principles like creepage and clearance, safety functions like emergency disconnect systems and isolation monitoring devices, and safety procedures such as Lockout/Tagout (LOTO) and the use of HV PPE. Students must be trained and certified before working on HV components. The UWAFI case study examples highlight real-world design problems like HV junction box construction, wire routing challenges, and mitigation of electromagnetic interference through chassis grounding of HV shielding.

LV systems are responsible for powering sensors, compute units, lights, and other electronics via a 12V battery. While less dangerous than HV, poor LV practices can still cause bodily harm, component failure, and fires. The design process involves systematic schematic creation, part selection, and modular wiring strategies. Best practices include selecting proper wire gauges, insulation, crimping techniques, and connectors. Consistent documentation regarding what is in the vehicle and what is yet to be installed helps teams in their efforts to debug power failures and adapt as the designs update. Part of this documentation effort is the upkeep of both high-level overview and device-specific schematics.

Serial communications facilitate the sharing of data between ECUs, primarily via CAN buses. Students should understand differential signaling, CAN wire construction, modular bus layouts, and how to debug a signal harness with an oscilloscope. Drawing out a serial network diagram helps organize communication buses between the many vehicle subsystems, including autonomous systems, propulsion controllers, diagnostics, and stock vehicle components.

Together, these chapters provide essential technical knowledge, practical insights, and safety frameworks for student teams building EV electrical systems.

6.2 Recommendations for future work

There was much that had to be cut from this paper for the sake of scope. Future compilations of technical knowledge for student EV teams could elaborate on such electrical topics as

- The design of HV components like batteries, motors, and inverters
- Physical implementation of regenerative braking
- PCB design and fabrication
- A review of the many sensors being used in the autonomous automotive field
- CAN transmission protocols

Additionally, student teams may benefit from the creation of similar collections of tools, techniques, and knowledge for both mechanical and software engineering as they apply to EVs.

6.3 Final Recommendations for Team Success

“Fail fast” is the motto of teams that win. Every team must get the bad designs out of their heads before they can refine their vehicle into a competitive machine. Hard work and overtime hours will not guarantee a successful build on the first attempt. So, schedule time for practicing with assembly tools, order more parts than the schematic calls for, and build the expectation of backtracking into the timeline.

Furthermore, designing a part or system that just meets the competition’s rules is not sufficient. True, it will be safe, but that mindset is not going to yield a high-ranking design. Partly because “above and beyond” sets a design apart when presenting to judges, but also because “meets regulations” can get in the way of true understanding. For example, UWAFT selected an HV loom that did comply with the Year 2 rules of EcoCAR5, in that it was orange, non-split, and covered the length of the HV wires. However, they had chosen a fabric loom with fire-retardant lining that was not designed for this use case and would not fulfill the actual reason the competition required HV loom: crush protection. Students need to make informed decisions, rather than choose the cheapest/easiest option that fulfills the letter of the law rather than the spirit of the law.

Above this, the most critical factor that separates the top performing teams from those beneath is the proactive involvement of experts. Students who invest the time it takes to track down subject matter

experts for every part of their design and consistently check in with them hold a distinct advantage. This thesis is not meant to be a replacement for live expert advice. The purpose has been to help students make fewer common mistakes and cover the basics so that the time they do spend with an expert can be about more niche/important things.

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Appendix A: UWAFI's HV Safety Certification Levels

Certification level	What they are qualified for	What they are NOT qualified for	How to obtain this level
L0: Bystander	N/A	Being within reach of any HV equipment	N/A
L1: Informed Member	Recognizing and working around HV equipment	Working on HV equipment	Complete the LEARN courses indicated in the UWAFI Onboarding Membership Form
L2: Electrical Specialist	Working on equipment that has been verified as de-energized	Working with live HV equipment	1. Review the UWAFI EC5 - Level 2 High Voltage Training with an HV Certified Member 2. Explain every HV element in the car to a team lead, including NO-GO Zones
L3: HV Certified	May perform LOTO procedures, conducting HV Connect/Disconnect operations, and training Electrical Specialists	N/A	1. Read through the UWAFI HV Safety Manual and demonstrate to the UWAFI leads that you know the material 2. Demonstrate proficiency in HV design 3. Get authorization from Supervising Professor

Appendix B: Wire fabrication checklist

- ☐ Do the gauge, insulation, and length of the wire accommodate the maximum expected current?
- ☐ Is the wire protected by an appropriately sized fuse?
- ☐ Does the wire exceed its maximum bend radius at any point along its route?
- ☐ Is the wire properly terminated?
 - ☐ Tug test
 - ☐ Connectivity test
- ☐ Is there any exposed conductive material?
- ☐ Is the wire properly secured and restrained?
- ☐ Does the wire have enough slack?
- ☐ Does the wire run along anything that will vibrate or chafe?
- ☐ Do signal and power lines run parallel at any point along the wire's route?
- ☐ Can a layperson identify this wire if given nothing but the schematics?

Appendix C

LV and CAN Wire Building Tools

Table 6: LV and CAN Wire Building Tools (List)

A	22 AWG yellow wire	I	Multimeter for connectivity testing
B	22 AWG green wire	J	Helping hands station to hold wires and pins in place
C	Power drill for twisting wire	K	Flux syringe to ease solder flow
D	Heat gun/station	L	Solder, preferably lead-free
E	Label maker	M	Desoldering gun for fixing solder mistakes
F	Deutsch connector and pins (male for the rib wire)	N	Wire cutters
F	DB9 connector (male or female depending on device)	O	Pliers
F	Heat shrink tubing (yellow and green if possible)	P	Generic crimping tool
G	Soldering station	Q	Wire strippers
H	Fan/Vent to remove toxic soldering fumes		

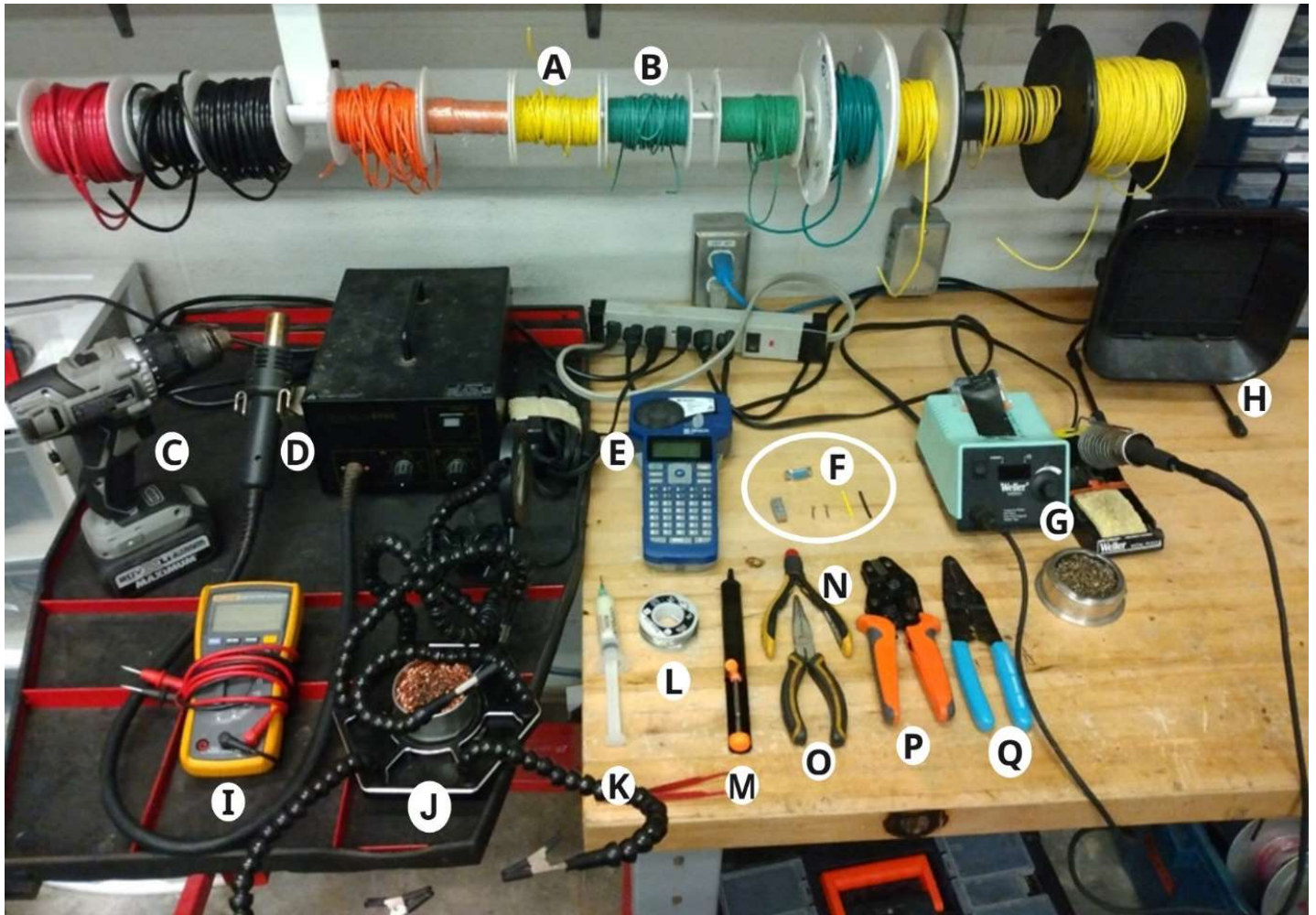


Figure 70: LV and CAN Wire Building Tools (Picture)