Experiential Learning with Respect to Model Based Design Applied to Advanced Vehicle Development

by

Gurhari Preet Singh

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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

With the need for greener powertrains every more present, automakers and part suppliers are lacking skill staff to fulfill design roles. It is estimated there are over 20 million lines of software code in vehicles today and many embedded controllers. The shortage of these engineers is compounded by the economic down-turn of 2008-2009, which resulted in massive 20% to 30% layoffs, reduced internships and reduction of programs designed to recruit new talent. To increase their workforce pool, automakers are working with universities and governments operate student competitions such as EcoCAR 2: Plugging into the Future, alongside traditional private/university collaborations. These programs present students with real-world engineering challenges and the opportunities to design/construction solutions. This also exposes students to the concepts of experiential learning.

The objective of this thesis will be to discuss the design, construction and operation of a vehicle for a student design competition or research group at an educational institution. A process based on model based design will be undertaken, which allows for a majority of the vehicle's design to be completed virtually prior to vehicle prototyping. In this work the model based design method is based on General Motor's Vehicle Design Process. A project management plan is also proposed, which breaks down tasks into three technical areas (mechanical, electrical and controls) and allows for parallelization and reduced development time will also be proposed. Finally, the resources required to operate a vehicle design team will be defined. This includes the support needed from the University, physical space, software and hardware tools, safety considerations and human capital. Examples are drawn from 2013 Chevrolet Malibu converted to a plug-in hybrid vehicle with an ethanol engine and a battery pack was designed and built.

This thesis will showcase the concepts mentioned above through examples from the University of Waterloo Alternative Fuels Team and its participation in international EcoCAR 2 vehicle development competition. The conclusion is that application of the concepts did result in the successful construction of an EcoCAR 2 vehicle. Generally projects that were successful were provided with sufficient technical information from suppliers and supported with past-experiences. Recommendations include: (i) working with suppliers who are familiar with academic environments (including working with students new to vehicle design), (ii) rigorous documentation of design for future designs; and (iii) close collaboration with industry experts to review designs, manufacturing, project management and budgets.

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Dedication

To my Father, Mother, and Brother. Thank you for absolutely everything.

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List of Acronyms

AER	All Electric Range
ANL	Argonne National Laboratory
AVTC	Advanced Vehicle Technology Competitions
AWD	All-Wheel Drive
BAS	Belted Alternator Starter
CAD	Computer-Aided Design
CAN	Controller Area Network
CD	Charge Depleting
CFD	Computational Fluid Dynamics
CIL	Component-in-the-loop
CO	Carbon Monoxide
CS	Charge Sustaining
DFMEA	Design Failure Mode and Effects Analysis
DOE	Department of Energy
DPF	Diesel Particulate Filter
ECU	Electronic Control Unit
ESS	Energy Storage System
EV	Electric Vehicle
FEA	Finite Element Analysis
FTP	File Transfer Protocol
GM	General Motors
HC	Hydro Carbon
HEV	Hybrid Electric Vehicle
HIL	Hardware-in-the-loop
HQP	Highly Qualified Personnel
HVAC	Heating Ventilation Air Conditioning
I/O	Input/output
MABxII	MircoAutoBox II
MBD	Model Based Design
NO_x	Mono-Nitrogen oxides NO and NO2
PHEV	Plug-in Hybrid Electric Vehicle
PIA	Project Initiation Approval
PWM	Pulse-Width Modulation
SAE	Society of Automotive Engineers
SIL	Software-in-the-loop
SOC	State of Charge
THC	Total Hydrocarbon Emissions

UW	University of Waterloo
UWAFT	University of Waterloo Alternative Fuels Team
VDP	Vehicle Design Process
VDR	Vehicle Design Review
VTC	Vehicle Testing Complete
VTS	Vehicle Technical Specifications
VTT	Vehicle Technical Targets

Chapter 1

Introduction

The rising cost of fuel prices and concern of the impacts to the environment caused by the transportation sector has increased interest in green vehicle technologies. Automakers, part suppliers and other interested stakeholders are looking towards green vehicle technologies such as hybridization, electrification of components (e.g. HVAC, power steering), light-weighting technologies, and improved aerodynamics to reduce energy and fuel consumption. It is known that these approaches work well, however stakeholders are facing challenges bringing these technologies to market. The challenges include the success of execution of key technical components (calibration/driver feedback, resulting improvement in fuel consumption), costs and delivery time.

The root case for most of these challenges can be traced to the lack of automotive engineers familiar with new green vehicle technologies. Automakers and part suppliers are looking for employees familiar with electrical and software systems. It is estimated there are over 20 million lines of software code in vehicles today and many embedded controllers [1]. The shortage of these engineers is compounded by the economic down-turn of 2008-2009, which resulted in massive 20% to 30% layoffs, reduced internships and reduction of programs designed to recruit new talent [2]. High unemployment still exists in manufacturing heavy states such as Michigan; however there are open job positions for engineers familiar with software and electrical systems. The result is employers are hiring engineers from overseas and the initiation of programs to bolster math and science programs for young people, as well as training personnel in currently in advanced degree programs with respect to vehicle technologies [1] [2].

Studies by the Original Equipment Suppliers Association find the number of companies reporting challenges related to hiring engineers and technical people stood at 42% in 2010; in 2011 that figure jumped to 70% [2]. The Engineering Society of Detroit reports the number of companies looking for engineers rose from 31% in early 2009 to 51% in 2012. The number of job applicants dropped from 1385 to 613 in the same time-frame [2]. Other causes for the deficiency/need for more automotive engineers include the thousands of automotive engineers who have retired, taken buyouts, or moved to other industries during the automotive sector restructuring and decided not to return. A large number of young software and electrical engineers are also considering more glamorous, better paying jobs in California, rather than the Midwestern United States, developing portable electronic devices and applications. Several companies are complaining that they are in competition with companies such as Google and Intel to recruit new talent [2]. This gap can also be blamed on the educational system, which has had difficulty showcasing the need for software/electrical engineering skills within the automotive industry and matching the skills required by employers with the curriculum taught to students. [3].

Universities can adapt their teaching techniques to include topics related to vehicle design and construction. Some schools offer specific automotive engineering degrees or graduate thesis topics and projects that involve various aspects of automotive systems (powertrain, materials, controls, etc.). Post-secondary institutions can also participate in various vehicle design student teams. These teams are groups of engineering or science students who come together to tackle an engineering challenge. Student teams can also compete against other schools in organized competitions, which provide motivation and fosters innovation. Some examples of these competitions include:

- Formula Society Automotive Engineers (SAE): competition that focuses on developing and constructing a Formula-style race car (open wheel) with a limit of 610cc with a restrictor;
- Formula Hybrid: Similar to Formula SAE, with a downsized engine and electric hybrid system;
- Formula Electric: The same Formula style race car, but with a fully electric powertrain;
- Shell Eco-marathon: Challenges high school and university student teams from around the world to design, build and test energy efficient vehicles powered by diesel, gasoline, hydrogen, or electricity;
- Baja SAE: Student engineering competition which designs and builds an offroad-racing vehicle focusing on vehicle dynamics and reliability;
- SAE International Clean Snowmobile Challenge (CSC): An engineering design competition that challenge engineering students to reengineer an existing snowmobile to reduce emissions and noise; and,
- US Department of Energy’s Advanced Vehicle Technologies Competitions (AVTC): Retrofitting an existing production vehicle to operate with a different fuel and/or hybrid electric system, while retaining consumer acceptability.

These competitions challenge students to apply classroom knowledge to real-world challenges. In particular, the students involved in Formula Hybrid/Electric and AVTC competitions face similar challenges that automakers face; working with green vehicle technologies such as hybrids/electric systems and vehicle control. Students with this experience are highly sought after and hired by both automakers and part suppliers [3].

With this level of interest, student teams provide Universities with two unique the opportunities: a platform to train highly qualified personnel (HQP), and an opportunity to carry out research directly in line with the needs of the automotive industry. This thesis will focus on how these vehicles can be built in an educational context and the necessary faculties/resources, design techniques, construction, and validation processes.

1.1 Objective and Contributions

The objective of this thesis is to discuss the resources, techniques and processes needed to design and construct a green research vehicle within a post-secondary institution, such as a university or college. Processes such as model based design and project management using controls, mechanical and electrical streams working in parallel are proposed. Throughout this thesis, examples will be drawn from the University of Waterloo's Alternative Fuels Team (UWAFT) and its various AVTC vehicles, which represents some of the most complex powertrains constructed at any post-secondary institution in North America, and the most defined and detailed set of competition expectations. Unique issues which arise from the academic environment (such as knowledge transfer and human capital) will also be discussed.

The goal is to document for institutions interested in participating in a student team or building a research vehicle of the challenges and benefits of these projects present. The challenges include setting-up the required facilities, execution of the design and construction phase, finding industry partners, and generating the required curriculum to support the development. The benefits include students who are exposed to hands-on, real-world engineering challenges, which produce some of the most desirable engineering graduates for employers. Additional benefits include a research vehicle platform, which is flexible and allows for real-world testing of new green vehicle technologies.

1.2 Thesis Outline

This thesis has seven chapters, including this introduction. The topics of each of these sections are as follows:

Chapter 1 serves as an introduction and highlights the need for green vehicles and outlines the need of qualified engineers in the automotive sector who can help develop green vehicle technologies such and hybrid electric vehicles. The lack of highly qualified personnel (HQP) can be attributed to the economic downturn of 2008-2009, computer/software engineers being drawn to work for Silicon Valley, and the advancement of electronics and embedded systems in vehicles today. Chapter 1 also introduces the concept of student teams to help develop more HQP. The objective and goals of this thesis are also introduced

Chapter 2 provides further background information into the issues surrounding HQP in the automotive industry. This chapter also introduces various types of automotive-based student competitions for student teams, specifically EcoCAR 2 and the Advanced Vehicle Competitions.

Chapter 3 covers in great depth the resources needed to operate a student team or vehicle research group. This includes the resources from the University, which includes: administrative support, workspace, design space, utilities and safety consultation. Software and hardware tools needed for the design and construction of the vehicle are also discussed. Finally, the types of students and methods to retain knowledge are described.

Chapter 4 provides a detailed overview of the design process, which focuses on a modified version of GM's vehicle design process. With this process, design targets are established, based on research goals and real-world driving habits. These goals are used by controls, mechanical and electrical team to guide design decisions. Tools such as model based design, software-in-the-loop and hardware-in-the-loop, computer aided design (CAD), finite element analysis (FEA) and electrical system simulation is used to virtually design the vehicle. The design of battery packs in described in detail, using UWAFT's EcoCAR 2 battery as an example.

Chapter 5 documents the challenges of moving from design to construction for the controls, mechanical and electrical team. Examples are taken from the construction of UWAFT's EcoCAR 2 vehicle. These challenges showcase the importance of experiential learning and allowing students to follow their design through to product realization. By going through the full design process students can apply their classroom knowledge to real world design, learn the limitations of design tools and make improvements for future design.

Chapter 6 and 7 provides conclusions and recommendations for this thesis. Chapter 7 provides references and a list of acronyms.

Chapter 2

Literature Review

2.1 Need for Electrification in Transportation

In 2008 the transportation sector in Canada accounted for 29.7% of secondary energy use in Canada. Secondary energy resources that do not occur naturally, but are refined from primary energy resources, such as crude oil. Road transportation consumed 78.9% of this energy. Greenhouse gas (GHG) emissions from the transportation sector account for half of Canada's total direct end use GHG emissions [4]. With transportation significantly contributing to both energy consumption and emissions it is clear that steps need to be taken to reduce the impact of transportation on natural resources and emissions. By introducing electrification into transportation, in the form of hybrid (HEV), electric (EV) and plug-in electric hybrid (PHEV) it is possible to reduce gasoline petroleum consumption and vehicle emissions by supplementing combustion based engines with electrical drive trains and energy storage systems (ESS). The electricity that supplements or replaces the fossil fuels traditionally used to propel the vehicle can be cleaner depending on the method of electricity production. In Canadian provinces such as Quebec, British Columbia and Newfoundland a majority of their electricity is generated from hydro-electric plants [5]; powering the transportation sector with this grid reduces petroleum consumption and emissions significantly. While other provinces do not enjoy a clean energy grid, steps are being taken to move towards a cleaner grid. Ontario for example is moving toward eliminating coal power plant production by the end of 2013 [6], and currently gets 75% of its electricity from GHG free nuclear and hydro. With the next generation of vehicles moving towards electrification and electrical grids moving toward reducing fossil fuels, it is logical to develop professionals familiar with electrification vehicle technologies.

2.2 Desire for Highly Qualified Personnel and Benefits of Student Teams

As mentioned in the introduction the automotive industry is finding it challenging to find professionals or students who are familiar with green vehicle technologies, specifically people familiar with electrical and software systems. These issues are not geographically restricted. Areas in the UK and Germany are facing shortages of professionals familiar with electrical and computer system on vehicles [7] [8]. Some factors contributing to this include an aging workforce and lack of enrollment in technical studies. In Germany automakers are beginning to recruit students from China and India, as well as collaborate with Universities locally to access new talent and train existing staff [8].

Education through student teams presents a unique and innovate method to teach students, specifically it provides an opportunity for experiential learning. As mentioned in the introduction, a student team is an organization of student who design and build vehicles to competition in various competitions. These competitions can include Formula SAE, where teams build racecars and compete on the basis of vehicle performance. All of these competitions operate on the basis of experiential learning. Experiential learning exposes students to concrete experience, reflective observation, abstract conceptualization, and active experimentation [9]. In contrast traditional academic learning the focuses is on the study of a subject without the need for direct experience. A study of graduating students taught traditionally have found that while students are comfortable with their technical knowledge and problem solving skills, students feel they lack leadership skills, practical preparation, management skills and experience working in multi-disciplinary teams [10].

The benefits of experiential learning are widespread. Typically post-secondary institutions expose students to experiential learning through co-op programs, which place students within companies for 4-16 months. Surveys have found students gain more ‘soft skills’ such as communications, leadership and working in organization. "Soft skills" also include a group of personal qualities, habits, attitudes and social behaviors that make someone a good employee and compatible within the workplace. Soft skills are not normally specifically covered in an academic setting, but critical for the workplace [11]. Furthermore, students have been found to better understand their academic direction and future carrier direction through co-operative (co-op) experiences with employers. Employers can also gain from co-ops; studies have shown overall cost of co-ops is lower than regular employees. Employers can screen students before hiring, and increase interaction with post-secondary education for further collaboration [11]. Providing experiential learning through co-op has its advantages, however experiential learning through a student team gives students greater responsibility and a longer time frame to take on complex and challenging projects [12].

2.3 AVTC and EcoCAR 2: Plugging Into the Future

2.3.1 AVTC

The Advanced Vehicle Technology Competitions (AVTC), sponsored by the U.S. Department of Energy (DOE) and managed by Argonne National Laboratories (ANL), is a unique series of competitions that bring government, industry, and academic partners together [13]. The goals of the competition include:

- Accelerate the development and testing of green vehicle technologies of interest to DOE and the automotive industry.
- Provide the automotive industry with a new generation of engineering leaders with highly desirable hands on experience.
- Help prepare the market to accept advanced vehicle technologies.

In operation since 1987, over 10 competitions have been held in partnership with Natural Resources Canada (NRCAN) and all three of the ‘Big Three’ U.S. Automakers. Typically each competition focuses on a fuel or technology. Past themes include: ethanol, propane, methane, hybrid and plug-in technology. Over 16,000 students have participated in AVTC from 91 institutions from across North America [13]. Additional sponsors include:

- part suppliers (e.g. Magna, Bosch);
- instrumentation companies (e.g. National Instruments, dSPACE);
- consulting organizations (e.g. AVL, Ricardo) ; and
- software companies (e.g. The Mathworks, Siemens PLM).

The benefit to sponsors is students who become familiar with their products/tools and future potential employees who have gained real-world practical application knowledge. Many students have been known to graduate from these AVTC programs and be hired by sponsors [14].

2.3.2 EcoCAR 2: Plugging In to the Future

The current AVTC is EcoCAR 2: Plugging In to the Future. It is a three-year university-level engineering competition that challenges 15 universities across North America to re-engineer a 2013 Chevrolet Malibu with the theme of plug-in technology. The modified vehicles will be designed to meet following technical goals:

- To reduce fuel consumption.
- Reduce well-to-wheel greenhouse gas emissions.
- Reduce criteria tail pipe emissions.
- Maintain or improve consumer acceptability.

The competition follows a modified of GM’s Vehicle Design Process (VDP). It is a standardized design process GM uses to design, develop, test and validate production vehicles. This globally used process allows for vehicles to be developed quickly with a reduction in workload and the number of prototypes [15]. The first year of the competition is devoted to modeling and simulation of powertrains and subsystems. Students utilize math-based models and modeling tools to select the vehicle architecture, components, and subsystems that meet the competitions goals and team specific goals.

Teams also bench test hardware and develop the control software for future migration of their vehicles. At the end of Year 1 (September to July) teams received their 2013 Malibu. The second year of the competition focuses on integration of their designs. They target a 65% complete vehicle (a ‘mule’ vehicle) with all major components functioning, but not yet fully calibrated. The final year focuses on refinement and optimization. All vehicles face a thorough safety inspection during year 2 and 3 to ensure they operate safely [15]. The overall timeline is shown in Figure 1. At the end of each year, there is a milestone:

- Year 1 - Project Initiation Approval (PIA): The final conceptual review before the vehicle construction commences. This review is supported by simulation and CAD modeling to prove the proposed design is feasible and will meet design targets.
- Year 2 -Vehicle Design Review (VDR): A midterm review of the vehicle’s performance with all functioning components. The current performance of the vehicle is compared to the design targets. Deviations are addressed and steps are outlined to bring the vehicle’s performance back to the design targets.
- Year 3 - Vehicle Technical Complete (VTC): A final review of the vehicle where the performance should match the initial design targets. Deviations are analyzed, discussed, and fed back into the design process of the next vehicle.

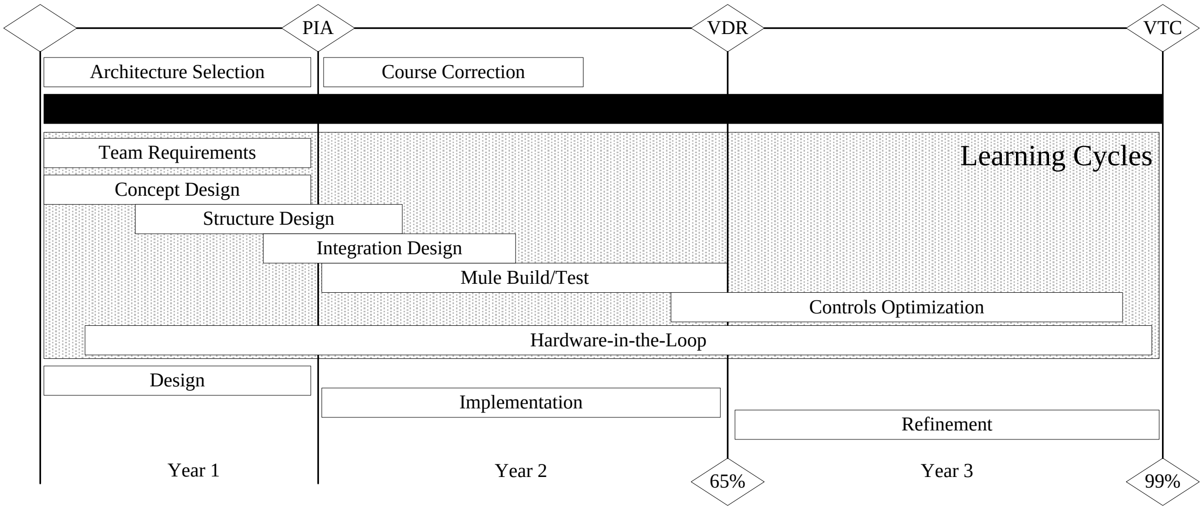

Figure 1 - EcoCAR 2 timeline with major milestones [13]

The PIA, VDR and VTC are all evaluated at a year-end competition in various locations across the US. The competitions are split into two sections; the dynamic on road events and the static design presentations. It should be noted that construction of the vehicles take place in Year 2, hence in Year 1 there is no dynamic event. The dynamic events consist of three types of events: drivability, dynamics and fuel consumption/emissions. The drivability event focuses on the refinement of the vehicle. Successful vehicles have low vibration and noise with predictable steeling, brake and acceleration feel. The dynamic events evaluate braking (shortest distance), acceleration (fastest 0-60 mph and passing 50-70 mph), and handling performance (greatest lateral acceleration and an autocross event). The fuel consumption event consists of running several laps around a test ring at a predefined speed traces (including idle stops), which represents both urban and rural driving habits. During this event fuel consumption and emissions measured simultaneously. The amount of electricity consumed is also measured and the upstream consumptions considered. The emissions event measures unburned hydrocarbon (UHC), carbon monoxide (CO), and Nitrogen Oxide (NO_x).

The static events are typically held after the dynamic events and consist of a 20 -30 minute presentation followed by a question and answer period. Two students present the content to a panel of judges selected for their expertise in the given subject area. There are several presentations covering a range of topics: mechanical, controls, electrical, business, and outreach. There is also a ‘project overview’ presentation, which evaluates the overall performance of the vehicle compared to the design targets.

The final score teams receive for the competition is out of 1000 with 55% of the points assigned to the dynamic events, 22% for the presentations given at competition and the final 23% for Pre-competition deliverables, which consist of design reports. This distribution is shown in Figure 2. Teams can win cash prizes for placing the top three positions for various static and dynamic events. In addition, sponsors typically hold separate awards for innovative use of their products. These awards do not contribute to the team's overall score, but do provide additional prize money. It should be noted each year the scores are reset to zero, thus all three years of the competition have a new winner.

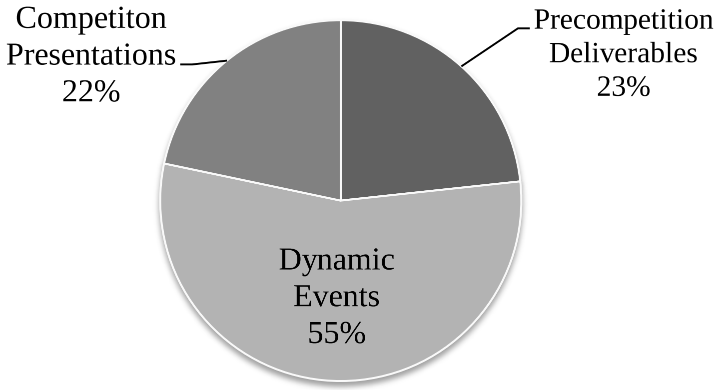

Figure 2 - EcoCAR 2 scoring breakdown

To do well in the competition, schools are recommended by the organizers to have three key teams: a technical team, a business team, and an outreach team. The technical team manages the design and construction of the vehicle and its various subsystems. The technical team is further broken down into the mechanical, controls, and electrical team. The business team is in charge of budgeting, recruiting new sponsorship, purchasing, and logistics for travel. The outreach team is tasked with educating the public about EcoCAR 2 and the school's vehicle/technology through various medium: social media, traditional media, attending events, etc. A student team lead (typically a graduate student) is in charge of managing all three teams on a day-to-day basis and for most schools it is an engineering student. A faculty advisor oversees the long-term objectives of the students and maintains team-to-faculty relationships. The org chart is shown in Figure 3.

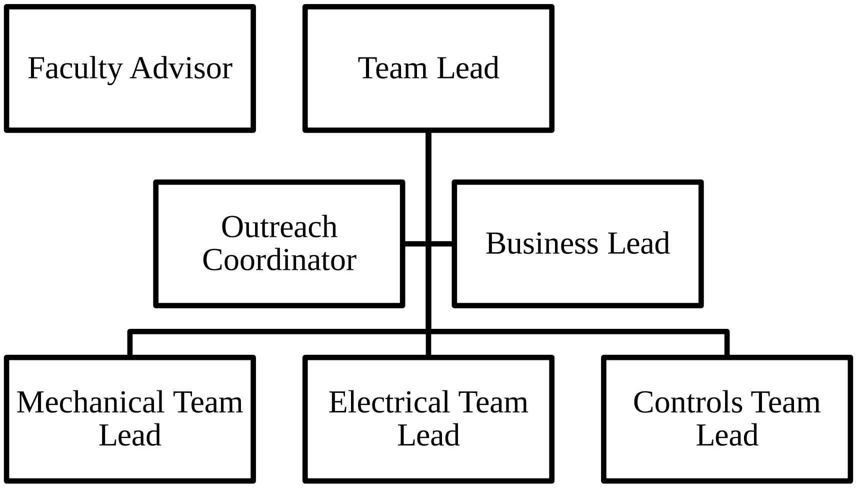

Figure 3 - AVTC recommended EcoCAR 2 team structure, used by UWAFT

Figure 4 gives a detail overview of roles of the various sub teams and how the evolve and interact over the three years of the competition. During year one the mechanical team carries out the component packaging, aids the selection of components and performs the detailed design. During year two the mechanical team modifies and integrates components. For the final year the mechanical team refines the NVH and aerodynamics of the vehicle. The electrical team defines the low voltage and high-voltage system requirements and routing. During years two and three the electrical team implements the design the refines it. The electrical team also works closely with the mechanical team on the construction of the battery, which requires thermodynamic, structural and electrical design. The controls team year 1 task include modeling various powertrain architectures and preliminary design of the safety critical control. During year 2 they work with the electrical team to integrate and commission various components within the vehicle. The final year is devoted to refinement and work improving the human machine interface (HMI). The business team's role in year 1 is to work on sponsorship, fundraising and develop marketing materials. During years two and three, they continue to work on fundraising, but also focus on risk analysis and knowledge transfer. They also work with the commutations teams on website development. The communications team spend year 1 on initializing social media platforms, outreach materials and video production. The second year is devoted to educating youth and the general public about the team, competition and green vehicles. They also work on showcasing key sponsors' contribution to the team. The final year continues the social media campaign and also has the team run influencer campaign, where they reach out to local stakeholders and educate these parties about the benefits of the competitions and green vehicles.

All of the teams work together on project management to insure shared tasks and resources are managed properly. For example, the component selection process involves all three technical sub-teams to ensure the components (motors, batteries etc.) meet the goals for performance (mass, 0-60 mph acceleration, compatible with other components). Another example of the various teams working together would be for attending an outreach event with the vehicle. The business team and communications team would work together on selecting the event, logistics, and budget. They would also work with the technical team to schedule a time that does not conflict with testing or construction of the vehicle.

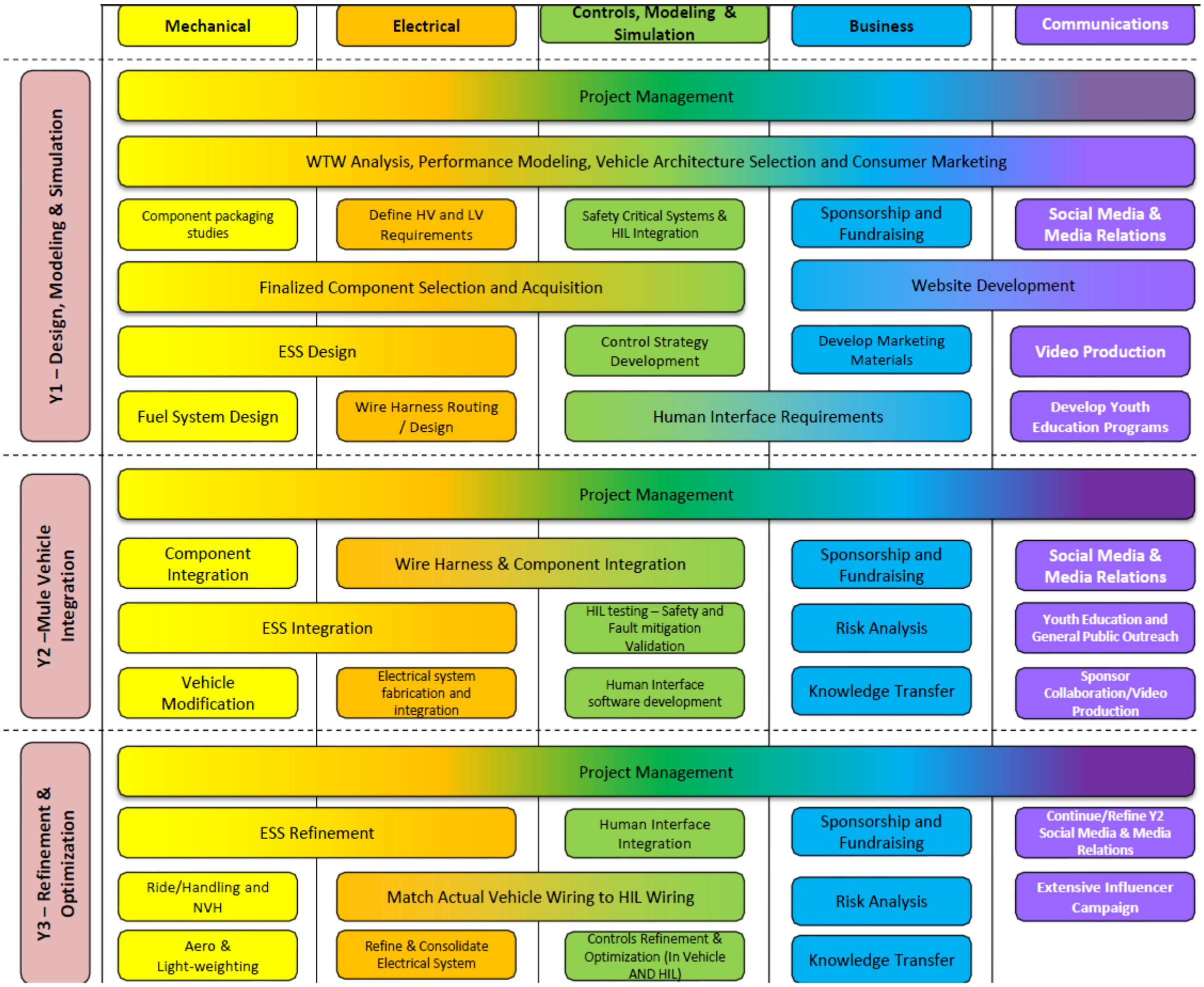

Figure 4 - Competition recommended roles and tasks [13]

The EcoCAR 2 competition prepares students by mimicking the real-world challenges faced by industry professionals: meeting fuel consumption and emission targets, developing dynamically enjoyable vehicles, scheduling and project management, developing safe control code, mechanically packaging complex powertrains, designing high voltage systems, developing captive presentations for stakeholders, educating the public about new technology, managing budgets and working in diverse teams.

2.4 University of Waterloo Alternative Fuels Team and Vehicles

The University of Waterloo Alternative Fuels Team (UWAFT) was founded in 1995 by Dr. Roydon Fraser. The team is comprised of a group of undergraduates and graduates from across the University of Waterloo and Wilfrid Laurier University campus. The mandate of the team is:

- Research, design and implement green vehicle modifications to existing vehicle platforms with the goal of reduced well-to-wheel (WTW) petroleum usage, GHG emissions and total energy usage.
- Weight the benefits and drawbacks of these technologies.
- Provide a platform for student to learn industry standard and next generation tools and processes.
- Educate the public about green vehicle technologies and methods to reduce their fossil fuel consumption.

Since its inception, the team has worked on: hydrogen fuel cells, hybrids, plug-in hybrids, propane, natural gas, and ethanol fuels. UWAFT was the first University team in the world to develop and operate a fuel-cell hybrid vehicle. As part of US DOE’s AVTC, UWAFT has worked six vehicles, trained hundreds of students and educated thousands about green vehicles technologies. This thesis uses examples from the last three vehicles constructed by the team, including:

- 2005 Chevrolet Equinox: Converted into a hybrid hydrogen fuel cell vehicle. It utilized a 65 kW Hydrogenics Hydrogen Fuel Cell System in conjunction with a Cobasys battery pack, custom design DC/DC converter and two 67 kW Siemens-Ballard Transaxle motors. The vehicle architecture is shown in Figure 5.
- 2009 Saturn VUE: Converted to a plug-in hydrogen fuel cell hybrid vehicle. Utilized a GM sourced ~100 kW Fuel Cell System, 10 kWh A123 Li-ion battery pack, Brusa DC/DC

converter, a GM 120 kW Transaxle motor and a 67 kW Siemens-Ballard Transaxle motor. The vehicle architecture is shown in Figure 6.

- 2013 Chevrolet Malibu: Converted to a series plug-in hybrid. An 18.9 kW A123 A123 Li-ion battery pack, powers two 105 kW TM4 motors (one on each axle). A GM sourced Flex-Fuel LE9 engine charges the battery via a third TM4 motor, which acts as a generator. This architecture is shown in Figure 7.

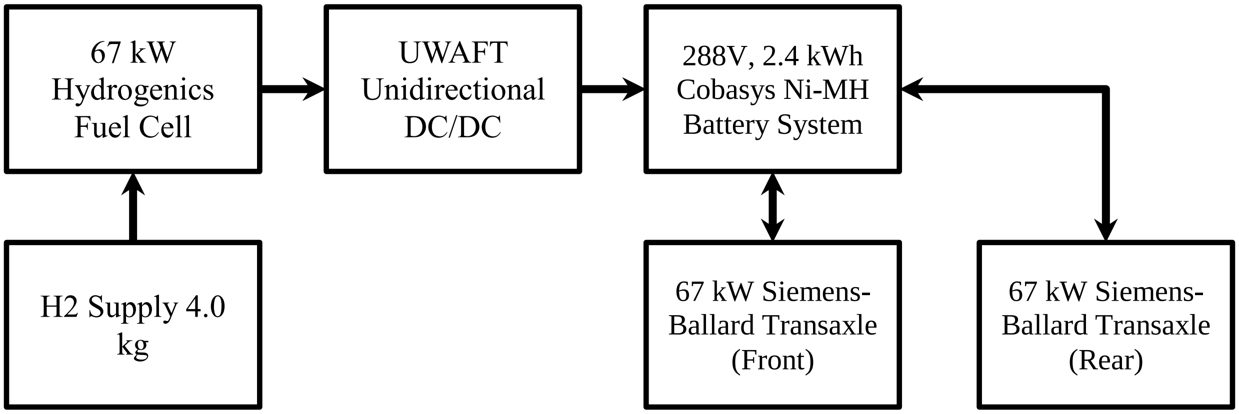

Figure 5 - 2005 Chevrolet Equinox hybrid hydrogen fuel cell vehicle architecture

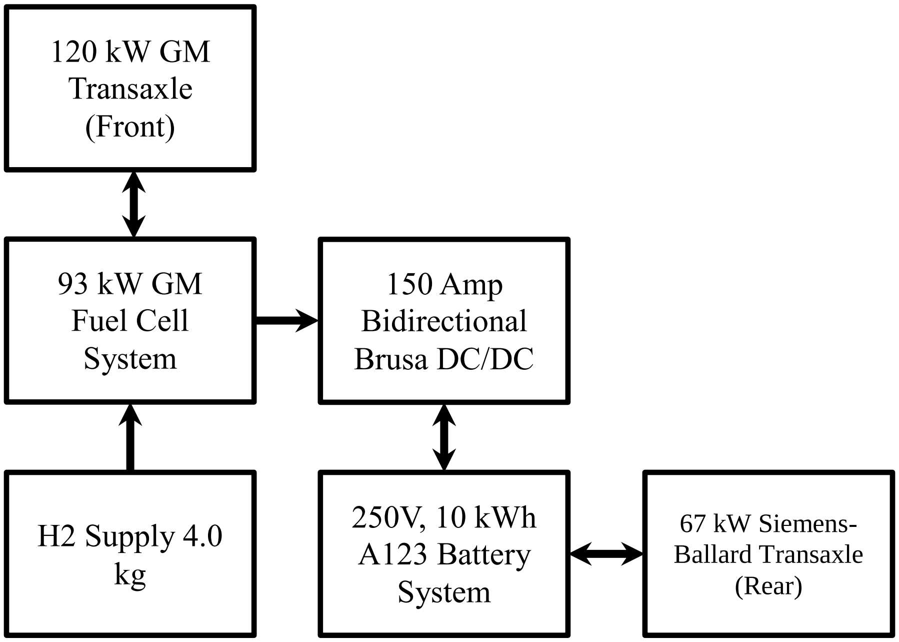

Figure 6 - 2009 Saturn VUE Plug-in hydrogen fuel cell hybrid architecture

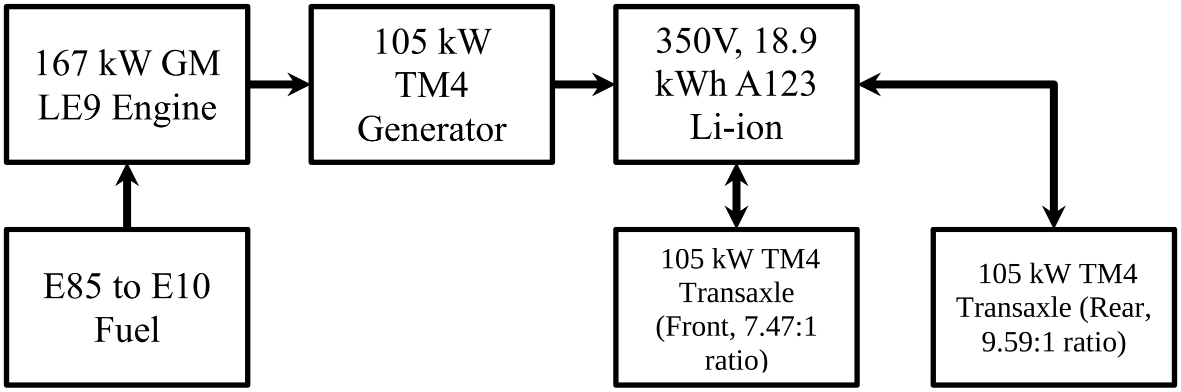

Figure 7 - 2013 Chevrolet Malibu Series plug-in hybrid architecture

Between each of the vehicles designed, improvements in power electronics, fuel cell and battery technologies allowed for progressively physically smaller powertrains, while maintaining or improving fuel consumption. All vehicles were designed primarily by students and are road legal in North America. Each vehicle was also designed to explore key research areas: the Equinox vehicle explore the construction of fuel cells, light weighting materials and power electronics. The VUE explored extended research into fuel cell operation optimization; custom made batteries packs and cooling systems, and adaptive powertrain control. The Malibu extended development in battery cooling technology, mechanical packaging and adaptive control. The three vehicles mentioned all follow the design process discussed in the following sections. The author participated in the mechanical integration of the 2005 Equinox, powertrain controls for the 2009 VUE and led the technical team for the 2013 Malibu.

Chapter 3

Facilities and Resource Considerations

3.1 Need for Facilities

The appropriate facilitates for vehicle construction within either a student team or research group is essential. The appropriate facilities will impact the vehicle's design/deployment process, final performance, overall project management and safety. Universities must also understand that their required resources go beyond what is found in a traditional maintenance garage; a lift and basic tools is not sufficient when constructing research or student vehicles.

The goal of this section is to highlight the resources that are needed for UWAFT and AVTC competitions. In addition to workspace, this section will also cover the resources needed to design, maintain, and operation of research vehicles. Traditional resources, such as materials, money and tools (software and hardware) will be discussed. Nontraditional resources will also be examined; this includes management of human capital knowledge transfer systems to ensure the project and research vehicle remain operational.

3.2 University Commitment

The support of the University or College is critical for several reasons: insurance and liability, space, and administrative resources. From an insurance and liability standpoint, UWAFT required the University's permission to accept a donated General Motors vehicle. Under the terms of the agreement of donation, the University needed to:

- Accept liability for any injuries that occur while operating or working on the vehicle.
- Understand the vehicle would be provided with no warranty.
- Ensure the vehicle must be disposed of after its use as a research vehicle.
- Provide "Comprehensive General Liability" with General Motors listed as an additional insured party.

Depending on if the vehicle will operate on public roads, the University also needed to provide vehicle insurance and registration. If there travel involved (for testing, or competition) the University needs to provide coverage for any damages or injury that may occur. This can be challenging for travel that occurs across international borders. For Canadian schools, consideration for the lack of healthcare coverage in the United States may require the Universities to provide health care coverage abroad.

The space required to design, construct and test research vehicles also needs to be arranged with the University. Within the context of this thesis, design space is defined as space/office allocated for designing systems for the vehicle (both hardware and software) in a modeling environment. The design space should include desks, computers, and a telephone for conference calls. For most Universities, this is not a challenge, but the design space should be within close proximity to the construction/workspace and student.

The workspace is defined as the space where construction of the vehicle and various subsystems occur. A hoist, worktables and tools are just some of the many resources the University will need to provide. If it is an unlicensed vehicle, such as a formula SAE racer, the University will need to provide space on non-public roads for testing. The space should allow for the vehicles to reach its desired design speed, allow for braking tests and lateral grip tests. The University of Waterloo provides its research groups and student teams two such spaces. The first is a parking lot that is unused afterhours for the Formula SAE team and other unlicensed vehicles. The second space is provided by an agreement between the University of Waterloo and the Region of Waterloo's Emergency Services Training and Research Complex. This closed test track provides space for both licensed and unlicensed vehicles to operate in a closed environment and reach a maximum speed of roughly 100 km/h for a midsized family car. Note that a trailer is required to transport the vehicle 7km to this test track.

The administrative resources required for prototype vehicles include procurement services, financial services, and brokerage/customs services. Procurement services are essential for research vehicles due to the cost of components such as batteries and motors which can exceed $10K each. Additionally, many companies will only sell via purchase order and will not accept personal credit cards or cash. Financial services are needed to manage the project's finances, which typically includes donations from sponsors, pay for interns or graduate students, and costs such as travel and parts. Brokerage and customs services are needed for travel across international borders. The University of Waterloo's student teams typically travel to competition within the US with vehicles and parts, all of which need to be documented for customs purposes. Customs services are also needed for vehicle parts such as batteries, which can be considered hazardous materials when being shipped.

3.3 Workspace and Tools

The workspace can be defined as the construction site for the vehicle and its various subsystems. The space is also used to store the vehicle when not in use. There are several requirements for the workspace to be effective; this will be listed in the following sections.

3.3.1 Physical Space

The space must allow for the vehicle, tools, parts storage, and room to move within the space. It is best if the workspace is located close to the design space, and is one location which provides storage and working area; this however can be split into multiple locations if needed. It should be located away from classrooms (to mitigate noise) and at the building's perimeter to allow for the vehicle to be moved outdoors easily. For student teams, the building which houses the workspace should be located as close as possible to other engineering buildings; this provides easier access for students to work on the vehicle between classes. The overall area dedicated to the workspace should be at least six times the footprint of the vehicle to accommodate for space to move around powertrain components and batteries. For example, UWAFT's vehicles have a footprint of 96 ft^2; the workspace for the vehicle is 580 ft^2 with an additional 515 ft^2 of shared storage/design space. It is also advisable to have a separate space for painting, sanding and welding; these tasks can generate undesirable airborne particles and chemicals. A separate, well ventilated space is advisable for these tasks. If batteries are used as part of a HEV, EV or PHEV vehicle, a separate, secure location should be used for safety, and only trained staff or students granted access to this space.

The overall workspace can be arranged anyway which fit best for the research group or competition. UWAFT set up its space with a hoist in the center, tools along the wall with worktables, parts storage and a space for personal belonging such as jackets and school bags. A hoist is necessary for any road-going vehicle and should be sized to accept the appropriate class of vehicle (pick-up or sedan). Operators of these hoists should understand how to operate them safely for each vehicle and understand the maintenance schedule required. The hoist should be located in a path directly in line with the main garage door. A schematic of the UWAFT workbay is shown in Figure 8.

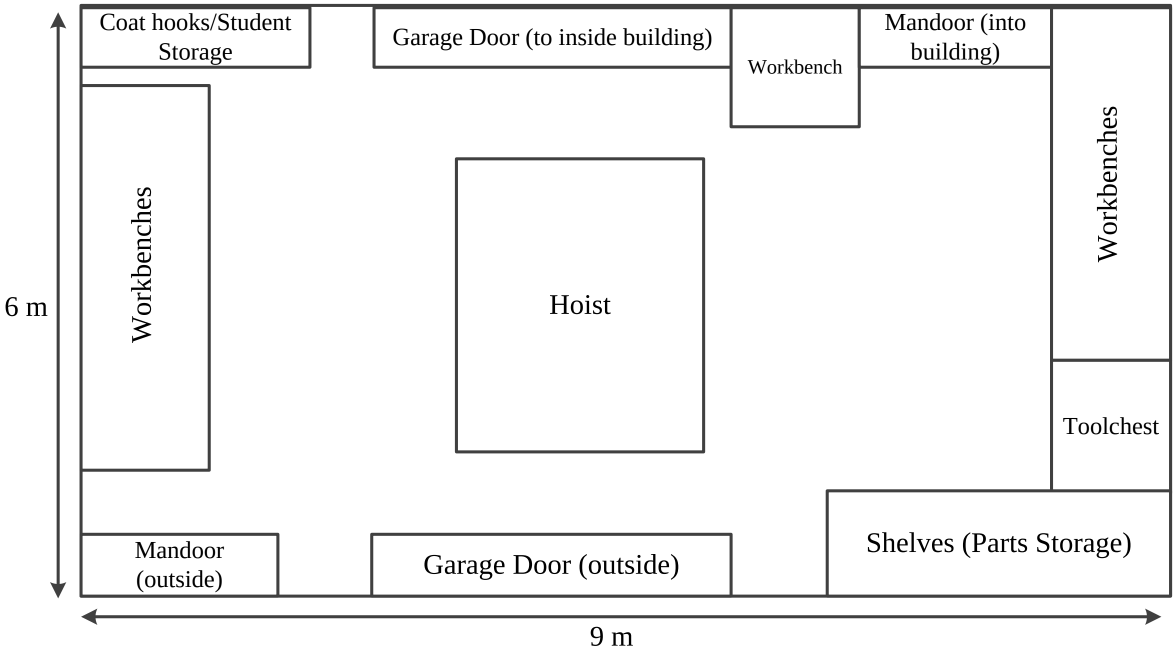

Figure 8 - UWAFT Workbay Layout

3.3.2 Utilities and Access

The utilities required for the workspace include traditional garage requirements such as 120 V power and compressed air supply. The compressed air supply should be supplied from a large compressor that can continuously supply the required air, rather than a smaller portable compressor that takes time to charge up after each use. The 120 V should also be ground fault interrupt (GFI) protected and free from any electrical interference; some EV chargers contain sensitive circuitry that can be damaged by ‘unclean’ power. Additional 240 V power supplies should also be installed for Level 2 SAE J1772 charging. These circuits should also isolated from lathes, mills or other high power machinery that can introduce electrical interface. Finally, if computer equipment is being employed in the workspace, an uninterruptible power supply should be used to prevent the loss of any important data.

During the construction process, it is not uncommon to run the engine at idle to take measurements and test various systems, thus an exhaust fan system should be installed to vent away harmful gases. A phone that can be used to contact the University’s emergency services should be installed in case of emergency. A Wi-Fi connection is useful, thus allowing for student to look-up repairs or specifications. A separate fuel storage locker is also used by the team; University of Waterloo rules mandate any amount of fuel over 250 mL must be located in a certified fuel storage locker. Chemicals are also stored in a chemical storage locker.

The access to the workspace should be limited to students who are trained to work with powertools and have taken a safety course, so security is an issue. UWAFT employs a numerical lock for both its workspace and office, with the code given to students who have completed the University mandated training course. Tracking of students who have completed this training is maintained by the technical team lead. Access to the workspace and office is open 24/7 to give students flexibility, however all students must work under a ‘two-person’ rule. A student must be accompanied by another student, so in the event someone gets hurt the other student can call for help.

3.3.3 Tools

The workspace should be equipped with standard automotive workshop tools, including: metric and imperial wretches, ratcheting wrenches, sockets, impact sockets, screwdriver, pliers, tap and die set, impact wretch, hammers, torque wrenches, punches, files, ring pliers, and a tool chest to store the tools. A scan-tool or ODB-II compliant computer is useful for diagnosing problems and trouble codes. 12 V battery chargers prevent lead-acid batteries from dying, a common event when diagnosing wiring and controls code issues. Task specific tools, such as spring compressors, can be borrowed from dealerships or local garages, saving costs.

There are several tools and personal protective equipment (PPE) needed for the high voltage (HV) electrical systems (the battery nominally operates at 300 Volts and 300 Amps). HV certified safety gloves, insulating covers/blankets and multi-meters are required. There are also HV isolated hand tools. In general, it is best to contact the University’ safety office or external specialist to review all HV related tasks and select the appropriate PPE to match these tasks. A good resource for review is High Voltage Safety for the Service Technician [16]. A heat gun (for heat shrink), wire stripper, current clamp, soldering iron and lug crimper are useful tools to have.

Plasma cutting and welding tools can also be used, however the user should be trained to use these tools and the workspace should have sufficient ventilation. Welding machines also require a high voltage/high current source. Large tools such as lathes and mills are great for building custom parts, but should be located in a separate space. They require room to work around and can generate flying debris which presents a safety hazard. At the University of Waterloo, a student machine shop houses several lathes, mills, drill presses and other tools students can use. It is also staffed by a technician who teaches students how to operate the machines safely.

3.4 Design Space and Software

As mentioned earlier within the context of this thesis, design space is defined as space/office allocated for designing systems for the vehicle (both hardware and software) in a modeling environment. An office environment is best suited for this, with desks, cabinets, tables, printer, networked storage and computers. Uninterruptible power supplies should be used on all computers. UWAFT's network storage was a server which hosted an FTP on a RAID disk array. The RAID is backed-up every month to limit the possibility of data loss. This server also hosted the team's network software licenses as well.

Each engineering team has their own unique set of software requirements. The mechanical team's software requirements are based around design of components. CAD software is a must. If the vehicle is being constructed in collaboration with an automaker, selecting the CAD software package and version the automaker uses makes transferring models easier. For example, UWAFT uses Siemens NX 7.5 because GM also employs the same software and version. The mechanical team will also require the use of finite element analysis (FEA) for stress/strain analysis. Computational fluid dynamics (CFD) may also be used for thermal or aerodynamics design. The computer required to operate CAD, FEA and CFD software typically requires a high performance graphics card, adequately RAM, and a large hard disk to store simulation results. Designing a computer to meet the software vendor's recommendations is the wisest choice. The electrical team's task requires two types of software; schematics/documentation and simulation/modeling. Schematics software would include Microsoft Visio, Altium, or any electronic design automation software. Simulation and modeling software is used to understand the behavior of various analog electrical systems. For example, electrical engineers may use the software to understand the interaction between various motor inverters. Simulink's SimPowerSystems or Simscape, PSpice and SPICE are typically employed for electronics modeling. Given the high frequency nature of inverters and other power electronics, a powerful processer is needed to simulate the electrical systems in high enough fidelity.

The controls team's software requirements are extensive. During the initial design phase, the controls teams typically will use energy modeling software such as AVL Cruise, PSAT or Autonomie. Software in the Loop (SIL) models can be written in Simulink or LabVIEW. Typically hardware-in-the-loop (HIL) systems execute Simulink derived C Code and have their own bespoke interface software. For example, dSPACE uses ControlDesk. When the controls team moves from the lab to vehicle deployment, laptops are needed to run calibration software. While the number of software programs needed is extensive for the controls team, the computational requirements are relatively low; a computer which can execute powertrain energy models with ease will also be able to operate all of the SIL and HIL required software.

3.5 External Resources

Beyond the resources provided at the workshop and design space, research and design teams may also need to employ resources from other University groups and beyond. Several universities have machine shops staffed by technicians who can machine, weld and fabricate various complex components for the vehicles. These machine shops may also have CNC machines and waterjet capabilities.

Other resources that should be considered include material suppliers; steel and aluminum of various grades. Vendors which supply car parts, mechanical fasteners and/or electrical components are also useful; many of these parts can also be ordered online for next day delivery as well. Services to consider include specialty machining such as splining, specially welding (titanium, magnesium), and heat treating. Testing resources which are beneficial include chassis and engine dynamometer.

3.6 Safety Considerations

Safety is paramount when working on any laboratory based work. Constructing a vehicle add several additional safety concerns which need to be addressed. Further complicating safety matters are if the vehicles are HEVs, EVs or PHEVs. It should be noted that the author is by no means an expert in safety and the appropriate safety overview should be taken with an expert (such as the University's safety office) before any vehicle projects are undertaken. Key issues that should be addressed include:

- Storage, handling and disposal of chemicals, fuels and batteries with updated material safety data sheets (MSDS).
- Spill procedures and kits.
- Body and eye wash stations.
- Fire suppression for various types of fires (gasoline, metals and batteries).

- Proper ventilation for the garage or laboratory space for sprays, solvents and other chemicals which generate dangerous fumes.
- Correct personal protective equipment for welding, grinding, noise, handling sharp objects, chemicals, hot/cold materials, HV systems and recertification of HV equipment.
- Procedures for lifting components and vehicles, including maintenance/training of lifting equipment.
- Lock-out, tag out for electrical systems, lift systems etc.
- First aid training and keeping track of certifications.
- Fire and evacuation procedures.
- Standard operating procedures for tools and other equipment.
- Emergency contacts.
- HV electrical safety training.

Most of the issues mentioned above maybe covered by the Provence/State’s occupational health and safety act, however each project is unique and require a distinctive safety overview. An additional challenge presented by a University work environment is the high turnover rate due to graduating students. Ensuring student’s training is up to date and that there is knowledge transfer between students is important.

3.7 Human Capital

As mentioned in Section 2.3.2, a team structure is needed to operate a student team successfully. The team needs controls, electrical, mechanical and project management groups. Additional aerodynamics, vehicle dynamics, engine, sponsorship and outreach groups can be added or placed under existing groups, depending on the project/competition being undertaken. Many existing engineering disciplines can be tapped to fill these roles. For example mechanical engineering students can handle most mechanical design, vehicle dynamics, and aerodynamics work. Partnering with the controls group, they can work on engine development. Electrical, software or computer engineering students can work on electrical or control systems. Reaching beyond the engineering facility and moving into business and communications programs can provide project managers, sponsorship and outreach students. The UWAFT actually works with students from the neighboring Wilfrid Laurier University on business and outreach projects.

A challenge that new students face when joining a student team or research group is the learning curve. The difference between classroom knowledge and real-world engineering problems makes it difficult for new students to take on projects immediately. Co-op or internships tend to help with this, but only if the previous positions were similar to work being carried out on the vehicle. To overcome this at UWAFT, students typically work under a mentorship program, shadowing senior students with those who are familiar with automotive tools and design processes. It also helps to have students work across disciplines. For example, mechanical engineering students who are familiar with controls will better understand controls systems capabilities and design their systems to take advantage of this.

Beyond the students, fulltime staff can be hired as well. Automotive Technicians, millwrights, welders, or other fabricators can aid in the design and construction of vehicle. Full-time engineers with practical hands on experience can also be beneficial. While there are additional costs associated with fulltime staff, unlike student who graduate frequently, staff can be retained to ensure the vehicle stays operational and is maintained. Due to the high cost of hiring fulltime staff, UWAFT has not done so; however other research groups on the Waterloo campus have done so.

3.8 Knowledge Transfer

As mentioned in the previous section, students turn over frequently. Ensuring their knowledge is transferred over to the next student is critical. This is important given their research vehicles are very different from conventional vehicles and traditional automotive technician can rarely solve these problems without proper documentation or guidance.

Documentation of mechanical design can be achieved by backing-up CAD files to a central server with a RAID hard disk arrangement which ensures data will be retained if a hard drive fails. A form of source control should also be implemented to ensure all students are using the most up-to date CAD models. CAD vendors will offer specialized software to do this; Siemens offers their Team Center application, which works in conjunction with NX [17]. Electrical teams can also back-up their schematics on a central server as well. Controls teams should use software such as Subversion, which allows for comments to be added to code, revision tracking, branching out code, and merging of files. It should be noted Simulink files are difficult to merge because they are not line-based code, but rather graphic in nature. SimDiff and SimMerge are two 3rd party software packages that support source control of Simulink code with merging [18]. UWAFT successfully implemented the central server approached with RAID services, however Team Center has never successfully implemented due to the challenges of setting-up a Team Center server; it requires intimate knowledge of the software package, which the team does not currently have. Subversion is currently used by the team, but not SimDiff or SimMerge, due to the high licensing costs for these software packages. Simulink files are managed by Subversion, however merging and comparing files is still extremely difficult.

Weekly meeting help students communicate the status of the vehicle's construction and highlight the goals for the week. Taking meeting minutes and publishing them via email or central file server allows for student who missed a meeting due to class understand the current status of the project. Preparing presentations for each technical team (mechanical, electrical, controls) can also be a useful method of communicating information and can also be distributed with meeting minutes.

Additional files to consider backing-up onto an FTP or other shared disk drive include:

- International Organization for Standardization (ISO) back-up images of software CDs (eliminating the need for physical CDs) and training packages for software.
- Competition results.
- Data capture from testing and updated HIL/SIL models.
- Logos for the team and sponsors.
- Component documentation (for batteries, motors, gearboxes).
- Conference proceedings, Rules, Regulations, and Photos.
- Design reports, dissertations and presentations.

Chapter 4

Design Phase

4.1 Vehicle Design Process

The vehicle design process (VDP) proposed below is based on a modified version of GM's VDP for EcoCAR 2, as mentioned in Second 2.3.2 EcoCAR 2: Plugging In to the Future. The process should work for any type of vehicle (e.g. Formula SAE, hybrid vehicle, solar car). The following chapters will assume there is one year for each milestone (PIA, VDR, VDC), but the process can be scaled, depending on the size and complexity of the project. For example, Formula SAE cars typically take one to two years to design, build and test.

This chapter will focus on Year 1, the design year. The research group or team will select their design targets and select a feasible powertrain to meet those targets. From there, the mechanical, electrical and controls team will design supporting subsystems to meet the design goals, culminating in the PIA milestone.

4.2 Vehicle Technical Targets and Vehicle Technical Specifications

The design of a vehicle requires a set of vehicle technical targets (VTT). These targets are the wish list for the vehicle's performance or functionality. For example, a 0-60 mph acceleration of 8 seconds is a VTT. An example of a functionality VTT is ambient cabin noise at 100 km/h should be less than 80 dB. The VTT help guide the vehicle design team as well. For example, to achieve the of 0-60 mph acceleration of 8 seconds, a mechanical engineer will select an engine, gearbox, and overall vehicle mass to achieve this goal. Controls engineers will work on calibration to ensure the gearbox shifts will result in the desired 0-60 time.

As a vehicle nears completion, it can undergo a series of tests to establish the resulting vehicle performance. These tests result in the vehicle technical specifications (VTS). If the VTS matches the VTT, the design can be considered successful. Once again returning to the example of the 0-60 mph acceleration, if the resulting acceleration is 6 seconds, the VTT was missed. While a two second reduction in acceleration is great for consumers, it indicates the modeling and simulation process used is untrustworthy. The engine may have been oversized, increasing vehicle cost, fuel consumption and emissions.

4.2.1 University/Group Mandates

In addition to the VTT helping guide the vehicle design, a set of team/group mandates is also very useful for focusing the selection process. These mandates may be guided by the University's expertise in a particular research subject or tied to funding sources. In the case of the University of Waterloo, their expertise in hydrogen fuel cells helped UWAFT select and fund work on two hydrogen fuel cell powertrains. The research areas of interest do not necessarily need to be within mechanical engineering. With the emergence technologies such as adaptive hybrid control and autonomous vehicles, a simpler powertrain would allow for more resources to be devoted to software development, rather than mechanical systems.

4.2.2 Establishing VTTs

There are several steps to establishing the VTT for a vehicle. The first is selecting the important VTTs. For a hybrid research vehicle, fuel consumption and emissions would be critical VTTs, but consumer acceptable elements such as a functional air condition system which cools the vehicle within 5 minutes may not be as important. Conversely for a Formula SAE vehicle, a VTT of lateral grip and linear acceleration are more important than fuel consumption and emissions. Once the targets have been selected the VTT should be ranked by importance. If there are two key decisions which are contradictory to two VTT, the more important VTT should take precedence.

The second step is determining the VTT values. This can be done by a variety of means. Rules and regulations for student competitors is a good starting point. They may dictate fuel consumption and performance targets. Student competitions can also use the results from past competitors to establish VTT. For road-legal vehicle projects, publically available vehicles are a great resource for establishing performance and fuel consumption values. Another option for full sized vehicles VTT is to establish them based on real-world driving habits; the next section will go over this novel concept in great detail.

4.2.3 Real world VTT

UWAFT decided to take a unique approach to selecting the VTT for their EcoCAR 2 vehicle. Using real-world driver data, UWAFT collaborated with FleetCarma. FleetCarma offers a system to fleet managers to help them make better-informed purchase decisions. The process involves installing data logger into fleet vehicles of gasoline powered vehicles for approximately three weeks. This data is then used to determine the total cost of ownership for a proposed alternative vehicle, such as an electric of hybrid vehicle.

FleetCarma provided UWAFT with over 171 000 km worth of driving data. Unfortunately, the data captured was from a range or vehicles, both commercial and private. Ideally the data should be filtered to include private midsized vehicles (closest matching the target consumer). Key metrics from these drive cycles were calculated including: average speed, trip distance, acceleration, power and load requirements, which were ultimately used to establish the VTT. By utilizing this process the team could design a vehicle that matched driving habits by using their own driving schedules. The scope of this section will be to discuss the process used to capture the drive cycles and how to calculate key metrics.

The drive cycles were obtained using FleetCarma's data logging system. The logger was attached to the On-board diagnostics port the vehicles. The vehicles range from commercial vehicles such as delivery vans to passenger vehicles such as Vehicle Speed and time was logged at a 1Hz interval with true time stamp (e.g. Monday, September 12th at 16:43). In total, 136 vehicles are part of UWAFT's real world drive cycle analysis. Each one of these vehicles records a trip. A trip is defined as one key-on-key-off cycle. A vehicle can have hundreds of these trips over three weeks. The 136 vehicles generated 21203 trips. The image below shows the data flow:

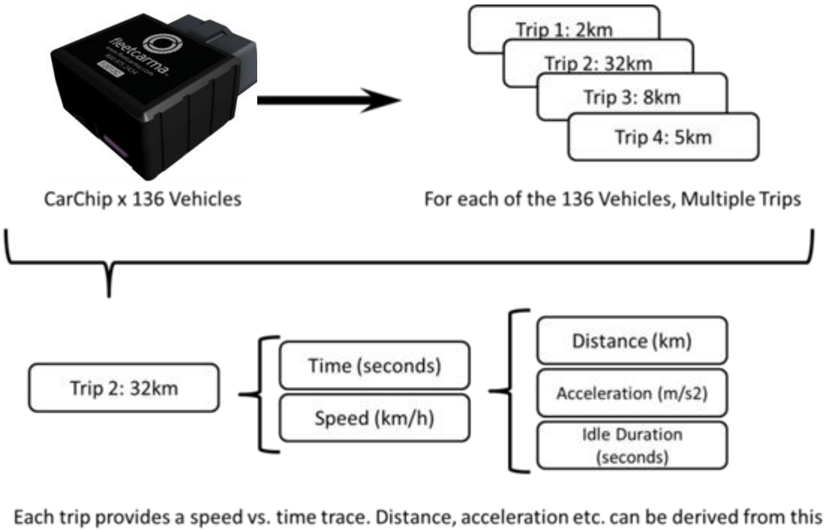

Figure 9 - Process and data capture from real-world vehicles [19]

Using MATLAB, preliminary calculations on the data were performed and summarized in Table 1.

Table 1 - Preliminary Calculations for real world driving data

Values	Result	Unit
Total Driving Distance Captured	171 675	km
Total Driving Duration Captured	205	days
Average Trip Distance	8.1	km
Average Trip Duration	14	minutes
Trip Max Average Speed	60	km/h
Trip Average Speed	26	km/h
Average percent of trip idling	25	Percent
Average Daily Distance Driven	57	km
Average Daily Driving Duration	1.6	hours

The drive cycles were further analyzed for patterns with the daily driving distance, duration and speeds plotted on histograms.

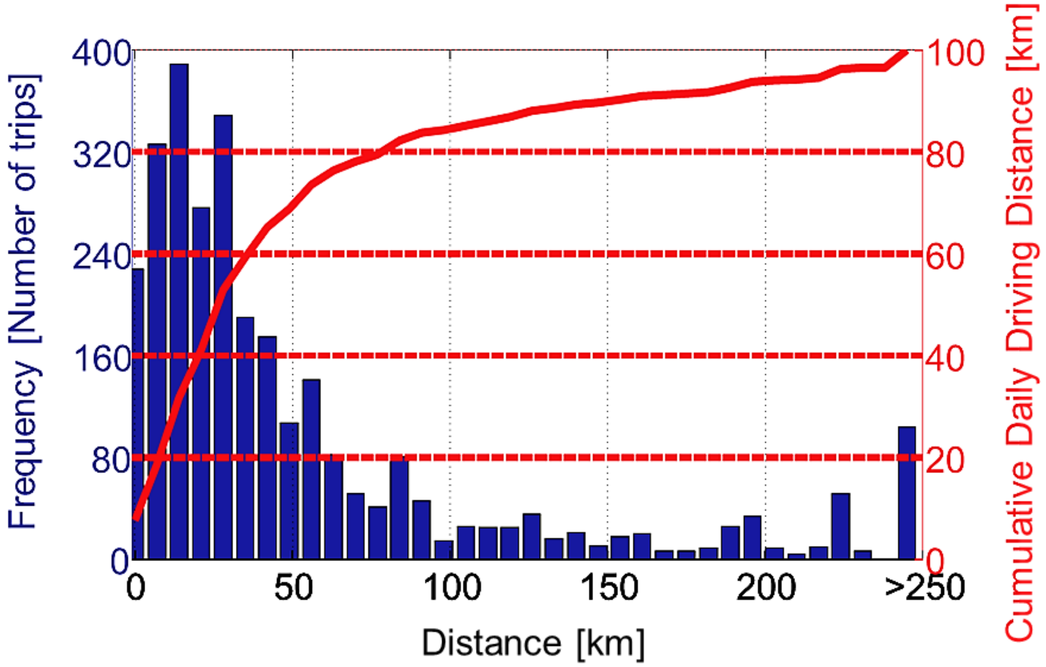

Figure 10 - Daily driving distance (average 57 km)

The average daily driving distance of the population is shown in Figure 10, with 80% of the population driving 70 km or less per a day. This suggests that a battery sized for a 70 km all-electric range (AER) would allow 4 out of 5 drivers to operate their vehicles without the need for a gasoline engine. There is still a small group of drivers who easily travel 100 km or more on their daily drive, requiring either a larger battery or range extending engine. The team used these findings to set the VTT for AER at 70 km or greater and the VTT for a range extender to provide additional range for drivers who require travel greater than 70 km.

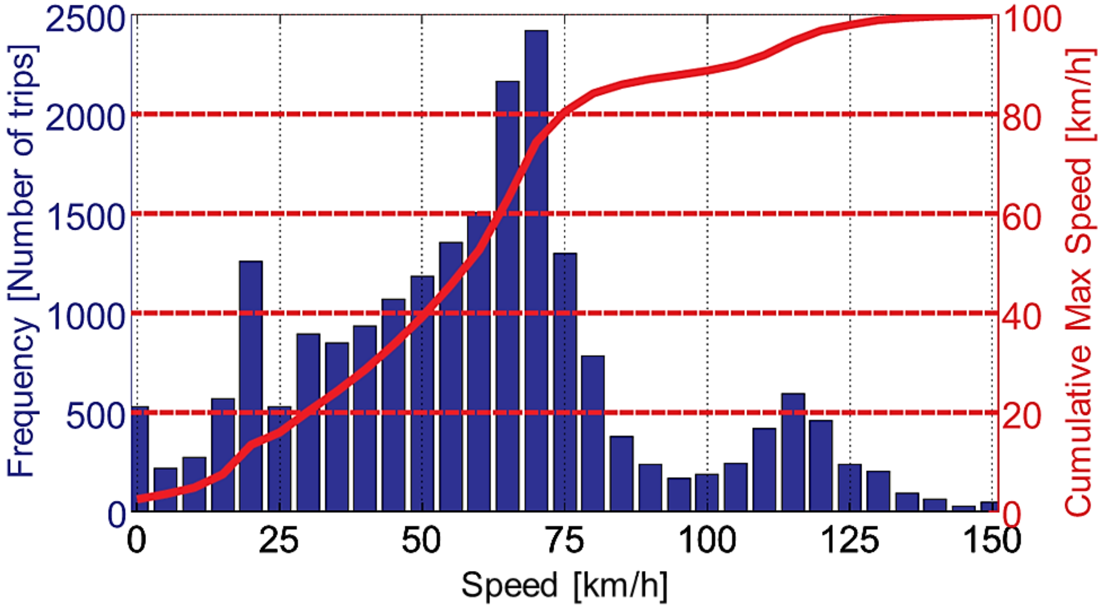

Figure 11 - Top speed of each trip (average 60 km/h)

The next analysis that took place was a review of the top speed of each trip as shown in Figure 11. Almost all the trips achieved a top speed of 150 km/h or less. This established the VTT top speed of 150 km/h and will likely influence the final drive gearing and motor speed. Additional observations on the average speed were done and are in Figure 12. It is interesting to note that a majority of the average speeds were between 10 and 50 km/h, suggesting the same population drove at urban environment speeds. While no direct VTTs were obtained from these data points, it does suggest the traction motors and gearing should be selected to optimize for urban performance.

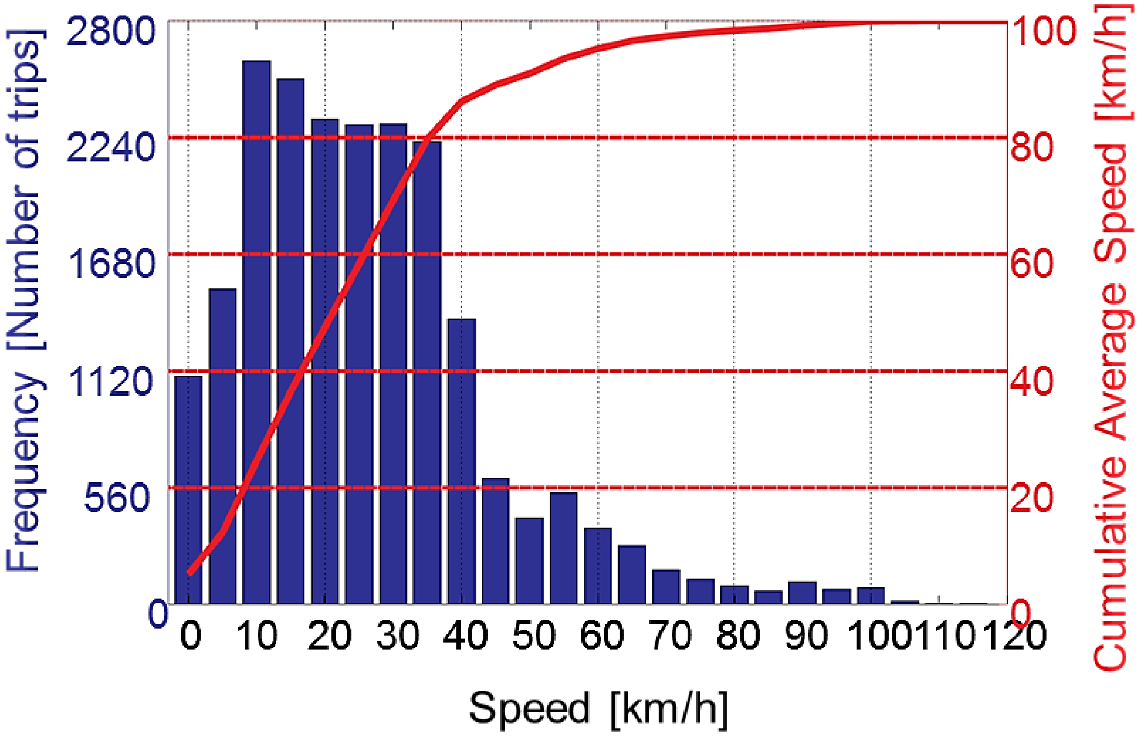

Figure 12 - Average trip speed (overall average 26 km/h)

To establish further VTT, a basic model of the 2013 Malibu was used to calculate road load. The drag, rolling resistance and power required to overcome these resistances were calculated with parameters provided by General Motors (at the time of writing, these values are propriety). These calculations are shown below:

Equation 1 - Force of drag calculation

$$F_{drag} = \frac{C_d \rho v^2 A}{2}$$

Where $\mathrm{C_d}$ the coefficient of drag, ρ for desnity of air (taken as 1.2 $\frac{\mathrm{kg}}{\mathrm{m^3}}$), v is the vehicle velocity and v is the frontal area. The rolling resistance is determined via experimentation for the stock vehicle tires. This calculation is:

Equation 2 - Rolling resistance correlation

$$F_{rolling} = C_{r1} v + C_{r2}$$

Where C_{r1} are the dynamic resistance and C_{r2} the constant resistance. The force applied by the vehicle to overcome the drag and rolling resistance ($\mathrm{F}_{\mathrm{propulsion}}$ or road load) is solved using a force balance:

Equation 3 - Force of propulsion or road load

$$F_{propulsion} = m_{vehicle}\dot{v} + F_{drag} + F_{rolling}$$

The power requirement is calculated by multiplying the road load by the vehicle's velocity as shown below.

Equation 4 - Power required to meet roadload

$$\mathrm{P}_{\mathrm{required}} = \mathrm{F}_{\mathrm{propulsion}}\mathrm{v}$$

Using the above method, the peak and continuous power requirement for each trip was calculated. The results are shown in Figure 13 and Figure 14. Note that the peaks at 200 kW in Figure 13 are likely due to errors in capturing speed from the data logger.

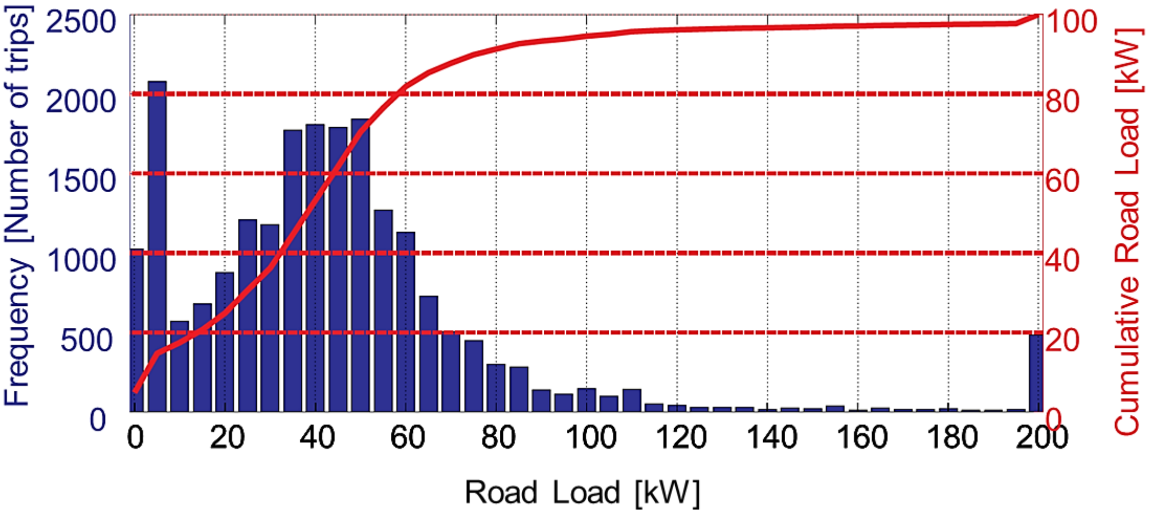

Figure 13 - Peak road load for each trip

Table 2 - Real world drive cycles and EPA standard road loads

Drive Cycle	Mean Road Load (kW)	Positive Mean Road Load (kW)	Maximum Road Load (kW)
HWFET	4.4	8.0	31
US06	5.7	21.5	95
UDDS	0.4	7.0	38
LA92	1.1	11.7	53
Real World	2.5	9.9	180

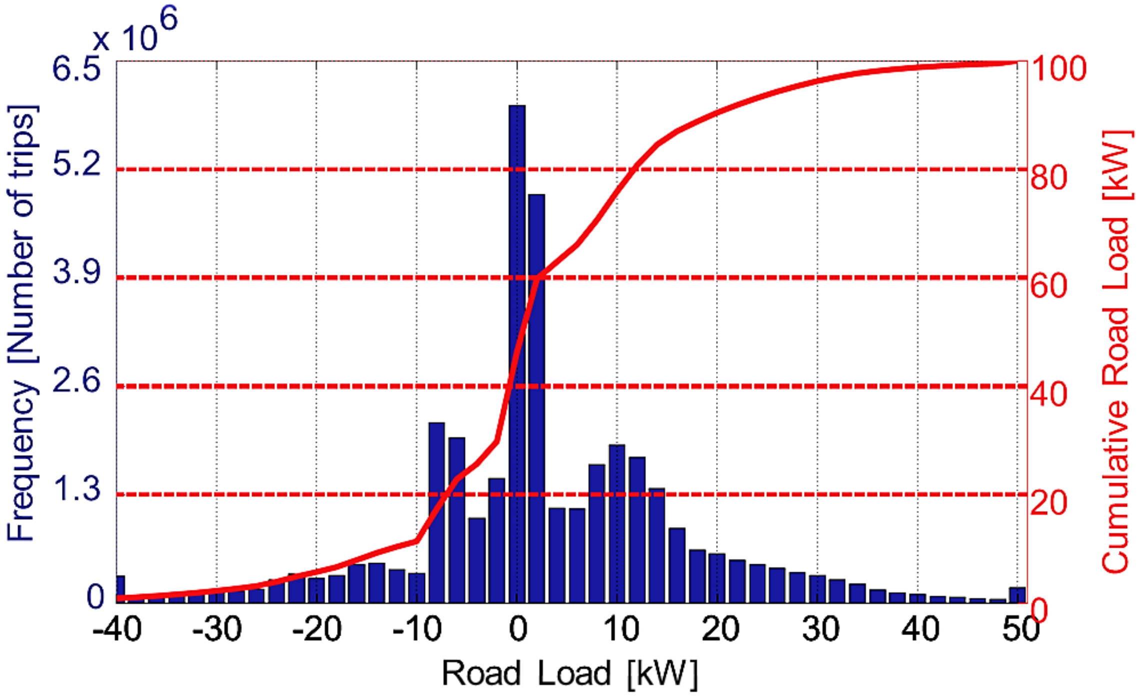

Figure 14 - Continuous power for all data (non-zero, all data points)

Reviewing the peak road loads, it can be seen that a majority of the peak road loads occur between 25 and 80 kW, as shown in Figure 13. There is a small set of trips that use more than 200 kW. Investigations are currently undergoing to understand if these are errors from the data logger its sampling rate. It is safe to assume a powertrain that can deliver up to 120 kW peak will satisfy almost all drivers' peak power requirements; this was used to establish the VTT for peak power of the powertrain. The continuous road load (i.e. all data points) was plotting for both positive and negative road load. Zero road load (i.e. vehicle idle) was removed to better demonstration the powertrain's continuous road-load requirements. This is shown in Figure 14. A powertrain sized to provide a continuous power of 35 kW will be able to meet 95% of driver's needs. The negative road-load gives a good indication of the amount of power that can be captured during regenerative braking. Translating this directly into a VTT for power captured from regenerative braking can be established; a motor and battery capable of capturing approximately 9kW continuous is ideal.

It should be noted that these road load calculations cannot be directly translated to motor power. For example a peak road-load of 120 kW does not necessarily mean a 120 kW motor should be selected. Losses through the powertrain must be factored in.

For reference, the EPA drive cycles were used to calculate the road-load for the 2013 Malibu and are shown in Table 2. The UDDS cycle seems to under represent driver aggressiveness, whereas the US06 and HWFET over represent aggressiveness. The LA92 cycle seems to represent this data population the closest.

4.3 Powertrain Modeling and Selection

4.3.1 Powertrain Model-Based Design Methods

Model based design (MBD) focuses on using a mathematical model and visual method of addressing problems associated with designing complex control, signal process and communication systems. Physics-based models or data captured from various components and programmed into a MBD tool, such as Mathwork's SIMULINLK. The complexity of these models can vary depending on the application. For example, when designing an engine, a complex fluids-based in-cylinder engine model will be used. This model may take several hours to compute one second in real-time and is excellent for viewing fluid flow and combustion characteristics. Conversely, this level of detail is not needed when using an engine model to optimize a hybrid control method. A simple look-up table representing fuel consumption as a function of engine speed and engine torque can be sufficient.

The MBD process begins by defining the plant model. Returning to the example of an engine, data can be captured from an engine dynamometer representing the peak torque, speed and fuel consumption. The input and output (I/O) for the plant model can also be defined. For an engine, the input may be the throttle position; the output may be the oxygen sensor or engine speed. The next step in the MBD process is to define the controller. The controller's I/O will match the plants I/O and some level of control algorithms will be programmed into the controller. For the engine example, the controller may sense the engine's speed and limit it to below 5000 rpm by closing the throttle position. An example of the MBD process is shown in Figure 15.

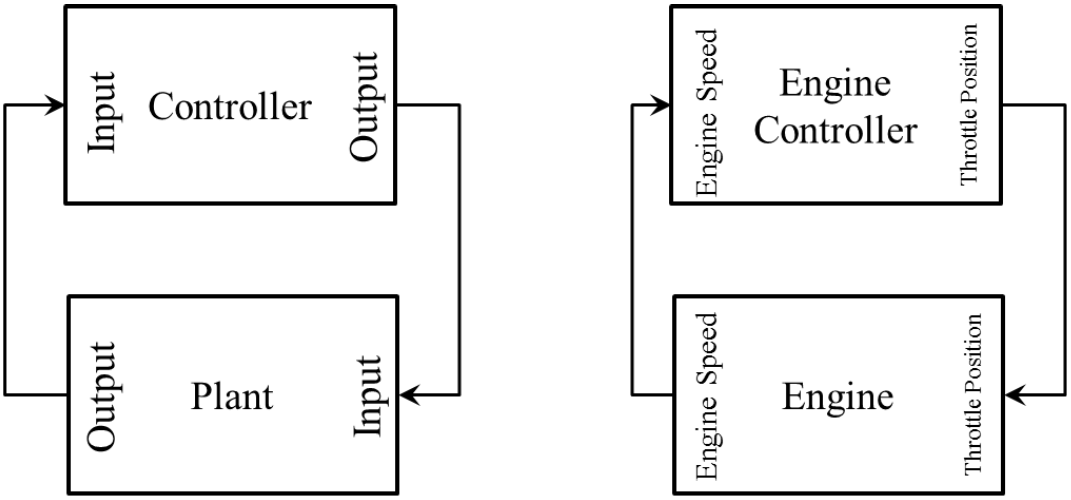

Figure 15 - MBD Process overview with example of an engine MBD

The MBD process can be expanded to include additional models 'in the loop.' In the example above, additional sensor and actuator models can be added to more closely represent real-world conditions. The engine controller's output may be a voltage, which is interpreted as a percentage opened by the throttle body (actuator). The engine's speed can be translated to a PWM signal by the sensor model, which the controller will need to interpret and translate into speed for the control algorithm to handle.

By adding more elements into the loop and better presenting the real-world, the controller code can be made more accurate and reduce problems that may occur as the control code is deployed in the real-world. Loops can also be placed within loops, as shown in Figure 16. This represents how controllers are currently distributed in the vehicle; there are many sub controllers, which communicate with one supervisory controller.

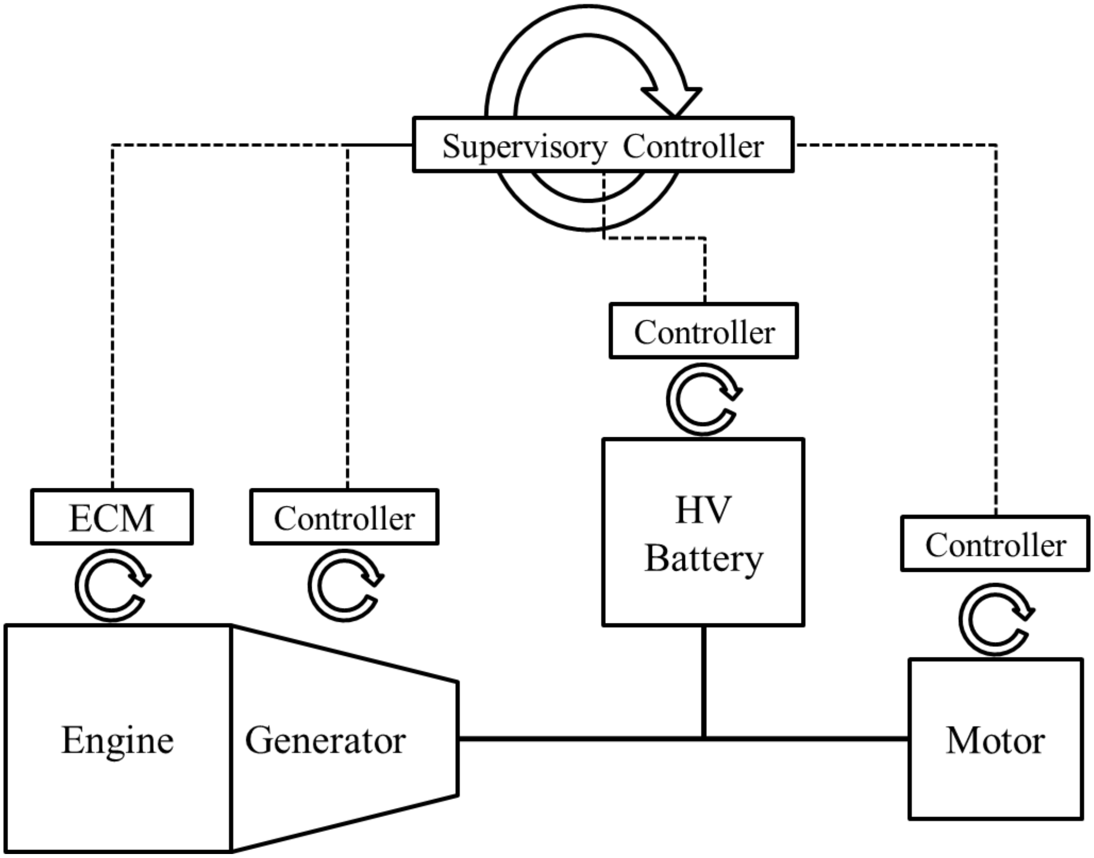

Figure 16 - Example of a vehicle level MBD 'in the loop' configuration [20]

During the controller design process, these loops can be split into different physical devices. This is known as HIL and component-in-the-loop. In the context of powertrain selection, the interest lies in SIL models, which run with relatively simple physics based or look-up-table based models. The goal of utilizing powertrain modeling tools is to select powertrain components using real-world derived data. For hybrid and plug-in vehicles, powertrain modeling also can help select a powertrain architecture as well (series, parallel, split etc.). Within the scope of powertrain modeling there are many types of models, as listed below:

- Energy model: ideally suited for observing efficiency losses and selecting powertrains which result in the best fuel consumption.
- NVH Drivetrain models: these models are used to improve drivability and consumer acceptability by allowing designers to set-up initial calibration and testing different technologies or components.

- HV bus models: used to verify HV components will operate without any issues due to voltage or switching frequency. Can also be used to model HV system bleed-down, fusing and much more.

The energy models are most useful during the initial design of the vehicle and will be the focus of the following sections. NVH models can further help justify components and architectures from a consumer acceptability standpoint. HV bus models can ensure HV systems are safe and compatible with each other. There are several benefits for student to use the MBD process and energy models when it comes to selecting powertrains:

- Student can begin to understand how powertrain components work through the development of the models.
- They can also understand how those devices are controlled by developing the actuator and sensor models; students also learn the limitation of actuators and sensors through this process.
- By varying component specifications, such as engine sizing, vehicle mass and battery energy, students can understand the relationships and tradeoffs between these specifications.
- The entire MBD process also gives the group a higher degree of confidence in their designs.
- Students can explore a large range of design options without worrying about the costs of purchasing components and developing a range of concepts.
- MBD is much safer for students; dangerous situations play out in a virtual environment and can be identified early in the development process.

As mentioned earlier, Simulink is an excellent MBD design tool for powertrain energy modeling. Toolboxes such as SimPowerSystems or Simscape can be used to develop plant models. These plant models will also execute on real-time HIL machines as well, allowing for SIL models to be carried to HIL hardware. Argonne National Laboratory's Autonomie works in conjunction with Simulink by providing a library of models, powertrain architectures and processes. Data provided by suppliers for batteries, motor, and engines can be fed into Autonomie and executed on a drive cycle. The drive cycle can consist of an EPA standard cycle such as the US06 or UDDS, or a 0-60 mph acceleration.

In addition to the provided models in the base software package, the user can generate and use their own models. AVL Cruse also is an industry standard tool, but does not work within the framework of MATLAB, but provides similar models, tools and processes as Autonomie.

While plant models are relative easy to generate, from experience UWAFT team found development of controller models for components the most challenging task. For example, to develop a software model of a battery control unit requires intimate knowledge of the start-up sequencing, charging logic and calculation of its operational envelope as a function of current draw, temperature and state of charge. This information is typically proprietary and difficult to obtain. CAN databases (a detailed list of CAN messages) and liberal assumptions based on past experiences is one option to build a relatively accurate software electronic control unit (ECU). Capture of CAN messages from components while bench testing is another method to reverse engineer the ECU logic. The best option is to ask the supplier for access or information under a non-disclosure agreement, if possible.

4.3.2 Hybrid Powertrain Architectures

Since the launch of the Toyota Prius in 1997, the automotive industry has made major progress in developing, demonstrating and manufacturing mass numbers of hybrid vehicles. By utilizing systems that reduce engine size, introducing electrified systems which allow for engine shut-off and utilizing regenerative braking, fuel consumption has greatly been reduced [21]. Further reductions in fuel consumption have been made by increasing electrical motor power and battery energy, thus allowing for increased periods of engine-off operation. Additional advancements in HEV engine sizing and controls have allowed the ‘second generation’ of HEVs to decrease fuel consumption even further [22]. Further improvements in HEVs are expected to be made by reducing cost and thereby expanding availability. General vehicle advancement such as weight reduction is also expected to improve HEV, PHEV and conventional vehicle performance [23].

There are many configurations for the battery, engine, generator, and motors. Common configurations include series, parallel, series-parallel, among many more. Each configuration combines both mechanical and electrical pathways to allow for energy to be sent to the wheels. Figure 17 shows a series architecture.

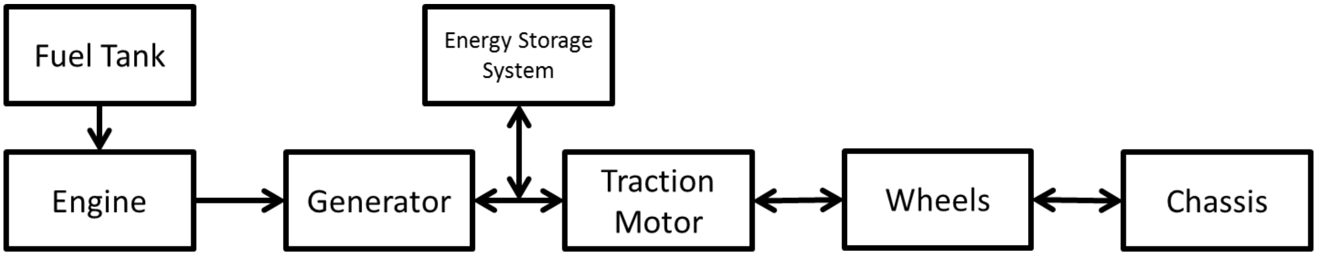

Figure 17 - A series hybrid powerflow

The engine acts as an energy conversion device, converting fuel energy into mechanical energy that is fed into a generator. The generator then converts the mechanical energy into electrical energy which can either be stored in an energy storage system (ESS) for later use, or sent to the wheels via traction motor. If a fuel cell is used, in place of the engine, a high power DC/DC power converter would be used to match the fuel cell voltage to the battery voltage. There are several key advantages to the series configuration. The first is that the engine is not mechanically coupled to the road, thereby allowing the engine to operate at its peak efficiency, regardless of the driver's demand. The second advantage, if the traction motor is powerful enough, is that there is no need for a multi-gear transmission. This greatly reduces complexity, cost and increases drivability. Extra tractive power can also be achieved by connecting a second traction motor to the rear-axle, which also releases the potential of all-wheel drive.

The disadvantage with the series configuration is the double conversion which the energy from the engine must undergo to reach the wheels. The mechanical to electrical and back to mechanical conversion reduces the overall system efficiency. The additional mass of the generator, compared to a single motor parallel configuration, also reduces the system efficiency. A parallel configuration is shown in Figure 18.

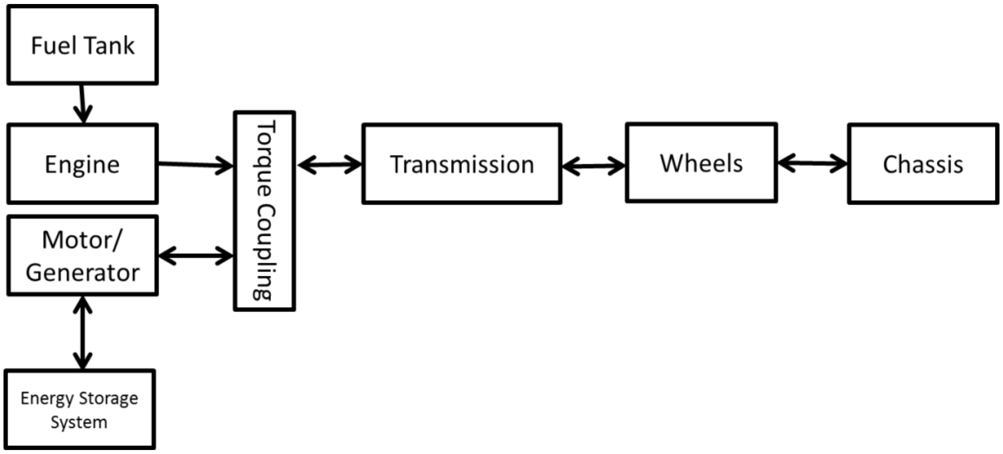

Figure 18 - A generic parallel hybrid configurations

In the parallel configuration, the engine can directly provide power to the wheels via a mechanical connection. The engine is assisted by a motor that is powered by the ESS. The engine and motor are connected to the transmission (which allows for the engine to operate in an acceptable operational region) via a torque coupling. When the engine produces more power than needed to drive the vehicle or during regenerative braking, energy now flows into the energy storage system (ESS) for later use and the motor now acts as a generator. The advantage compared to a series hybrid is a direct mechanical connection, which allows for minimal energy losses between the engine and the wheels. Also, the use of only one motor makes it more compact and light weight. The disadvantage of the parallel system is that because the engine is mechanically coupled to the wheels, the engine operating point cannot be set for the optimal efficiency. Also, the torque couplings can be complicated to design and build.

There are several different variations of the parallel architecture, with the major difference being the location of the motor/generator. Two common parallel architectures are the pre-transmission and post-transmission parallel hybrids, as shown in Figure 19.

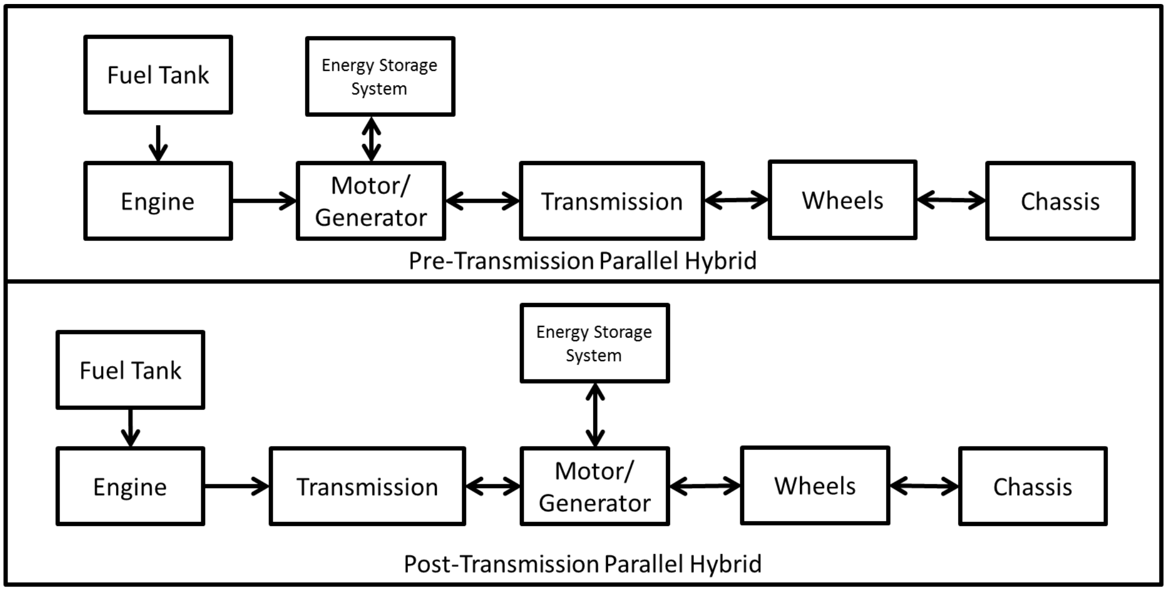

Figure 19 - Parallel configuration; pre-transmission (above) and post-transmission (below)

In both parallel configuration cases shown in Figure 19 it appears that there is no torque coupling; the motor is either sandwiched between the engine and transmission, or the transmission and wheels. In fact the torque coupling is the single shaft where the rotor of the electric motor functions as the torque coupler with a ratio of 1. The advantage to this is a simple construction.

With the pre-transmission set-up, the engine is typically downsized with the motor providing extra assistance. The motor also acts as a starter and a generator. The Honda Civic Hybrid uses the pre-transmission configuration and GM’s belted alternator starter (BAS) system is similar. The post-transmission set-up is typically employed with a large motor, which improves the vehicle’s performance and engine operating efficiency. Note that the battery cannot be charged by the engine with the post-transmission configuration when the vehicle is at a standstill because the motor is directly coupled to the wheels.

A parallel through-the-road architecture is another possible configuration and is shown in Figure 20. The through-the-road character derives from the flow of excess engine power that can be delivered to the energy storage system (ESS) though the chassis by providing excess power to the front wheels in parallel to loading the rear wheels with the motor acting as a generator.

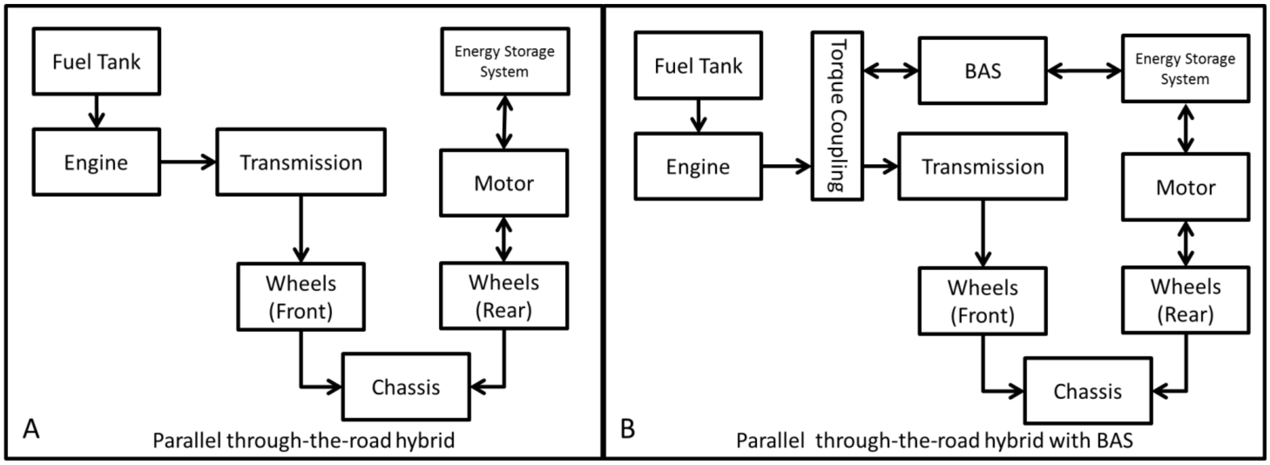

Figure 20 - Parallel through-the-road hybrid with (a) and without a BAS system (b)

In the non-BAS parallel through-the-road configuration (Figure 20 (a)) (the first configuration on the left) the front of the vehicle contains an engine, transmission and connection to the wheels, similar to a conventional vehicle. An electric motor and battery are connected to the rear-axle. The advantage to this system is its simplicity; the disadvantage is that the battery cannot be charged when the vehicle is not moving (similar to the post-transmission parallel). This issue can be solved by adding a BAS type system to the engine, as shown in Figure 20 (b), where an alternator or generator is added.

With all parallel architectures, clutches and planetary gears acting as speed couplings can also be used. While planetary gears can be used to efficiently transfer energy from the engine to the wheels, they are complicated and difficult to build. Off-the-shelf solutions are few and far between. It should be noted that GM’s Two-Mode transmissions and Toyota’s Hybrid Synergy Drive use planetary gear systems with great success.

Additional notes about the components in hybrids:

- The ESS does not necessarily need to be chemical batteries. Hydraulic, flywheel storage systems and ultra-capacitors can be used standalone or in conjunction with chemical batteries.
- Engines can vary in technology and fuel. Turbo charging, direct-injection and variable valve timing can increase the efficiency of engines immensely. Fuels that can be used besides gasoline or diesel fuel include ethanol, hydrogen, diesel, bio-diesel, natural gas and propane.

- Traction motors and generators can vary from permanent magnet to induction structures. Most motors are typically linked to an inverter which takes DC high-voltage and generates three-phase AC power. The inverter varies the phase and amplitude of the AC power to generate the required speed and/or torque.
- Most traction motors and inverters allow for regenerative braking. During braking or coast down, the traction motor acts as a generator and captures energy that would normally be lost as heat via the friction brakes. This is the key energy recovery feature and mileage improvement future for hybrid vehicles.
- Accessories such as HVAC systems and power steering are increasingly becoming powered by electrical systems. They are either fed directly by the high-voltage system or fed via a DC/DC converter which steps-down the voltage to 12 V. Electrical systems tend to be more efficient because their output can be varied according to demand.
- Pure electric vehicles have not been considered primarily due to the high amounts of energy needed to reach the range requirements, and limitations on packaging such copious amounts of energy.   Using a rough calculation, with an energy consumption of 250 Wh/km and a required range of 322 km, 81 kWh of usable battery energy would be needed at a 350 V nominal. The pack would weigh roughly 675 kg. Vehicle components package would be an interesting challenge.

One feature of a HEV is its need to charge sustain the battery within a narrow state of charge range. That is the energy level or charge in the battery after being depleted must be re-charged by the primary energy converter, be it an engine or fuel cell. With advancing battery technology allowing for higher energy-density, the option to use the battery to aid or even replace the primary energy converter is a viable option with re-charging of the battery coming from the electric grid [23]. This concept is known as a plug-in hybrid electric vehicle (PHEV). All of the hybrid architectures discussed above can be implemented as a PHEV, if the motors and generators are sized correctly.

Within the context of a University, some of these architectures are easier to build than others. Based on experience at UWAFT, the pros and cons of each of the architectures are as follows:

- *Series Hybrids:* Series hybrids are relatively easy to construct and control. They require two or more electric motors/generators, which can be purchased from a supplier. A gearbox or transmission to transfer power to the wheels can also be purchased. A simple torque coupling device between the engine and generator can be either purchased or designed and built. Hybrid control is relatively simple even when power is split between the battery and the engine. Control simplicity results from the fact that the engine is not mechanically connected to the wheels enabling all power to the wheels to be controlled through the motor alone. A series all-wheel drive hybrid would serve as an excellent research platform, thanks to its flexibility. The two motors allow for torque splitting strategies to be tested, and the lack of mechanical connection between the engine and generator allow for freedom of engine operation.

- *Pre/Post Transmission Parallel Hybrid:* Mechanically these hybrids are challenging to build. Motors need to be sandwiched between major powertrain components, which can result in packaging issues. Production parts for this relatively unique architecture are difficult to source and purchase. In most cases they would need to be designed in house or by contract. Issues such as lubrication, vibration, fatigue and manufacturing would have to be considered. The control between the motor, engine and gearbox is not difficult, however achieving a calibration between these components that results in smooth operation, can be time consuming.
- *Parallel Through-the-Road Hybrid:* Of all the architectures investigated, this architecture would be the least challenging to construct. The stock engine the stock engine and transmission from front wheel drive vehicles can be retained. A disadvantage is that the battery cannot be charged unless the vehicle is moving; a BAS system can be added to solve this issue. A rear motor would be required; if the vehicle platform is front wheel drive with an available AWD system, this makes the design of rear motor integration easier. The controls systems are relatively simple; however calibration would need to be done to improve drivability.

4.3.3 Emissions Controls

Each fuel requires its own unique emissions control system. Hydrogen can be combusted with air; however it is more efficient to generate electricity via a fuel cell than to combust hydrogen in an internal combustion engine [24]. The three major emissions that are measured with any internal combustion engine are nitrogen oxides (NO_x), total unburned hydrocarbons (THC or HC), and

Carbon Monoxide (CO). Diesel Engines will need to also reduce particulate emissions via a diesel particulate filter.

NO_x emissions are formed by three mechanisms. Thermal NO_x is formed by atmospheric N_2 breaking down and reacting with oxygen at high temperatures, via the Zeldovich Mechanism. The Zeldovich mechanism is a reaction, whereby normally inert N_2 forms NO_x under high temperature conditions with O_2 [25]. Reducing hot and lean combustion can reduce the Zeldovich mechanism in reaction rate in cylinder. NO_x is also formed by the Fenimore mechanism in the reaction zone [25]. Here, CH, C_2H, CH_2 and C_2 react with N_2 to form NO. Via the same mechanism, NO_2 is formed by HCN, CN and HN reacting with each other. Finally NOx can be formed from trace amounts of nitrogen within the fuel reacting during combustion [25].

HCs are typically formed in the cylinder through incomplete reactions. Flame quenching at the cylinder walls stop the chemical reactions and generate HCs. These will build up as a layer on the cylinder wall and will be scrapped by the piston rings. Excess fuel also causes HCs as all the fuel cannot completely oxidize. CO is formed by incomplete combustion caused by excess fuel. During the expansion stroke CO chemistry freezes due to the rapid cooling of combustion reactants during expansion. This prevents the CO from reacting with oxygen to form CO_2. To manage emissions, several methods can be employed. They are listed below [25]:

- Avoiding hot and lean conditions will help reduce NO_x formation.
- Using slightly rich fuel mixtures and adding air to the exhaust to can be used to oxidize CO and the HC. The downside to this is reduced engine performance and higher fuel consumption.
- Operating at near stoichiometric mixtures and using a catalytic converter can be used to do the following:
    - Reduce NO_x to O_2 and N_2;
    - Oxidize CO to CO_2 and O_2; and,
    - Oxidize HC to CO_2 and H_20.
- Exhaust gas recirculation (EGR) can be used to reduce $NO_{x.}$ by reducing in-cylinder temperatures. EGR sends a faction of the exhaust gas back into the cylinder and by acting as an inert agent absorbs heat and reduces cylinder temperature.

Catalytic converters operate at high temperatures, therefore, for the first minute or so emissions are treated incompletely. Electronically heated catalytic converters reduce this time and have been tested with great success; however, high amounts of energy are needed to heat the converter [26].

Diesel engine emissions systems are more complex than spark-ignition systems. Whereas a spark ignition system will have exhaust gas recirculation and a catalytic converter, a diesel emissions system will have these components *plus* a diesel particulate filter (DPF) and a lean burn NO_x reduction system. A diesel particulate filer (DPF) soot captures generated using a porous substrate. All DPF require some form of regeneration to remove accumulated particulate once sufficiently loaded to eliminate substantial backpressure. Regeneration involves either in-cylinder post-injection or downstream exhaust fuel injection to raise temperatures to adequate levels for soot oxidation. Due to the lean operation of diesel engines, NO_x emissions are handled by either a lean-NO_x trap or a selective catalytic reduction (SCR) system. A lean-NO_x trap is made up of zeolite and traps NO and NO_2 molecules, which are then burned off in a manner similar to a DPF. A selective catalytic reduction system typically uses aqueous ammonia, which is converted to ammonia, to break down NO_x with the help of a catalyst. The entire diesel emissions system is complex to package and control (thanks to regeneration). Furthermore, the cost of these systems can be very high [25].

4.3.4 Selecting Powertrains

Using the processes, constraints and design targets discussed above, the final selection of the powertrain and components can be broken down into a flow chart, as shown in Figure 21.

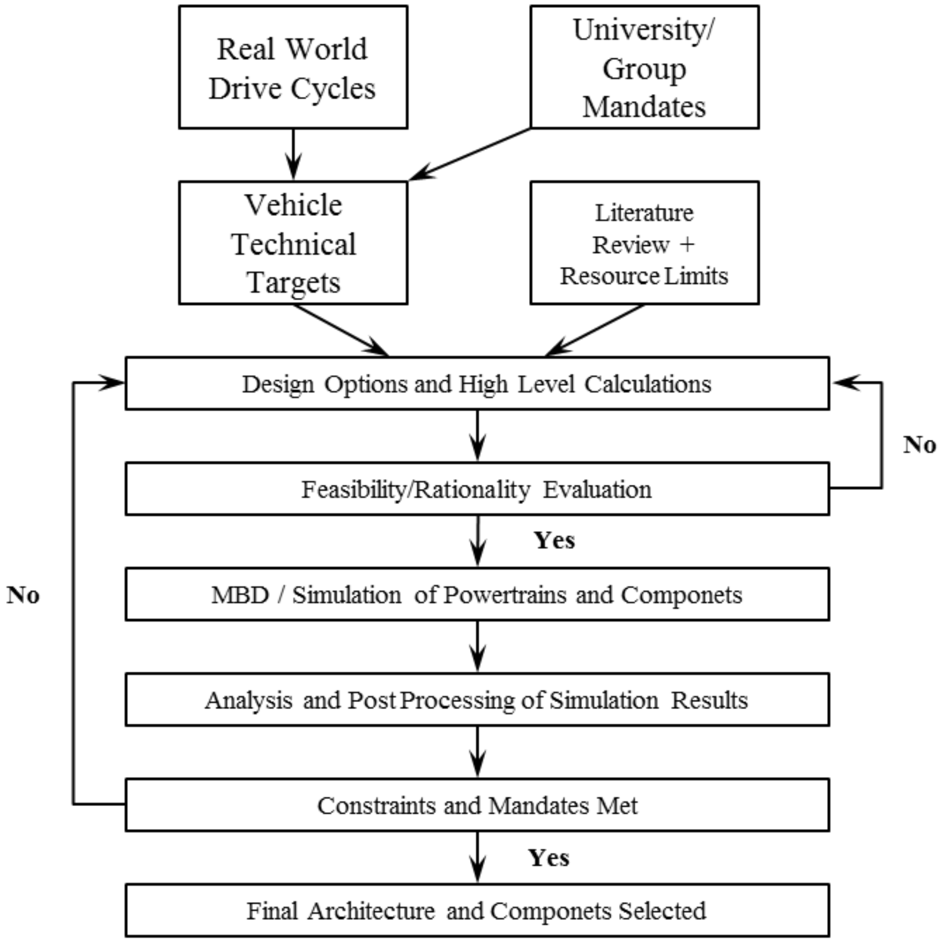

Figure 21 - Flow chart for powertrain selection process

1. *Real world Drive Cycles:* Drive cycles can be capture to understand the behavior of drivers and design a vehicle that meet's real world driving challenges. This was discussed Section 4.2.3.
2. *University/Group Mandates:* These are the research goals of the University of research group undertaking the vehicle's design. This is discussed in great detail in Section 4.2.1
3. *Literature Review:* A literature review will highlight several vehicle architectures, technologies and control strategies. An excellent area of research is emissions control (as discussed in Section 4.3.3), which is difficult to model, and hence a literature review is a good alternative. These are fed into the design options.
4. *Constraints Vehicle Technical Targets:* The VTTs are the desired vehicle performance the research team is looking to achieve. This was discussed in Section 4.2.2.

5. *Design Options/High Level Calculations:* Three architectures should be proposed at this point, to help narrow the design focus and reduce simulation time. Components can still be varied in sized (i.e. engine or battery size).
6. *Rationality/Feasibility Check:* Before powertrain simulations and space claims are started, a rationality check is done. Voltage, power and capacity limits are checked alongside rough volume and weight estimations.
7. *Modeling/Detailed Simulations:* Here vehicles powertrains are simulated in Autonomie or AVL Drive and space claims assessed with CAD Software.
8. *Analysis + Post Processing:* All the data from the prior stage is compiled and processed. A VTS is calculated for the resulting vehicles and compared to the VTT.
9. *Constraints Met:* A team meeting is called and the entire process and results are reviewed. If the vehicle is approved, it will be proposed as the final vehicle to be built for the research team.

4.4 Controls Development

4.4.1 Role of Supervisory Controller

Supervisory control essentially describes a controller running software to manage the various components in a vehicle. In most cases, the control code for component level operation (i.e. motors, batteries or engines) is provided pre-programmed, if purchased commercially. A supervisory controller is tasked with:

- Ensuring the safety of the vehicle, components and occupants.
- Managing start-up, shut-down and operation of components.
- Managing requests from the drive (throttle position, braking and steering).
- Optimizing the operation of various components such as the engine, gearbox, motor and battery.
- Fault management control of components.

The controller hardware is a rapid prototype embedded controller, that executes complied C-Code, which itself can be derived from Simulink with the use of a Simulink to C-Complier. Further details about controller hardware will be provided in Section 4.4.3. It should be noted that depending on the application, supervisory controllers can be repurposed to operate specific components. For example, if a University wanted to build a custom battery pack, a supervisory controller can be repurposed as a battery management controller.

4.4.2 Controls Design Process

There are nine key steps within the V-diagram approach to vehicle controls development. Each of these steps is iterative; information gained from the current step is fed to the previous step. For example, the data gathered the validation phase of vehicle development, is used to validate and improve the models used in the MIL (model-in-the-loop), SIL (software-in-the-loop), HIL and, CIL (component-in-the-loop) steps.

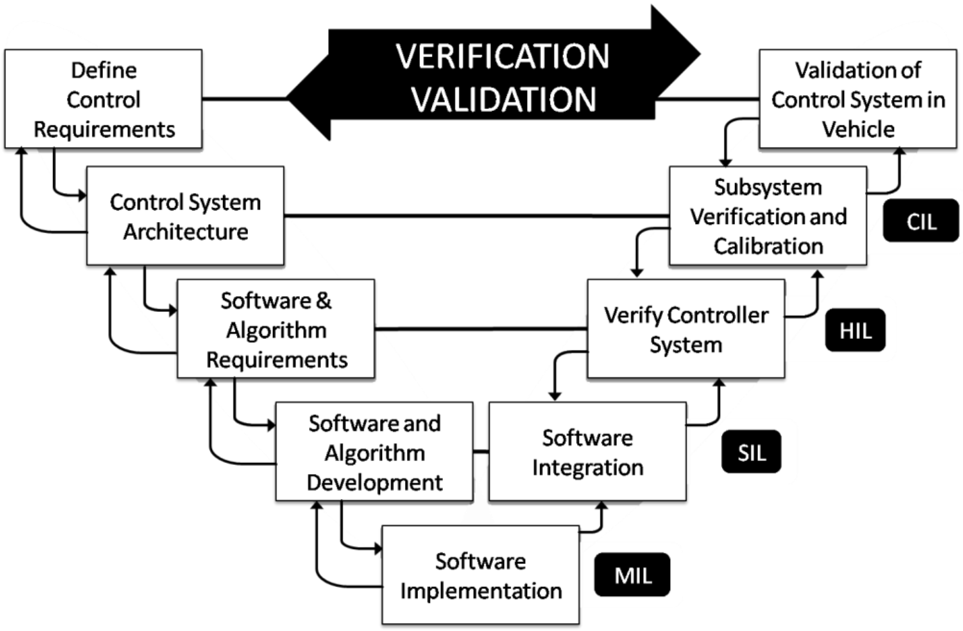

Figure 22 - V-Diagram for Controls Development [27]

Control Requirements: High level control functions are identified during the control requirements phase. For example, the electronic traction system will require a torque request, which is derived from the accelerator pedal, brake pedal and available power. This is also the stage where devices that require control of safety-critical elements such as torque or power are identified.

Control System Architecture: The controls team will review each component and decide what needs control, the interface, required level of safety and mitigation of failure. These areas are identified to meet the control systems requirements. The physical controller communications network is designed before software development begins.

Software and Algorithm Development: Software development attempts to achieve the software requirements at an algorithm level. Pseudo code is used to design high level control and safety algorithms. For example, the torque security between the accelerator pedal and the supervisory controller is designed at this stage. The safety algorithm is driven by the design failure mode and effects analysis (DFMEA), which is continuously updated as more information about the system is gained.

Software Implementation (Model in the Loop – MIL): Autonomie or AVL Drive provides predefined plant models and basic hybrid control strategies, written in MATLAB and SIMULINK, that users are allowed to modify to suit a particular application. Autonomie models do not include any safety or custom hybrid algorithms, as defined in the previous step. The next step, Software Integration, addresses this issue.

Software Integration (Software in the loop – SIL): The next stage of control strategy development is the transition from Autonomie development to SIL testing. Here, the Autonomie models serve as a basis for the SIL and the Autonomie graphic user interface (GUI). The safety and hybrid algorithms mentioned earlier are implemented and tested at this step. The I/O between components is reprogramed to mimic the vehicle with data provided by suppliers. The powertrain controller, actuators, sensors, driver, and vehicle plant models will be kept as separate blocks to ease the transition to controller and component verification. The SIL model is initially executed on a PC at clock speed, and then the entire model (controller and plant) is executed on the HIL. This allows for any compiling issues to be identified before moving on to the HIL.

Verify Control System (Hardware in the loop – HIL): HIL testing separates the vehicle controller (i.e., the hardware) and the plant models (i.e., the powertrain simulator) and connects them by a wiring harness that can be used in the vehicle. The vehicle controller sends actuation signals to the simulator and the simulator provides feedback signals to the controller based on powertrain model response. It allows testing of control algorithms and controls hardware without requiring a prototype vehicle. HIL can lead to a safer prototype vehicle, for example, with early identification of communication problems or unsafe torque requests that would otherwise not be identified until vehicle deployment.

Subsystem Verification and Calibration (Component in the Loop - CIL)*:* Component in the loop replaces the plant models running on the simulator with the actual component hardware. CIL allows for more accurate simulations and increased confidence, since uncertainty of the plant model is removed from the simulation.

Validation of Control System in Vehicle: Initial control system calibration can begin at the HIL testing stage. Once the control system is implemented at a vehicle level the calibration parameters can be tweaked to meet the required output. Data captured from this step feeds back to earlier steps via validation of plant models. Errors or faults discovered here are added to the HIL test portfolio and replicated until a solution is found. This is done to eliminating the risk of damaging the prototype vehicle.

4.4.3 Selecting Controller Hardware

Controller hardware should be able to communicate with various components of a vehicle. Most automotive components use a controller area network (CAN). CAN communication requests to components can be sent; for example, a battery can be requested to close contactors and begin to provide current. CAN can also be used to receive information for the supervisory controller. Typically battery controllers will broadcast (send) messages related to battery voltage, current and temperature.

Besides the requirement for the controller to receive CAN communications, the controller I/O should also include analog and digital I/O. The driver’ throttle/braking requests are typically sent via analog input. Analog outputs are useful for switching relays for pumps, and waking up various controllers. Digital inputs can be used to sense PWM signals from wheel speed sensors. The number of CAN channels and analog/digital I/O is dependent on the application, through the controller code design process and review of the requirements from components should help dictate the number of I/O channels needed.

To simplify the workflow process, a controller compatible and supported by Mathwork’s xPC Target solutions should be selected. It allows for control code developed in SIMULINK/MATLAB to be directly complied onto supporting 3rd party controllers [28] [29]. SIMULINK/MATLAB is typically used during the powertrain selection process, where preliminary supervisory control code is developed and can be transferred to real-time hardware.

An additional consideration is the processing power needed. If a real-time optimization will be deployed, a controller with a high amount of memory and processing speed would be best suited. If a rule-based or logic control system will be deployed, a simpler lower cost controller can be used.

An example of the control hardware selection process is shown below for the UWAFT EcoCAR 2 vehicle (refer to Figure 7 for an overview of the vehicle architecture). The key components of the E85 Four-Wheel Drive Series E-REV that require control and level of control are listed in Table 3.

Table 3 - Components which require control and level of control

Component	Interface	Level Of Control	
		Input	Output
GM LE9 Engine	CAN and Analog Pedal Input	Torque via analog input	Resulting torque, speed and thermal status via GMLAN
TM4 Motors x 3	CAN Enabled	Speed (generator) and Torque (2 traction motors)	speed, power consumption and resulting torque
GKN Gearbox	CAN Enabled	Parking Pawl lock request	Parking pawl status and error
A123 ESS	CAN Enabled	Close contactor requests and charging	Peak charge and discharge current, voltage and temperature requests.
Brusa NL513	CAN Enabled	A123 ESS Controlled	A123 ESS Controlled
Freescale HMI	CAN Enabled	User commands	Critical vehicle information
GM 12V DC-DC	CAN Enabled	Voltage Output*	Resulting voltage output, power consumption*
GM AC Compressor	CAN Enabled	On/Off*	On/Off status*

*Assumed Commands

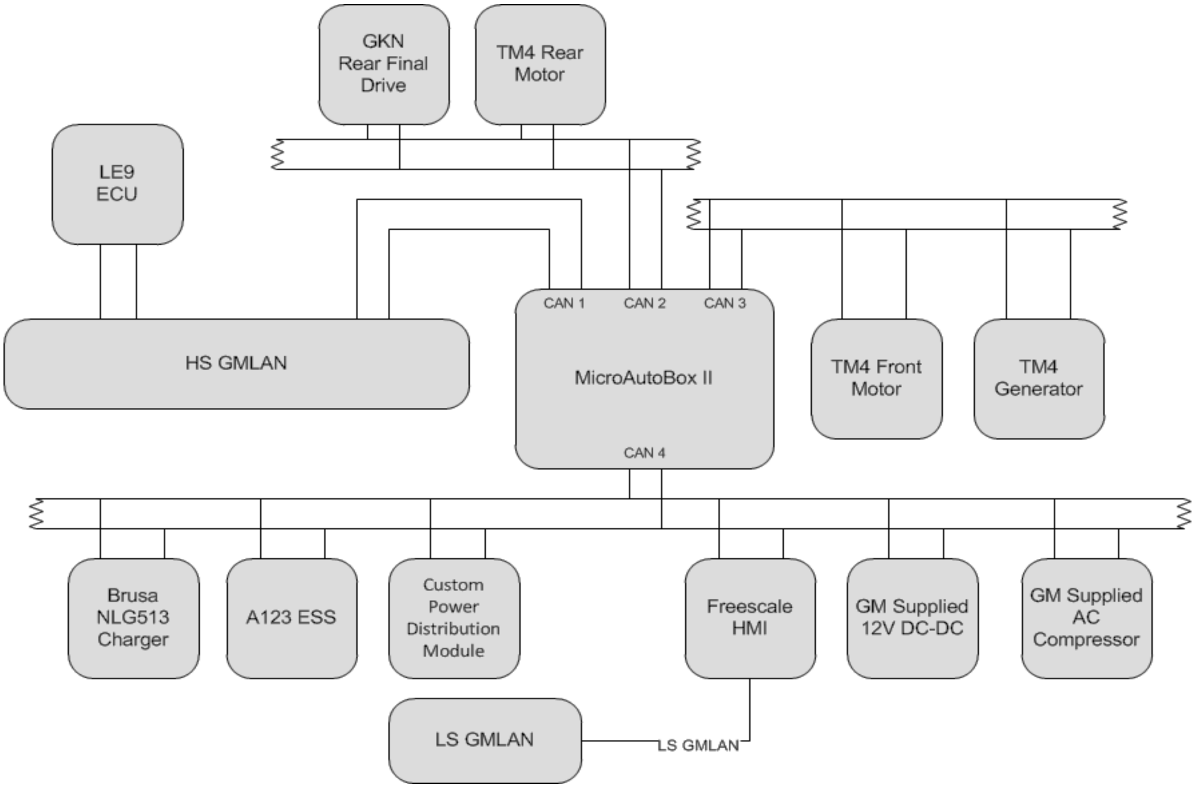

Figure 23 - UWAFT EcoCAR 2 CAN Architecture

With Table 4, the requirements for I/O are established. For almost all components, UWAFT did not have to manage the low level control. For example, the spark timing and injector are handled by the engine controller. The same applies for both motors; the IGBT control is handled by the inverter. Non CAN-enabled devices that require control include fans, pumps, sensors and competition required switches. With this information, the overall CAN bus structure is shown in Figure 23. UWAFT selected a dSPACE MicroAutoBox II (MABxII) controller for its supervisory controller. It monitored torque/power security, handled fault mitigation, and operated the hybrid control strategy. The team has a very strong background in using dSPACE controllers and software for the EcoCAR 1 competition. This, combined with the fact that the team is using a dSPACE HIL Simulator which uses the same software environment as the MABxII, makes the MABxII a much better controller to work with and train students.

The I/O for the MABxII meets most of our requirements as shown in Table 4. Unfortunately, due to current limits, there are several components which the MABxII is unable to actuate; for example, an automotive relay. To facilitate the actuation of low voltage components such as pumps and fans, the team built a custom power distribution module. This device will communicate on CAN with the MABxII and will complete the team's I/O requirements. An alternative commercial product is New Eagle's MPDM-NE1 which provides similar functionality.

Table 4 – Sample required I/O compared to MABxII controllers capabilities

Controller	Role in Vehicle	I/O	Available	Required
dSpace MABxII	Supervisory Controller	Ethernet	1	1
		CAN 2.0	4	4
		Analog Inputs	16	6
		Analog Outputs	8	2
		Digital Inputs	40	4
		Digital Outputs	40	2
Custom Power Distribution Module	Low voltage actuation (fans, pumps, etc…)	High Current Capable Digital Outputs	16	4
		CAN 2.0	1	1
New Eagle MPDM-NE1 (Optional)	Same as above	High Current Capable Digital Outputs	8	4
		CAN 2.0	1	1
Human Machine Interface (HMI)	Reports operational state and LS CAN gateway	CAN 2.0	1	1
		Low Speed CAN	1	1

Communication with the vehicle powertrain is primarily handled via CAN. The fuel system communication occurs primarily through the ECU on the engine. The fuel level sensor, however, is connected to the MABxII as an analogue input. Engine control is to be done by mimicking the pedal inputs using the MABxII and using a basic PID controller to operate at the intended speed/torque.

Five CAN busses are used to communicate with the powertrain. A summary of the CAN busses is given in Table 5. A graphical representation is provided in Figure 23.

Table 5 - Summary of CAN busses and components

CAN Bus	Components
1	MABxII, Engine Control Unit, Body Control Module
2	MABxII, Rear Final Drive, Rear Motor, HMI
3	MABxII, Front Motor, Genset
4	MABxII, Battery Controller, Battery Charger, 12 V DC/DC, HVAC, Custom Power Distribution Module /New Eagle MPDM-NE1, Freescale HMI
5	HMI, LS GMLAN

The MABxII is on all four High Speed CAN busses which allows it to control each of the components and mimicking missing messages from controllers that have been removed Mimicking messages is the process of broadcasting messages to replace messages that are missing, primarily due to a component being removed... CAN 1 is reserved for GM's HS GMLAN bus. This ensures that CAN message conflicts and bus loading caused by new components will be kept to a minimum. CAN 2 is used for controlling the rear motor. CAN 3 is dedicated to the front motor and generator. The rear motor is separated from this bus in order to allow for a limp home mode if for some reason CAN communication on one of the busses is lost. CAN 4 is used for battery related communication and low voltage hardware. CAN 5 is dedicated to interfacing with the LS GMLAN bus using the UWAFT custom HMI; it is not connected to the MABxII.

The Medium Speed Dual Wire CAN bus and the Chassis Expansion bus (GM standard CAN channels) are retained as provided since changes to these busses are not required to control the vehicle powertrain. The Powertrain Expansion Bus along with its components has been removed. Signals from these components to other components on the High Speed GM CAN Network (HS GMLAN) bus was mimicked by the team's software control system to ensure components that are removed (such as the gearbox) do not cause errors between components. For example, the engine still operates without real CAN messages from the gearbox.

4.4.4 Hybrid Control Strategy

There are many methods of managing energy between the battery and engine. The key to all methods is to reduce fuel consumption, respect the operational envelopes of the components, manage emissions, and maintain an acceptable state of charge for the battery, and satisfy consumer drivability expectations. A PHEV has two operational modes. The first is Charge-depleting (CD) mode where the state of charge (SOC) of the battery will fluctuate, but on average decreases while driving. The second is charge-sustaining (CS) mode, where the battery's SOC still fluctuates, however overtime an average SOC is maintained on-average within a narrow range [30]. Figure 24 highlights these two operational modes.

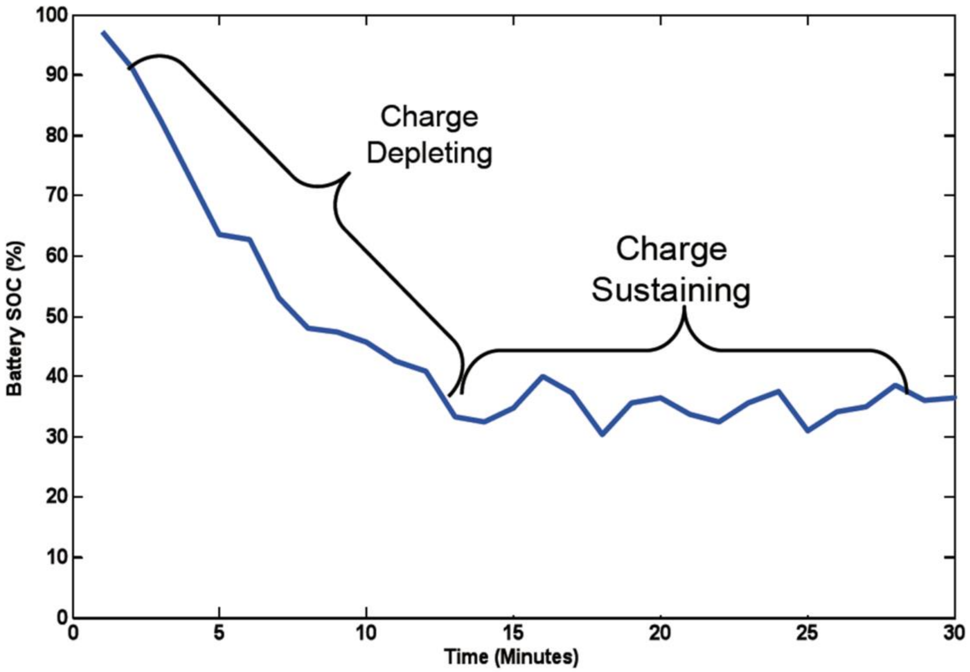

Figure 24 - Charge depleting (CD) and charge sustaining (CS) operation for battery SOC

For a PHEV's charge depleting operation, there are two operational strategies. The first is to use a blended strategy, where the engine is used to supplement the battery/motor power. From a cost and local emissions perspective it is generally best to power a PHEV on battery stored energy as much as possible. From an energy source perspective global emissions often also favor using as much battery power as possible. The downfall of this strategy, however, is that, at the end of a trip, there may be some unused battery energy that could have been used. The second strategy is full deplete operation, where the battery is used quickly as possible during charge depleting (CD) operation, thereby offsetting the use of fuel. This method helps ensure the battery is depleted, and the greatest pump-to-wheel (PTW) fossil fuel is displaced.

During charge sustaining operation, the key is to operate all components in an efficient manner and maintain SOC. There are many methods to do this:

- *Max SOC:* Maintain a high SOC to ensure the battery is capable of providing energy for frequent acceleration. This is not as effective for PHEVs with large battery capacity.
- *Engine On-Off (thermostat):* The engine is turned on and operates at the optimal efficiency. It charges the battery to a set SOC and then turns off, after which the vehicle is propelled

solely by the battery and motor. This works well with the series architecture where the motor is sized to drive the vehicle over the full operating range.

- *Fuzzy Logic:* A fuzzy logic approach considers the state of parameters that are partially true rather than only considering the state of parameters to be true or false. The example below illustrates this for battery SOC. In this example, each SOC value is given a degree of membership. For example, at 55% SOC the degree of membership between "low" and "too low" state of charge is 0.5 for both. Based on this, a control decision can be made to charge the battery. The advantage of fuzzy logic controllers is the ability to easily describe situations where there is some ambiguity or no right or wrong. The disadvantage is that the optimal solution will only arise if the designer considers all possible situations and optimally draws power from the fuel cell and battery for each given instance [31].

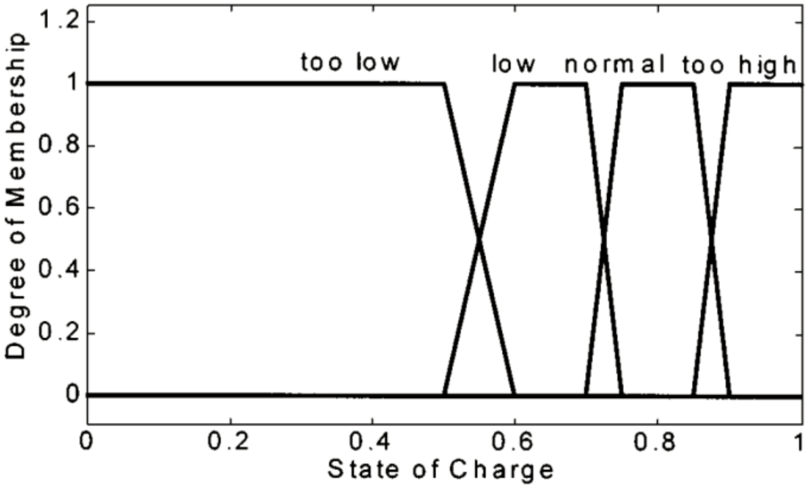

Figure 25 - An example of fuzzy logic applied to battery SOC [31]

- *Global Optimization Using Dynamic Programming:* Knowing the drive cycle, dynamic programming can be used to find an optimum engine/battery split control strategy for CD, CS, or blended operation. The optimum is defined by minimizing a cost function which for a PHEV could be fuel consumption, energy consumption, emissions, or even EcoCAR 2 competition points. There are two main drawbacks, however, to dynamic programming. The first is that the drive cycle needs to be known ahead of time to achieve a truly global solution. This fact does not allow for in-situ use because the drive cycle is not known prior to or during vehicle operation. The second issue relates to computational time. Dynamic programming can take several hours to solve [32].

4.4.5 Safety Control Code Development and Integration

Safe control of the vehicle, passenger, by standards and components is critical. The process to design safety control code begins with a DFMEA for each component, the interaction between components and the entire vehicle. The DFMEA takes place before the actual code is written, and it's updated through the vehicle design and construction process. The focus is on identifying problems early and designing them out of the system (if possible). DFMEA can also be used to evaluate different powertrains, i.e. a powertrain which has less DFMEAs or DFMEAs that can easily be 'designed out' would be a good choice. An example of a DFMEA is shown in Table 6. The SEV (Severity), OCC (Occurrence) and DET (Detection) columns are multiplied together to get the Risk Priority Number (RPN). The SEV, OCC and DET numbers are ranked out of 10 based on the criteria stated in Table 7.

Unfortunately listing and ranking the DFMEA is based primarily on experience. If the research group has built several vehicles in the past, inviting alumni to participate in the DFMEA process is good practice. Industry experts can also be brought in to help. New schools may find this process difficult and should consider erring on the side of caution and listing as many DFMEA items as they can.

Table 6 - DFMEA Example [33]

#	Item/ Function	Potential Failure Mode	Effect of Failure	SEV	Potential Cause of Failure	OCC	Current Design Controls	DET	RPN	Recommended Action
1	Battery System	Loss of communication with battery	Loss of high voltage power	8	Loss of CAN; loose wires	2	All wires protected by loom, proper connectors used. BCM will close contacts when heat beat is lost	2	32	Vehicle should follow a controlled shut down
2	Battery System	Loss of communication with battery	Loss of high voltage power	8	Loss of 12 V power to BCM	2	BCM will open contacts; no intervention needed	2	32	Vehicle should follow a controlled shut down
3	Generator	Broken coupling	Not proving desired power	8	Loss of battery charging	5	Belt and pulley designed to meet power requirements	2	80	Ensure belt is kept maintained; detect failure mode by monitoring engine speed and comparing to generator speed.

Table 7 - Severity, Occurrence and detection ranking criteria ranking table [33]

Severity		
#	**Criteria**	**Category**
10-9	Government noncompliance or death	Regulatory Compliance
8-7	Total or partial loss of primary function	Primary Function
6-5	Total or partial loss of secondary function	Secondary Function
4-3	Appearance or audible noise noticeable to most customers	Annoyance
2-1	Appearance or audible noise noticeable to some customers	Minor Annoyance

Occurrence		
#	**Probability of Failure**	**Criteria**
10-9	Very high, new design with no history	1 in 20 to 10 likely of failure
8-7	Failure is uncertain	1 in 50
6-5	Frequent failures with similar designs	1 in 2000
4-3	Isolated failures with similar designs	1 in one hundred thousand
2-1	No observed failures with similar designs	1 in 1 million

Detection		
#	**Detection**	**Likelihood of detection**
10-9	No method of detection	Cannot detect or currently not analyzed
8-7	Difficult to detect	Failure not correlated to modeling (FEA, models)
6-5	Detectable prior to launch	Failure can be induced via on-road testing
4-3	Detectable during design	Failure can be found during subsystem build
2-1	Detection during preliminary design	Failure can be found by FEA, or other models

Another method of detecting failure modes is a fault tree analysis (FTA). It is a top down approach to analysis starting with an undesirable event and drilling down into all the possible events that can lead to the undesirable event occurring. It provides a documentable and logical framework that looks beyond single point causes of failure (like a DFMEA) and into multiple causes. FTAs can also be performed with *function* in early system design stages, rather than DFMEA which needs well defined *components*. For example, an FTA can begin with an undesirable event, such as the vehicle not starting. This can be defined early in the vehicle's design, regardless of the components involved in the vehicle starting process. All possible causes can be analyzed; loss of 12 V, driver doesn't engage the brake, engine immobilizer does not disengage. Conversely with a DFMEA the vehicle's design would have to precede forward before the failure modes of 12 V power losses and engine immobilizer can be identified. FTAs are also graphical, and can make complex, multiple failure modes easer to follow. An example of an FTA is shown in Figure 26; note that not is a complete FTA and is only being used as an example.

At the top of FTA is the failure to be investigated. Below are events leading to the failures that are triggered by conditions. Some conditions occur under an OR clause; if any of the events occur, they will trigger the failure. Other conditions fall under an AND clause; several events must be true to trigger the failure. The example from Figure 26 illustrates how one failure can have many causes and conditions; in this case 13 possible events can lead to one failure. Steps can be taken to ensure that the base event does not occur, or if the event does occur, it can easily be tracked for repair. It should be noted that, like DFMEAs, FTAs depend on groups who have had experience working with vehicles. Bringing back alumni or industry professionals to aid in constructing an FTA is good practice.

The DFMEA and FTA will drive the development of the safety algorithm. For each line item within the DFMEA or each branch of the FTA the fault can attempted to be 'designed out' or code can be added to handle the fault and ensure it does not affect the vehicle's performance. DFMEAs and FTAs make work distribution easer as well; students can be assigned several lines on the DFMEA or an FTA for a particular failure. The DFMEA and FTA will also help generate test cases for the HIL, to ensure each of the faults is automatically tested for every new code release.

The location of the control code in the overall structure of the supervisor's control code is entirely up to the designer. UWAFT deployed its safety control code as shown in Figure 27. The safety code is located in three areas: (i) diagnostics, (ii) component interaction control and (iii) component control. The diagnostics check all messages received from components for any new faults and handle them accordingly. The component interaction control acts as a rationality check for interaction between components. For example, if the motors are requesting torque (and thereby electrical current) from the battery, the current draw should not exceed the battery's limit. If it is exceeded, the torque request to the motors will be limited. Another example is the interaction between the rear and front motors; the torque should be split between both front and rear motors at a reasonable split. The final safety control is the component level control, which ensures that the requests sent to individual components are valid. For example the, generator's speed doesn't exceed operational limits.

To ensure all of the safety control code works correctly, HIL tested is used. This will be discussed in the next section.

4.4.6 HIL Development

As discussed in Section 4.4.2, the HIL allows for the control code to be tested on real-time control hardware. Figure 28 shows how the code is split and tested. The code is ported to a physical controller which will later be used on the vehicle. Code is added to translate the control code algorithm's requests into requests that can be sent on physical mediums such as analog, digital, CAN or RS232 signals. On the HIL side, a plant model representing the actuator is added. It will interpret the physical signal into a value the plant model can understand and act upon. The sensor model on the HIL side will then generate electrical signals or digital messages which will be sent to the controller by the wiring harness. The controller side will then translate the electrical signals into code the control algorithm can understand.

Challenges that exist when first migrating from an SIL or MIL framework to an HIL system include ensuring the control code operates in a real-time environment. Compilers will typically catch any code that will not operate in real-time, allowing for the programmer to correct the issue. Other issues that arise include selecting the correct software-to-hardware blocks and settings within Simulink (i.e. if an xPC Target compatible HIL is used). The final and most challenging task is deciding what level of detail the plant, actuator and sensor models should have. Generally speaking the HIL models and harness should represent the vehicle to the point where the controller can be removed from the HIL and placed on the vehicle without any modification of the controller's code. This may take some time to develop. As the vehicle is driven and characteristics of the plant, actuator and sensors are better understood, the HIL code should be updated.

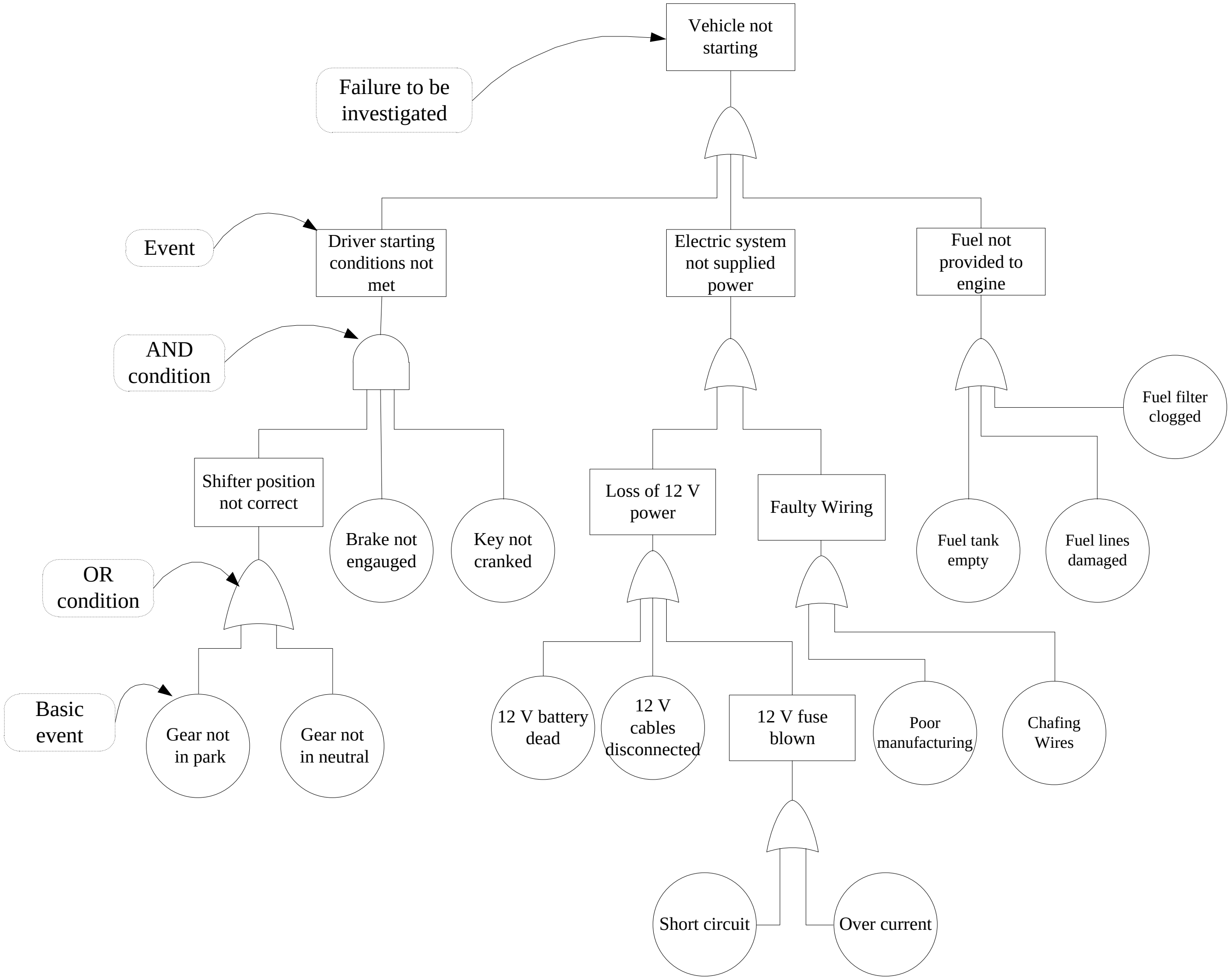
Failure to be investigated
Vehicle not starting
Event
Driver starting conditions not met
Electric system not supplied power
Fuel not provided to engine
AND condition
Shifter position not correct
Brake not engauged
Key not cranked
OR condition
Basic event
Gear not in park
Gear not in neutral
Loss of 12 V power
Faulty Wiring
12 V battery dead
12 V cables disconnected
12 V fuse blown
Poor manufacturing
Chafing Wires
Short circuit
Over current
Fuel filter clogged
Fuel tank empty
Fuel lines damaged

Figure 26 - Sample FTA for vehicle not starting

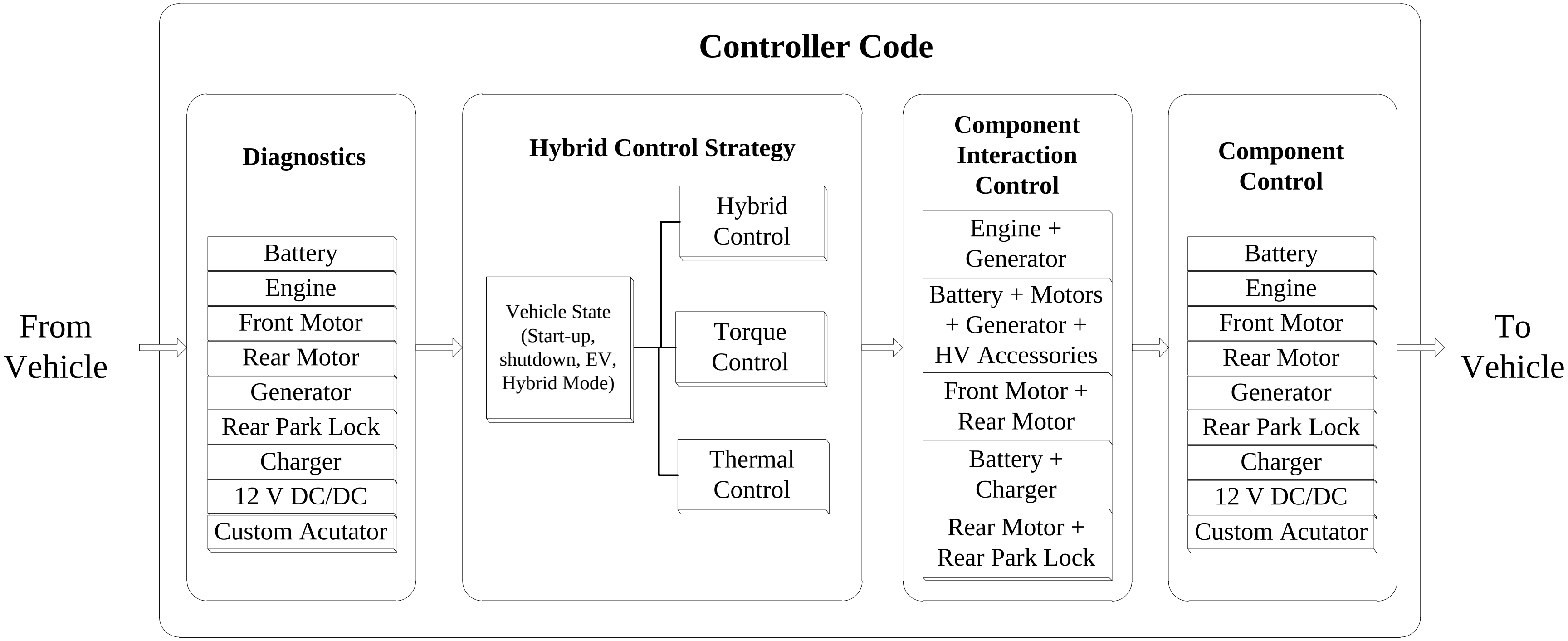

Figure 27 - UWAFT EcoCAR 2 vehicle control code layout [34]

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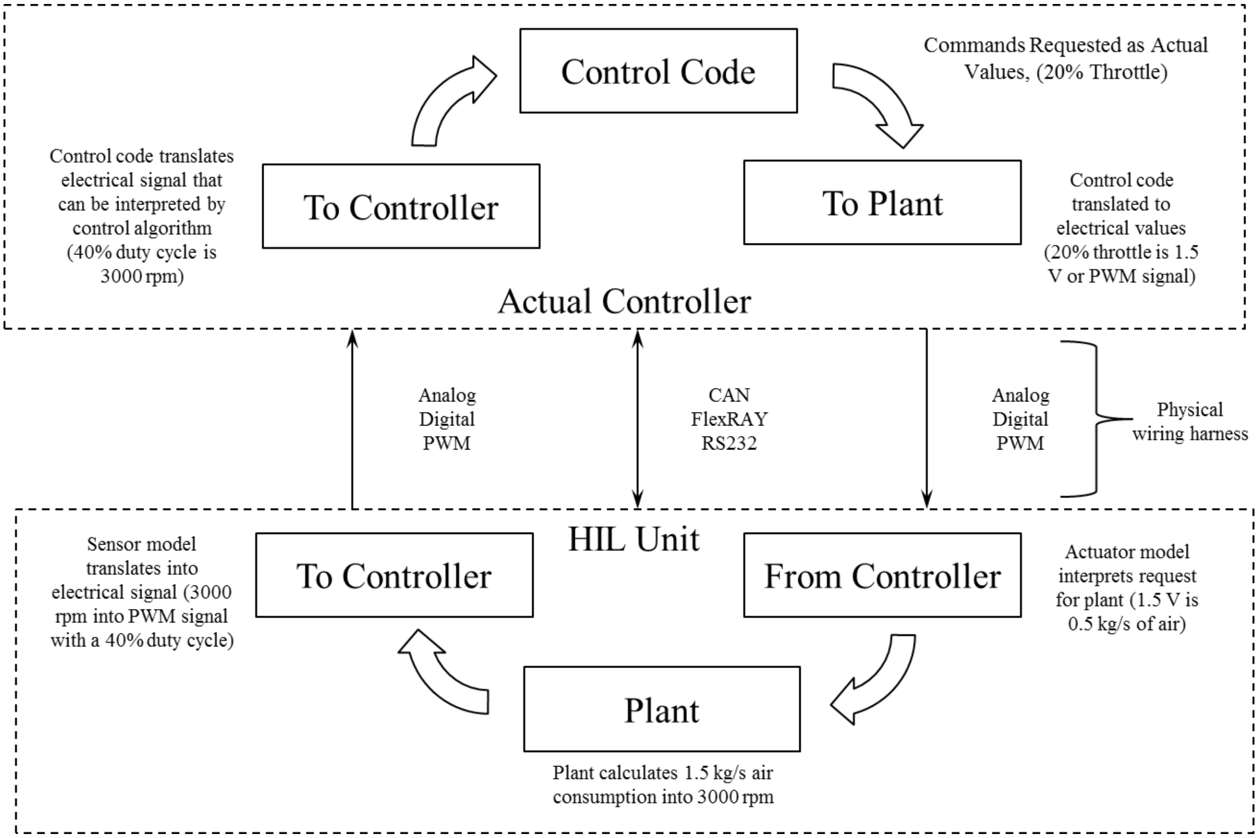


Figure 28 - Interaction of Controllers and HIL with engine control example [20]

Certain HIL manufactures offer automated testing software. This allows for the user to develop a set of test cases which execute on the HIL automatically. For example, the automation software can tell the HIL’s human model (i) depress the brake pedal, (ii) shift into drive (iii) attempt to turn the car on. If the control code is written correctly, the vehicle should not turn on when in drive. The automated software can monitor the controller’s response to ensure it doesn’t turn the vehicle on, as expected by the test case. Typically the software will allow for automated reports to be generated at the end of the test cycle. Automated testing is a huge asset; every update to the controller code can be tested quickly and automatically, ensuring the safety of the controller remains intact. In industry, hundreds of tests are executed overnight and typically in parallel to on-road testing. The test cases can be drawn up from the DFMEA and FTA established during the safety evaluation discussed in the previous section.

4.5 Mechanical Design

4.5.1 Space Claim Analysis

Mechanical design begins during the powertrain selection phase. As various powertrains are proposed, the mechanical team will perform a space claim analysis to:

- ensure the proposed component will fit within the structure of the vehicle;
- ensure minimal or no interfering with the crash structure;
- ensure ease of installation/removal of components;
- ensure sufficient ground clearance and ramp angles; and,
- ensure proximity of components to each other, with close attention paid to bend radius of cables, hot exhaust parts and fuel lines.

Most vehicles are constructed using a unibody design whereby most of the floor and roof of the vehicle are used as structural elements, as shown in Figure 29. Modification of these elements can affect the vehicle's performance in a crash. In previous experience, UWAFT has attempted to avoid any modification to the unibody; parts are added to it, but rarely removed.

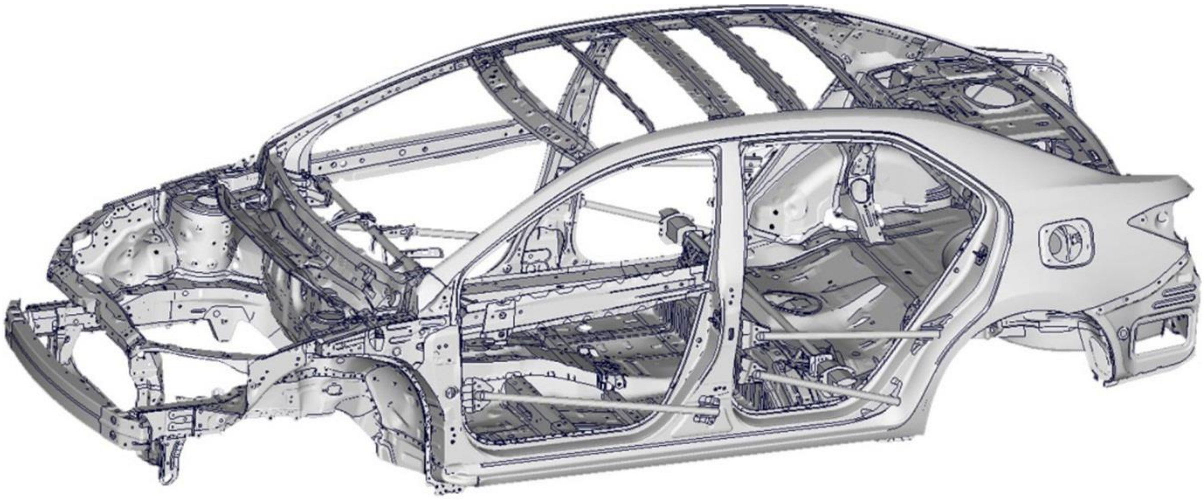


Figure 29 - Unibody vehicle structure [35]

Body-on-frame vehicles, such as pick-up trucks, offer more freedom for powertrain integration. As long as the frame-rails are not removed, components can be added in and around the frame of the vehicle. Figure 30 shows an example of a body on frame vehicle.

Figure 30 - Body on frame design; structural frame in black [36]

CAD models of the vehicle and components are strongly encouraged at this stage. If CAD models of the donated vehicle are unavailable, a 3D scanner may help measure the contour of surfaces. Blocks can be used to estimate the size of donated component without supporting CAD files. An example of a space claim completed as part of UWAFT's EcoCAR 2 design process is shown in Figure 31 and Figure 32.

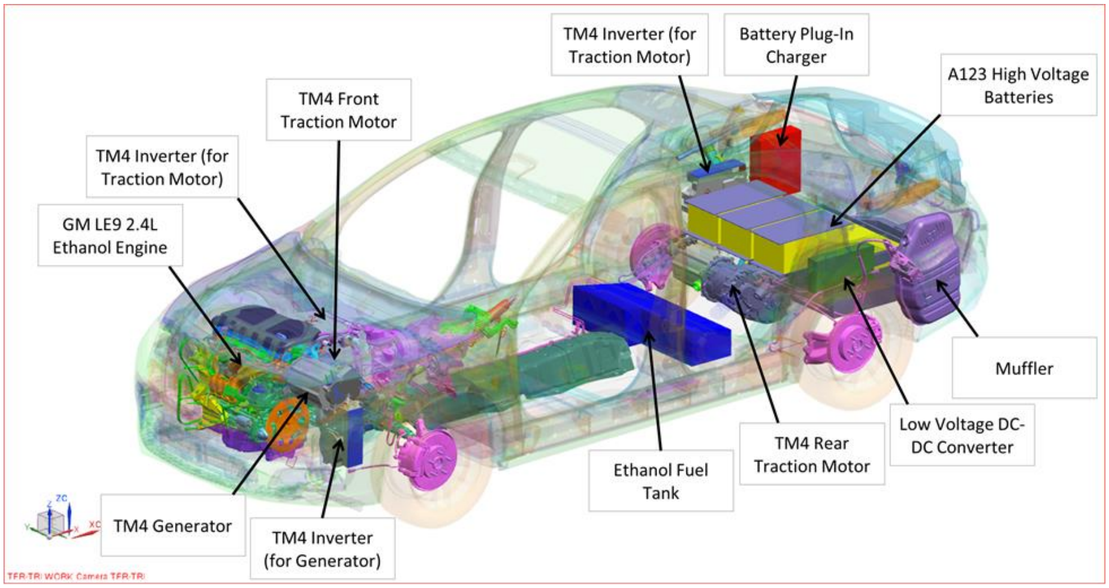


Figure 31 - Space claim example from UWAFT's EcoCAR 2 vehicle (3/4 view) [37]

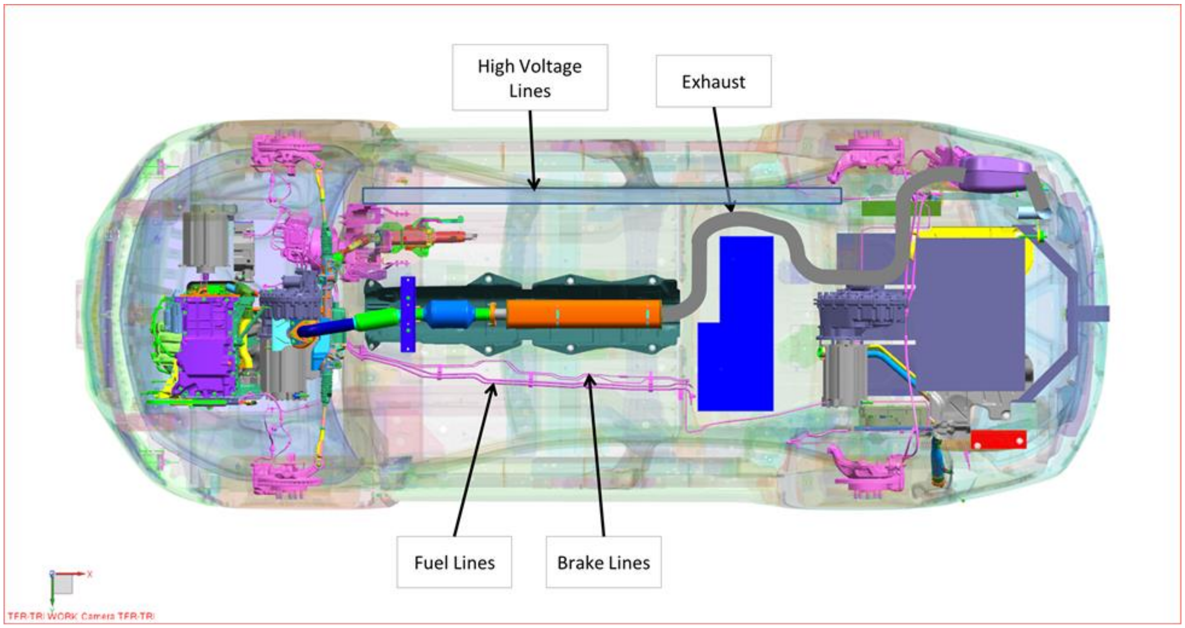


Figure 32 - Space claim example from UWAFT's EcoCAR 2 vehicle (bottom view) [37]

Note that all brake systems and the unibody model was retained. Ensuring components cleared the stock brake vacuum booster, brake lines and steering system resulted in less modification during the design process. Blocks were used to represent the fuel tank (later to be designed by UWAFT, but currently without detailed design) and the charger (CAD not provided). Routing of the exhaust and HV lines are also included, ensuring there is sufficient space between them. A preliminary packaging of the battery pack was included. Attempts were made to limit the amount of intrusion into the cabin space; specifically HV and fuel systems.

During the space claim phase, a rough calculation of the vehicle’s mass can also be carried out. Generally speaking, the limit to overall vehicle mass is the braking system’s ability to still slow down the vehicle within a reasonable distance. UWAFT was advised by GM on this mass limit. Liberal estimation should be made for the mass of brackets to hold components in place. UWAFT generally added 10-15% of the component’s mass to represent the estimated mass of brackets. A final consideration during the space claim process is to ensure the components are oriented and spaced correctly (information typically supplied by manufacturer). Special attention should be made to:

- cooling loops to ensure the bleed point in the highest point in the system;
- sufficient airflow for cooling radiators and fans;
- sufficient space amount hot components such as engines and exhausts;
- gearboxes are oriented correctly (typically EV motor gearboxes use splash lubrication, which requires a specific orientation);
- outputs of gearboxes line-up with wheels (reduces stresses with half shafts);
- overall center of gravity of the vehicle is reasonable (vertical and front/back); and,
- adequate clearances for rotating parts (such as half shafts, under loaded/unloaded and steering conditions).

Once the final space claim design has been carried out it should be reviewed by everyone, specifically the electrical teams. Catching issues early in the design stage reduce delays and increased costs later in the vehicle design and build process.

4.5.2 Detail Design Process

Once the space claim is complete the next step is to carry out the detailed design. These designs can be simple brackets to hold parts such as the wall charger or HV air condition compressor. Other designs such as the battery pack may be more complicated, with electrical isolation and cooling requirements. Front and rear subframes for a unibody vehicle can either be designed from the ground up, or based on production parts with additions made to accommodate motors and gearboxes.

There are multiple methods to carry out detailed design of mechanical systems. One such method is proposed in the following sections based on the process taught at the University of Waterloo. The major steps include:

- A *detailed background review* to understand more about the component being designed and vehicle body that's being modified to support the part. Reviewing documents supplied by the manufacturer will help understand correct ordination and mounting points. The background process may include reviewing previous mechanical designs carried out by industry or other universities. This is particularly useful for battery pack design. Designers should also review the location of their part to the overall vehicle; does it interfere with other components being designed or the occupants?
- *Defining the objective and scope* is needed to ensure the design process stays on task. An example of objective is: "Design and manufacture exhaust system that will minimize emissions and noise for an E85 fuelled vehicle for the EcoCAR 2 competition." Note, this objective clearly stated the designer will also be tasked with manufacturing as well as design. The designer will need to plan his time and budget accordingly. A scope will help narrow down the design and reduce 'scope-creep', which is unintended expansion of the design project. An example of scope for the exhaust design is to only consider emission post-exhaust (i.e. do not consider changing the engine calibration) and only consider using commercially available catalytic converters, rather than developing one from scratch (although such an item could also be considered a constraint in the design process).
- *Development of Constraints, Criteria and Risks* are the next step is the design process. Constraints are fixed design specifications that can be used to eliminate design options that do not satisfy these constraints. For an exhaust system, a constraint maybe there are no leaks, a fixed budget, a fixed delivery time, a maximum temperature, and restrictions on location. Criteria are a set of design goals, where by the best design option meets as many goals as possible and is ultimately used to select the best design. For an exhaust system, criteria can include low mass, reduced backpressure, low emissions, and ease of maintenance. A risk assessment can also be carried out to investigate possible dangers in the design, manufacturing and installation process. Once again, with an exhaust system

risks can include high heat, injuries from manufacturing and injuries that can occur during installation.

- *Design options* are introduced at this stage. Three or more designs can be proposed at this stage. The designs at this point do not necessarily need detailed FEA and budget quotes for manufacturing; however this may result in better confidence in the design's success and improve criteria metrics. Each of the designs should meet the constraints. The designs should also show the amount of modification needed to the vehicle, or any interactions with other vehicle parts. Each design should address manufacturing, installation, maintenance and end of life (disposal of the parts, safely and environmental considerations).
- *Design selection* based on criteria is followed by *detailed design.* As mentioned earlier, the design selection should be based on the design excelling in all criteria. A decision matrix may be used for this. Modeling tools such as FEA and CFD tools can be employed at this point to ensure the final design will perform as expected. When using these modeling approaches, the designer should understand the limitations of the models, use correct boundary conditions and appropriate load/test cases. If the model is incorrect set-up, the result is useless. UWAFT consulted frequently with GM to establish the correct boundary conditions and load cases. Generally speaking, a 20 G load was applied in the horizontal plane and 8G in a vertical direction for all components mounted (i.e. motors, engines, batteries and chargers). The resulting stresses needed to be less than half of the material's yield point. Structures such as sub frames had their own unique load cases provided by GM; the stresses and displacements were also measured and needed to be less than the stock sub frame's stress and displacement.
- *Manufacturing Considerations* should be carried out in parallel with the detailed design. Material cost, availability and machinability should be researched thoroughly. If the University has an engineering machine shop, staffed by technicians, their review of the designs are extremely beneficial. Consulting with CNC operators on reducing machining complexity, number of set-ups, selecting tolerances, and tooling can reduce costs and delivery time significantly. Booking time on CNC machines, depending on the time needed to complete machining is also important to consider. If welding is involved, supporting jigs may need to be made. A welder should also be consulted to ensure that there is minimal

warping during welding. With aluminum welding, thicker sections can be difficult to weld and may need to be taken to a specialist.

- *Releasing the design for final manufacturing* is the final phase in the design process. There may need to be some redesign during manufacturing, but if experienced technicians are consulted, redesigns should be few. Just prior to releasing the design, the criteria and other design options should be reviewed one last time. It is not uncommon during any of the design steps to discard a design and investigate a new path. The lessons learned from the design process should also be communicated with the rest of the team.

4.6 Battery Design Considerations and UWAFT's EcoCAR 2 Battery

The following sections will go over the battery pack design process in great detail. Design consideration the final design selected will be discussed. The design was carried out by Mark Cremasco, Eric Evenchick, Kelvin Law, Trevor Sabiston and the author of this thesis. UWAFT was supported by A123 Systems, which supplied the battery modules, controller, HV circuitry and technical support.

4.6.1 Components of a Battery Pack

The cell is the smallest unit of energy storage. Cell as placed in together into parallel groups or pouches to increase capacity. The pouches can be a cylinder, much like an AA battery or a prismatic cell (Figure 34 and Figure 35) where the cell is ribbon which is spiral wound. These groups/pouches are then wired together in a module (Figure 36). The wiring is typically a combination of series and parallel configurations. Modules also contain an electronic monitoring system which is used to balance the cell pouches, and monitor temperature/voltage. A pack is comprised of several modules wired together with copper bus bars in series (Figure 37). A controller monitors each of the modules. The controller is also the main form of communication with the overall vehicle. Additional components include:

- High voltage interlock loop (HVIL): It is a low voltage circuit (~5 to 12V) that is hardwired into the battery's main contacts. If the loop is breaks, the contactors will open the battery will not provide current. Items within this loop include emergency stops (one located near the driver and the other on the outside of the vehicle), inertia switches, limit switches in the battery enclosure and within the manual service disconnect (MSD). The HVIL voltage is also typically sensed by the battery controller for diagnostics purposes.

- The manual service disconnect (MSD): Typically wired at the halfway point of the modules. Removing the MSD should break the HVIL and bring the pack's overall voltage to half. Some MSDs also contain the main battery fuse. The MSD should always be removed during servicing of the battery; some battery pack enclosure designs do not allow for the enclosure to be removed until the MSD is removed. The MSD should also be part of a lock-out-tag-out procedure; if anyone is servicing the pack, it should be locked/tagged out.

- Main Battery Contactors and Precharge Circuit: As mentioned earlier, the main battery contactors are wired into the HVIL. One side of the contactors contains the pack's live circuitry; the other side is the vehicle side bus and will only be 'live' if the contactors are closed. There are typically two contactors, one for the positive bus, and the other for the negative bus. The precharge circuit is also included. It allows for the vehicle side's voltage to match the battery pack's voltage in a controlled manner before the contactors close. If there was no precharge circuit, there would be a rush of current as the contactors close due to the high capacitance of the motors and their inverters. The precharge resistor will need to be sized for each application to precharge the circuit in a timely manner, depending on the electrical characteristics of the vehicle side HV bus. An example of the main contractor and precharge circuitry is shown in Figure 33. UWAFT was provided a complete kit known as the electronic distribution module (EDM), which contained the contactors and precharge circuit.

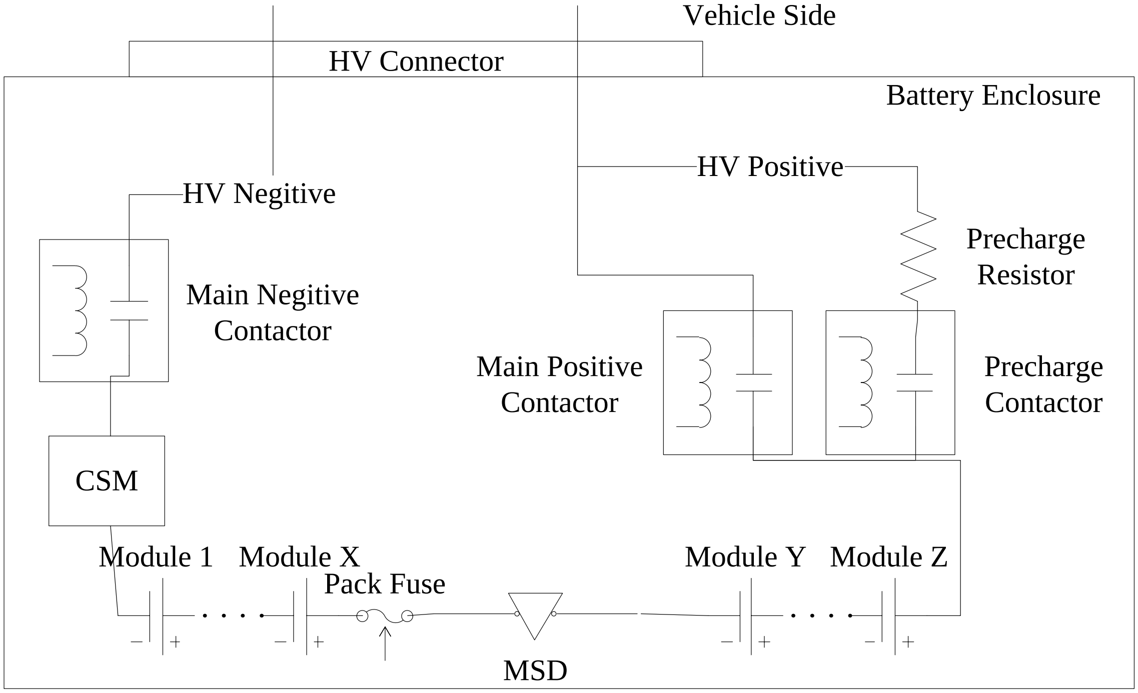


Figure 33 - Sample HV battery internal wiring

- Current Sense Module (CSM): CSM is a HV isolated device that measures bus voltages and battery pack current. It also may monitor the isolation between the HV bus, LV and chassis ground. The CSM is monitored by the battery control module (BCM), which is sometimes referred to as the battery management system (BMS). The role of the BCM is explained later in this section.
- Battery Modules: As mentioned earlier, the battery modules have sensors which monitor the temperature and voltage of cell pouches/groups. The battery modules also have circuitry that helps balance the cells during charging. The battery modules communicate information to the BCM by an internal network.

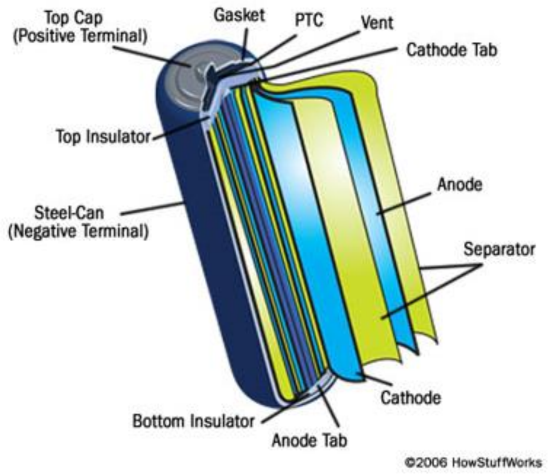


Figure 34 - Cylindrical Li-ion pouches [38]

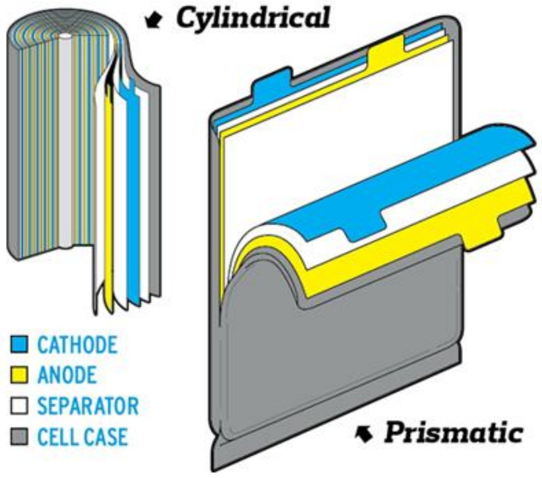


Figure 35 - Cylindrical and Prismatic Li-ion groups/pouches [39]

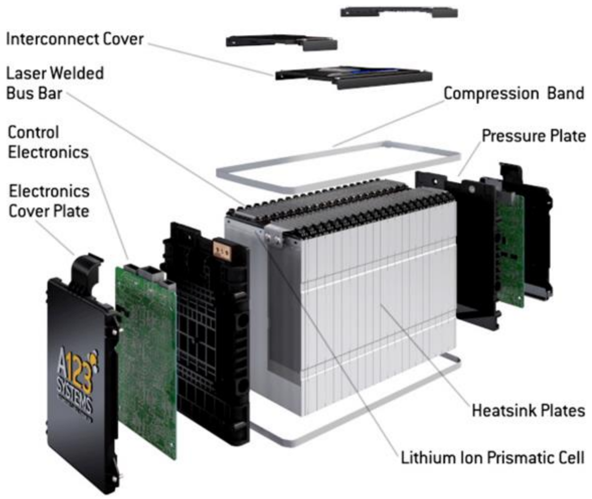


Figure 36 - Internal view of A123 battery module [40]

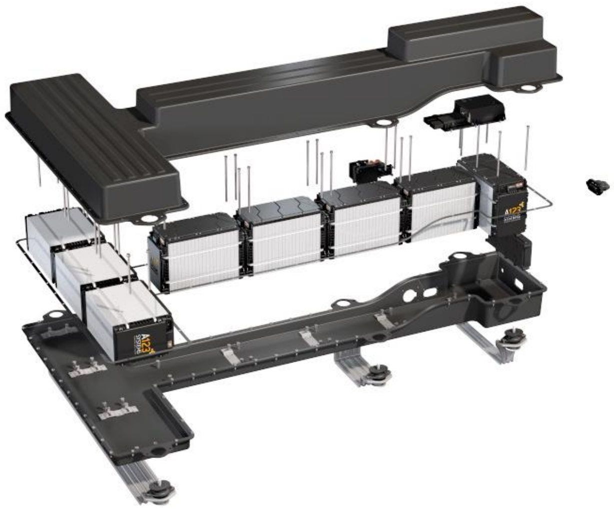


Figure 37 - Battery pack comprised of A123 modules [41]

- *Mounting Structure and Enclosure:* For UWAFT, all the components mentioned thus far were supplied by A123 systems. The mounting structure and enclosure were designed by the team. The structure will hold the modules in place and is typically made of steel or aluminum. It is designed to carry the weight of the modules and mounts to the vehicle's structure. The enclosure isolates the batteries and HV systems from the rest of the vehicle. It can be made from aluminum, steel or carbon fiber, as long as the inner surface has been treated with a material that is electrically isolating. In some designs, such as the one shown in Figure 37, the enclosure and mounting structure combined.

- *Thermal Control System:* The thermal control system is the final component which is used to maintain a reasonable operating temperature for the cells. Forced air or liquid cooling can be used. Like the enclosure and mounting structure, the thermal control system was designed by the UWAFT team.
- *Battery Control Module (BCM)*: Also known as a battery management system (BMS), it the main controller within the battery pack. It communicates with the CSM, battery modules and vehicle. It takes commands from the vehicle; for example, close contactors or begin vehicle charging. The BCM will perform several calculations including the state of charge (SOC) and state of health (SOH) of the battery. Combined with information from the battery modules, the BCM has the ability to monitor individual cells and can open contactors if a cell begins to fail. The BCM will also handle the charging of the pack, at the request of the vehicle's main controller [42].

4.6.2 Electrical Safety

As suggested in Section 3.6, consulting with the University's safety office prior to any work with HV systems is important. It is critical to understand that batteries are always live. Unlike combustion engines where fuel can be drained and stored separately, HV batteries are always energized. The battery pack's design should only have live circuitry within the enclosure and when the MSD's removed, no high voltage potential outside of the pack. An excellent reference is C. Merkle and L. Kennedy's "High Voltage Safety for the Service Technician" [16].

All students working on the vehicle should be trained on how to work with HV systems, even if they will never open the battery pack or work with HV components such as the motor. Proper personal protective equipment should be used at all times. This includes HV gloves (also known as linesmen gloves) and external leather protectors. The leather protectors are designs to protect the HV gloves from tears or nicks, but themselves are not HV isolated. The leather gloves should be 2 to 3 inches shorter than the HV gloves. To reduce sweating and discomfort due to rubber gloves, cotton liner gloves can be worn under the rubber gloves. HV gloves also require recertification every six months and should be long enough to reach the mid-forearm. Class 0 gloves provide protection up to 1000 V (as tested by the American Society for Testing and Materials [43]) and should be sufficient for most hybrid and electric vehicle applications. The gloves should be tested for holes prior to every use by inflating the gloves and inspecting for air loss. HV gloves should not be stored in direct sunlight.

Additional PPE includes insulating covers, which can be placed on exposed battery modules. Insulating bags can be used for cells or pouches. A face shield should also be used when working on batteries. Insulated HV tools should also be used. HV tools tend to be bulker; tool clearances should be a consideration. Student or technicians should also only wear cotton when working on exposed HV systems, in case of injury due to arc flash. Rubber soled shoes should also be used.

When working around HV systems all jewelry should be removed (rings, watches, necklaces and bracelets). Long hair should also be tied back. Wooden or composite work surfaces should be used and clear of an obstructions or conductive items. The work area should also be located away from any water sources such as sinks and batteries never placed on the ground, in case of a flood. The work area should be blocked off from personnel or machine traffic. During UWAFT's pack construction phase, a separate room was used with a lock. A two-person rule was also used; work on the pack could only be conducted if someone else was in the room. The door was only locked when work was not being conducted; if there was an emergency when someone was constructing the pack, EMS can get into the room without difficulty. Signs were also placed around the pack indicating the system is always energized. The room should also be air conditioned to reduce the possibility of condensation formation. There should be ample room to move freely around the battery module. A Class D, Li-ion fire extinguisher should also be within the room.

The National Fire Protection Association (NFPA) has standards for working with electrical systems available on their websites. The standard recommended is NFPA 70E: Standard for Electrical Safety in the Workplace [44].

There are several modes of failure that can cause damage to the batteries and pose a safety risk. The first is a short circuit. It can be caused by an unintended connection of the positive to negative terminal, without a load in between. The battery cells can physically damage beyond repair and would require replacement. A common cause for this failure during pack construction is an unintended contact on the battery terminals by a metallic object such as a tool. Leaked coolant can cause this failure as well. A less common cause is material can build up on the battery modules and cause a 'soft-short' resulting in heat generation. This is more common in air cooled batteries; air used to cool the battery should be filtered. The second failure is overcharging. This fault occurs is the cell's voltage exceed ~4.0 V. If overcharging occurs, gas will build up in the cell pouches and could vent.

The BCM should monitor and mitigate this failure mode by opening the battery contactors. The battery enclosure should also be designed with a vent that opens outside of the vehicle. The final failure is pouch penetration. If a foreign object were to penetrate the cell pouch, it can cause several failures a short would occur, which can lead to a fire or the generation of heat. The electrolyte can leak, which is corrosive. The enclosure and location of the battery should prevent the possibility of pouch penetration.

4.6.3 Battery Charging and Cell Balancing

The Li-ion battery charging process occurs in four stages. The process is monitored by the BCM, which dictates to the vehicle charger requests for current and voltage. During stage one, the cell, module or pack is charge at a constant current. The second stage, called the saturation stage, switches from a constant current to a constant voltage charge profile. At the third stage, the current is stopped and voltage may dip slightly. The fourth and final stage, the standby stage, holds the cells' voltage constant until the charger is stopped (or vehicle unplugged). The process is shown in Figure 38.

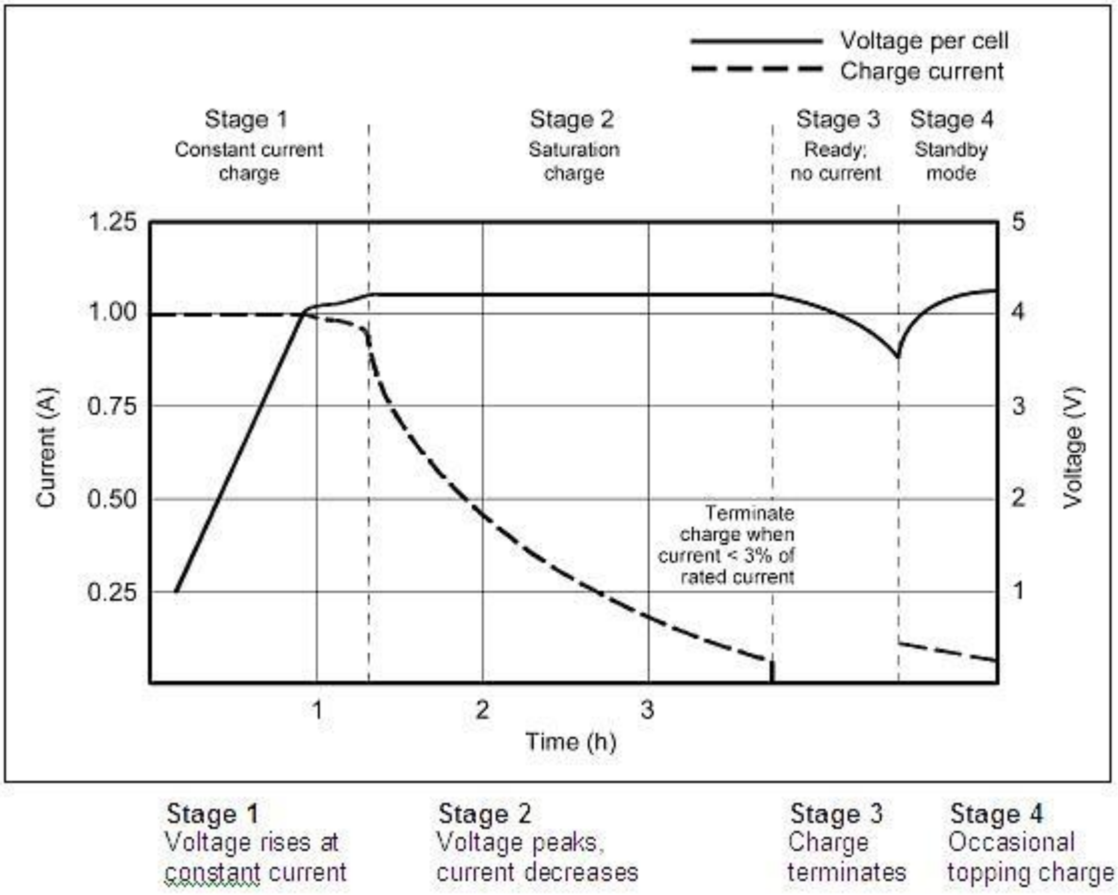


Figure 38 - Li-ion battery charging process [45]

In battery packs, there are hundreds of cells. These cells require a balancing system. Balancing is required because not all cells are made the same; some have a slightly higher internal resistance, others are located at the end of the module and may have different thermal dissipation. Due to this imbalance, during charging one or more cells may charger earlier than the rest. If charging were to continue, while all the other cells maybe a 90% SOC, the one cell maybe at or near 100% and risk facing an overcharge situation. To combat these misbalances, a cell balancing system is used.

There are two types of cell balancing systems; passive and active. The passive system senses the cell(s) with the greatest voltage and applies bypass resistor which consumes energy until the voltage matches the rest of the cells. The circuitry resides on the battery module and is controlled by the BCM. It’s the lowest cost option, but can take a long time for the cells to balance and is inefficient because energy is dissipated into useless heat via a resistor. Active balancing is based on the principal of shifting energy internally between one of more cells. For example, energy from the cell with the highest voltage can be sent to the cell with the lowest voltage. Energy can also be transferred from one cell to the entire pack or conversely, from the entire pack to one cell. Capacitors or DC/DC systems can be used. Active balancing is expensive and complex to implement, but more efficient and faster than passive balancing.

UWAFT's battery supplier, A123 Systems, provided a BCM with modules that supported cell balancing. The BCM also managed grid level charging by managing current and voltage requests to a Brusa NLG513 on-board charger.

4.6.4 Selecting the Battery Pack Performance Specifications

The goals when selecting the battery pack performance specifications are to select an acceptable voltage range, power/current output, energy (or capacity). Voltage dictated is by the number of cells in series. A Li-ion cell's normal voltage, the voltage of the cell when at 50% capacity, is typically 3.3 V (which depends on the specific Li-ion chemistry). The peak voltage can be 3.7 V when fully charged and as low as 2.5 V when fully discharged. These voltages can vary slightly depending on the cell specific chemistry used; there can be a range of cathode, anode, electrolyte and separator materials.

While the voltage of a battery back increases depending on the number of cells in series, the capacity remains the same. Capacity is the amount of electrical charge (or current) that a battery can deliver at a given voltage. Connecting cells in parallel increases the capacity, however the voltage remains the same. This concept is shown in Figure 39. Note that the total energy for both examples is the same.

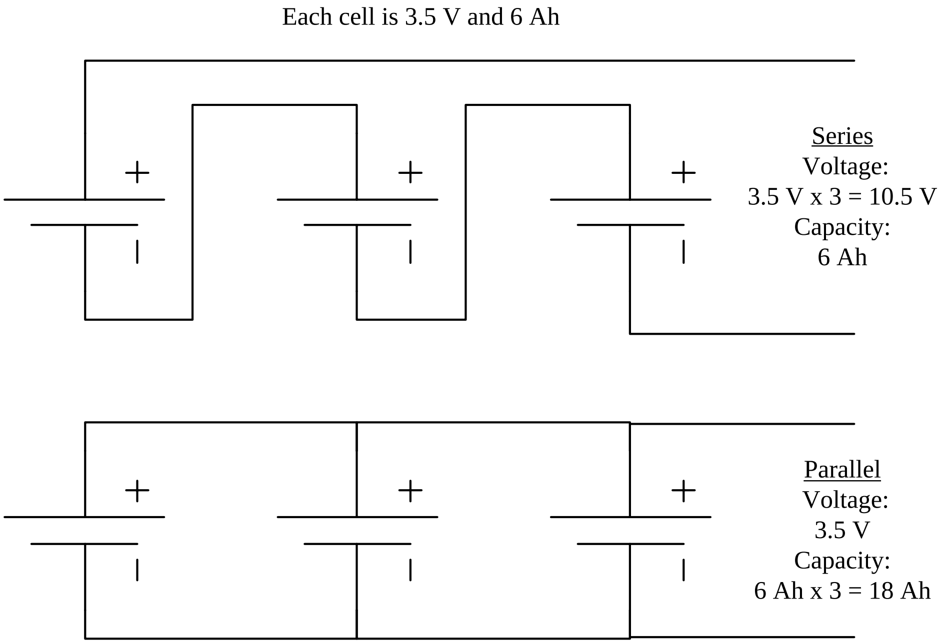


Figure 39 - Relationship between cell voltage and capacity for series and parallel strings

For UWAFT establishing the voltage was affected by the voltage range of the devices on the HV bus. The motors, 12 V DC/DC and AC Compressor have a voltage range of 320 – 400V DC. Ideally a battery providing 400 V would result in lower line losses (due to less current), however a battery rated at 400 V when fully charged can still exceed 400 V under regenerative braking. A 350 V was ultimately selected for the nominal battery voltage; it provided the highest nominal voltage while still respecting the 400 V limits of other components under regenerative braking conditions.

The peak power requirement for a battery depends on the peak and continuous power demand of the powertrain. If the powertrain contains only one load, for example a 15 kW peak 5 kW continuous motor, then the battery's power can be sized to match this requirement. Using a powertrain model (see Section 4.3), the peak/continuous power can be calculated by examining the power demand of the battery under a range of drive cycles, including real-world drive, EPA cycles, acceleration and gradeablity drive cycles.

For UWAFT's powertrain, there are two traction motors, a generator, A/C Compressor and 12 V DC/DC that all depend on the battery. To size the battery, the 'worst case scenario' was used to select the peak power demand: 0-60 mph acceleration with EV power only, with the A/C system operational, and the 12 V DC/DC converter operating a full capacity. The resulting power demand would be 210 kW from the motors and 6 kW from the A/C Compressor and DC/DC. A total of 216 kW for less than 10 seconds would need to be provided by the battery. Unfortunately A123 could not provide a battery with this peak power so a compromise was found. A 176 kW peak battery pack was selected. The remaining power would need to be sourced from the engine/generator (40 kW). The continuous power demand was found by running the vehicle on gradeablity simulation of 3.5% grade at 60 mph for 20 minutes; this was found to be 34 kW. The A123 sourced battery pack provided 60 kW continuously.

With an established voltage and power requirement, the resulting current demand from the battery can be found. Taking the example of UWAFT's battery, under continuous operation of 60 kW at 350 V, the resulting current would be 171 Amps. The number of parallel strings depends on the cell/pouch capacity and heat generation. For UWAFT, the capacity of a cell pouch is 20 Ah and three parallel strings were selected. This resulted in ~60 Amps per a string or a C-rate of ~3C. Heat generation within the cells can also be reduced with parallel strings, which reduce the current drawn from each cell pouch and thus I^2R heat generation, where R is the internal resistance of the pouches.

With voltage, current/power requirements, the energy/capacity can be calculated. Range is typically the driving factor for battery energy. Referring back to Section 4.2, a target range should have been determined. For UWAFT, the target range for EV operation was 75 km (based on 80% of real-world driver's requirement). An Autonomie powertrain model was used calculate the energy needed to meet this distance, using a UDDS drive cycle that was repeated 6.25 times (the UDDS cycle is 12 km is length, thus to achieve 75 km, it needed to be repeated 6.25 times). This is an iterative process; the vehicle's mass would change as the battery capacity changes, thus model would need to run again with a new vehicle mass. A regenerative braking strategy was also used within the model allowing for the energy normally lost to braking to be recovered. This helped reduce the battery capacity. The resulting capacity needed was 15 kWh to provide 75 km of driving under a UDDS cycle. With Li-ion batteries a buffer was need to allow for capacity fade; 20% was selected and in consultation with A123 an 18.9 kWh total capacity battery pack was provided. It should be noted, in production vehicles, the buffer can be much larger. For Chevrolet's Volt, the useable energy is 10.8 kWh, the total energy is 16.5 kWh; 5.7 kWh is set aside for capacity fade and not usable by the driver [46].

With a voltage, power/current and capacity selected, the size/number of the modules can be determined. For UWAFT a 350 V, 176 kW peak/60kW continuous, 18.9 kWh battery pack were the required specifications. Hypothetically one single module can be provided with 105 cells in series in

3 parallel strings, however the practically of packaging and assembly this configuration would be challenging. Hence, A123 provided 7 modules with 15 cells in series in 3 parallel strings (15s3p) each. Each module had a nominal voltage of 50V and was much easier to physically handle and package. Figure 40 gives an overview of the final configuration.

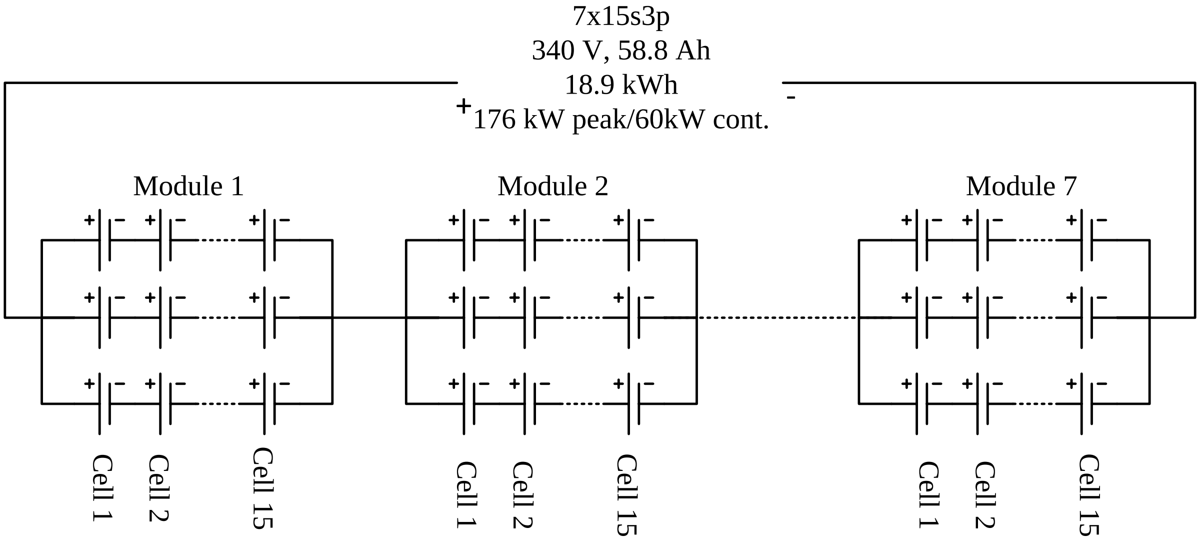


Figure 40 - Overview of UWAFT battery cell pouch and module configuration

4.6.5 Thermal Systems for Batteries

Batteries' capacities are highly dependent on temperature. A warmer battery will experience degradation; a cold battery will experience reduced performance (energy and power) [47]. Therefore, the role of the thermal system is to:

- Heat the battery in cold operations to an optimal temperature, as specified by the battery supplier.
- Cool the battery in warm/hot temperatures to optimal temperature.
- Evenly distribute heat among modules and cells to reduce premature degradation of cells.

Depending on the conditions the research vehicle is being used, a simple air cooled thermal system or no thermal system whatsoever may suffice. If the vehicle is only operated for short periods of time, there may be sufficient thermal mass in the battery that would result in only a limited increase in battery temperature; no thermal system would be needed. For UWAFT, the conditions required the vehicle to operate in hot temperatures due to testing in Yuma, AZ where temperatures can reach 40°C (105°F) in June. UWAFT did not intent to operate the EcoCAR 2 vehicle is cold temperatures; hence a heating system was not necessary. Additional design considerations for UWAFT included:

- The cooling must meet the aggressive US06 cycle. This cycle was selected because of its high acceleration and deceleration. The rationale for selecting this cycle was further proven by comparing the RMS current of several different EPA drive cycles, as shown in the next section.
- The internal battery conditions (voltage and internal resistance), should represent the worst case scenario. Given the battery chemistry, this would be a low SOC situation where the internal resistance is high and battery voltage low.
- Reduce energy consumption of cooling system. By selecting the appropriate cooling pumps and fans, the electrical demand on the 12 V systems can be reduced and the overall vehicle efficiency increased. An intelligent thermal control strategy that turns on the pumps and fans as required can help reduce 12 V electrical demands.
- Maintain the battery temperature within the A123 specifications. Unfortunately, this information is confidential and property to A123. The temperature at which the BCM beings to limit the battery’s performance will be known as the lower limit and the temperature at which the BCM will open contactors will be known as the upper limit.

- Limiting the number of leak points (hose clamps, threaded connections, etc.) in the cooling system whenever possible. The battery system is not compatible with coolant. Every effort needs to be made to ensure that the connection points do not leak and that the hoses and clamps are rated for the application (fluid compatibility, pressure rating, resistive to damage from the clamping device, etc.).

Determination of Heat Generation

The heat generation of the battery can be modeled by using the internal resistance of the battery and current drawn by the vehicle powertrain, as per the battery model shown in Figure 41.

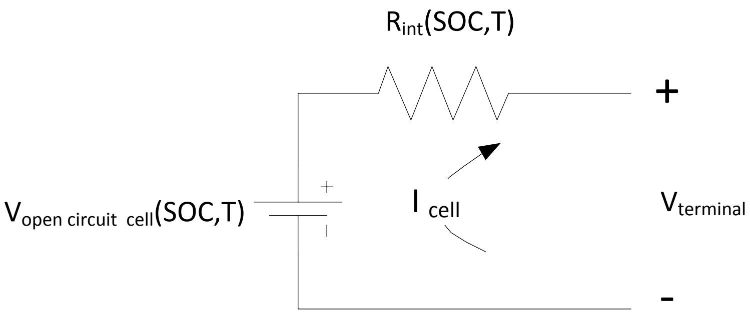


Figure 41 - Simple battery model of a battery cell

Here, the internal battery resistance (R_{int}) and open circuit battery voltage ($V_{open\ circuit\ cell}$) are both functions of the battery SOC and temperature. This data should be provided by the battery supplier. As mentioned earlier, to select the worst case scenario, a low SOC (and thus low voltage) and higher temperature condition resulted in the highest R_{int}, and was ultimately selected. The battery current (I_{cell}) depends on how much power is being drawn from the battery and is ultimately a function of the drive cycle and vehicle design. The relationship is defined in Equation 5.

$$I_{cell} = \frac{Power}{V_{battery}}$$

Equation 5 - Relationship between battery power, current and voltage

$$\dot{Q}_{cell} = I_{cell}^2 R_{int}$$

Equation 6 - Internal battery heat generation, as a function of current and internal resistance

The heat generated by the battery is due to the internal battery resistance and can be calculated in Equation 6. A few additional notes about the model:

- The model showcased is for a single cell. The approach taken here will be to calculate the heat per a module, factoring in parallel strings, and multiple by the number of modules to find the overall heat generated by the battery pack.
- The R_{int} is different for charging and discharging, however for the A123 cells used, there is only a slight difference between the charge and discharge current; the average of the two will be used.
- The R_{int} also differs depending on the duration of the charge or discharge. The longer the duration, the higher the resistance. The 10 second pulse data was selected because the peak power of the motors is limited to 10 seconds as well.
- It should be noted, there are many more complex battery models that can better represent the heat generated, however the one presented should suffice. The models proposed above assume all losses are converted directly to heat.

Determining which drive cycle, and ultimately battery current to use for the thermal calculations is the next step. Because the current for a drive cycle varies over time, it is easier to calculate the root-mean-squared (RMS) current of the battery during a drive cycle. RMS is preferred because it captured both the positive and negative current. This static value can then be used with Equation 6.

The challenge of selecting a drive cycle still resides. Ultimately the EPA's US06 drive cycle was selected. To select this cycle, the vehicle models discussed earlier were run on several different drive cycles. The cycles were repeated 10 times to ensure the vehicle entered charge sustaining operation. The resulting RMS current and power of the cycles were calculated. The RMS current for charge depleting, charge sustaining and combined operation were observed. The results are shown in table below, along with the mean current.

Table 8 - RMS current for various drive cycles and operational modes

	Measurement	**UDDS (x10)**	**US06 (x10)**	**LA92 (x10)**
Entire cycle	**RMS (amps)**	40.4	71.3	56.8
	Mean (amps)	7.7	12.2	7.7
Charge Depleting	**RMS (amps)**	38.0	114.7	63.2
	Mean (amps)	16.2	48.1	23.4
Charge Sustaining	**RMS (amps)**	42.3	90.2	53.4
	Mean (amps)	0.5	8.1	0.2

The current requirement for the vehicle operating at a 3.5% grade for 20 minutes was also considered. Assuming a vehicle weight of 2038 kg as proposed in the VTS, roughly 34 kW of tractive power is needed. Factoring other electrical vehicle loads, this translates into 102 amps from the battery. The US06 cycle had a greater current demand; 115 amps and hence it was selected.

The next step is to calculate the heat generated in one of the seven modules. To do this, the resistance of the module needs to be calculated. Each module consists of three parallel strings of 15 series cells. The calculation is shown below:

$$\frac{1}{R_{module}} = \frac{1}{3R_{series}}$$
$$where\ R_{series} = 15R_{cell\ int}$$

Equation 7- Resistance calculation for battery module

At this point, all information is found to calculate the heat generation per a module. As stated earlier, the data provided from A123 is confidential, thus only ranges can be discussed. UWAFT's heat generation per a module was roughly 100 to 200 W.

Resulting Cooling System Layout

The cooling method selected is unique for each application. The following sections will highlight UWAFT's design for EcoCAR 2. The team decided to utilize a liquid cooling system. This cooling method was selected over air cooling for several reasons, including past experience, support from industrial sponsors, and higher performance. The liquid system requires a radiator, pump, reservoir, cold plates, lines and several valves, as shown in Figure 42. The reservoir serves three purposes. The first is it provides a volume for the liquid to expand during heating, the second as a fill port and the third as a location for air to escape during the bleed process. Due to the last requirement, the reservoir should be located at high as possible within the vehicle. The reservoir feeds the pump directly, which in turn feeds the radiator. The radiator was placed in the wheel well, ensuring a constant flow of ambient air can be provided. A T-valve splits the flow between the 3 module upper pack and the 4 module lower pack. UWAFT considered a series configuration whereby the 4 module section would feed the 3 module configuration, but this idea was disbanded because this would result in non-uniform heat distribution between the pack sections. By splitting the flow, a more uniform heat distribution should be generated between the two sections and all modules. UWAFT will have to ensure that flow stays constant between the two sections. A bypass for the radiator is not included in this system. This decision was made because the vehicle will primarily be operating in above 20°C and there little need to heat up the pack in cold temperatures. It also further complicates the bleed process. If testing in later years requires the use of a bypass valve, this can easily be added. The final validation of the cooling system's performance will be carried out during on road testing.

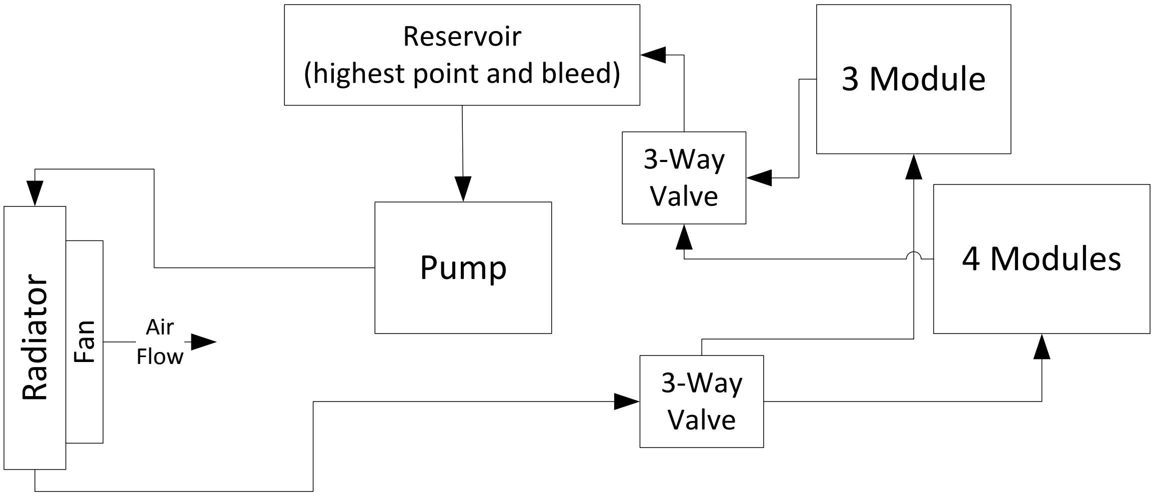


Figure 42 - Layout and flow of cooling system for UWAFT's EcoCAR 2 vehicle

4.6.6 Space Claim Analysis and Mounting Structure

With an established number of modules, cell configuration and cooling system, the space claim analysis of the battery pack could be performed. To goals of this analysis is to ensure all required components will fit within the vehicle which:

- Avoid extensive modification to the vehicle’s chassis and retains balance of the vehicle.
- Avoid exposing the passengers to HV systems,
- Is easy to fabricate, install and service, and;
- Provides a reasonable level of protection during an accident.

The following section will outline the UWAFT’s battery space claim process. Three iterations for placing the battery pack were considered. The first design placed the battery back below the rear seats, as shown in Figure 43. Note that the dimensions of the battery modules were increased slightly to factor in the additional space needed for the enclosure. The benefits of this design were the battery could be assembled outside of the vehicle and lifted into place. The downsides included a major impact on interior space for the rear passengers and extensive modification of structural elements within the vehicle.

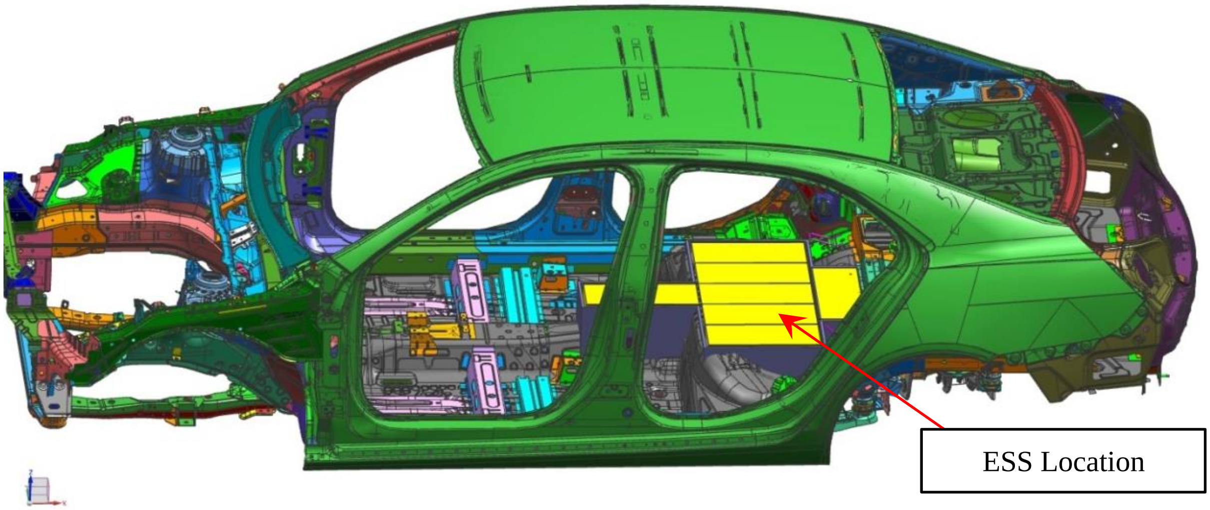


Figure 43 - First iteration of UWAFT proposed battery back space claim; batteries in yellow

Seat belt mounting points would also need to be moved; seat belt mounting points are considered critical safety items according to GM. Another issue with this design was the fuel tank. The fuel tank is required to be between the wheels and the only other location that would allow for this is the transmission tunnel. The transmission tunnel did not provide enough volume for the desired range.

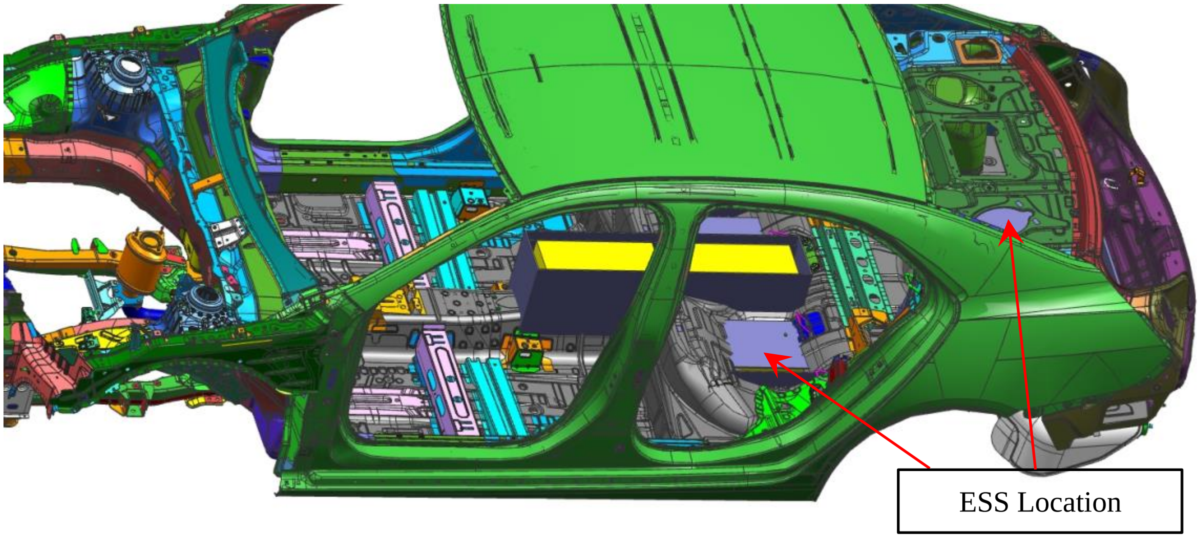


Figure 44 - Second design iteration for ESS, splitting the modules into two sections

The second design iteration split the battery back into two sections, as shown in Figure 44. Four modules are located in the front half; two vertical and two on their sides. The remaining three modules are located vertically in the trunk, where the spare wheel is normally stored. This design allowed for the rear seats to remain the same and retain the location of the seat belt mounting points. The design can also be manufactured outside of the vehicle and installed. The issue of a small fuel tank and extensive modification to the unibody chassis still remain. The third and final design is shown below, in Figure 45. Here, four of the modules are located vertically where the spare wheel is normally located. Three of the modules are located on their sides. See Figure 46 for the position of the modules. The fuel tank would remain in its normal location (under the rear seats) and little modification to the unibody design would be needed; only the space wheel area would need to be removed and this was deemed acceptable by GM. The downside to the design is the pack assembly would need to take place within the vehicle, which expose HV lines and can make repair challenging.

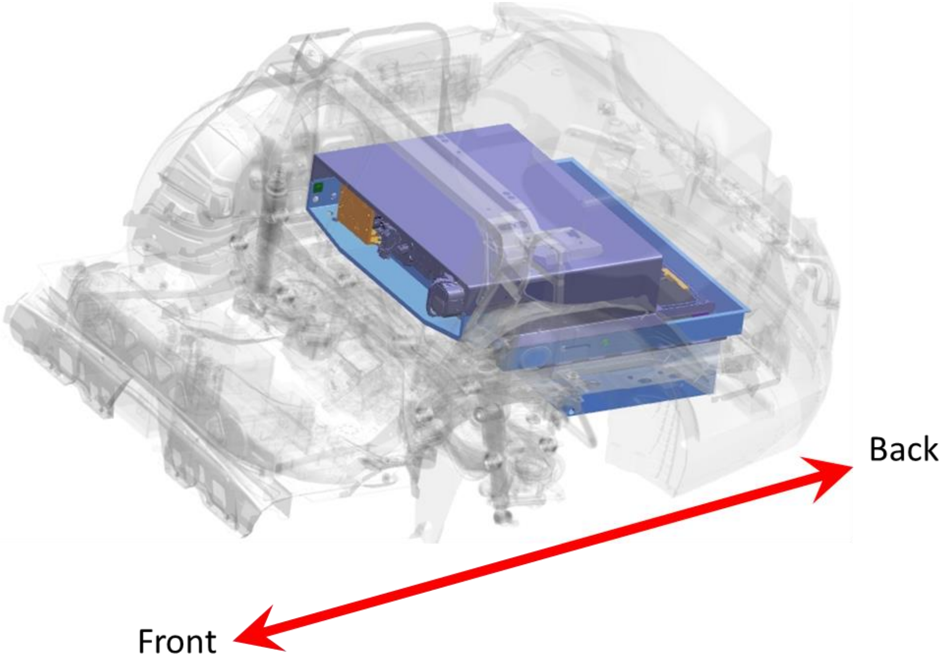


Figure 45 - Final proposed ESS design, located within the trunk

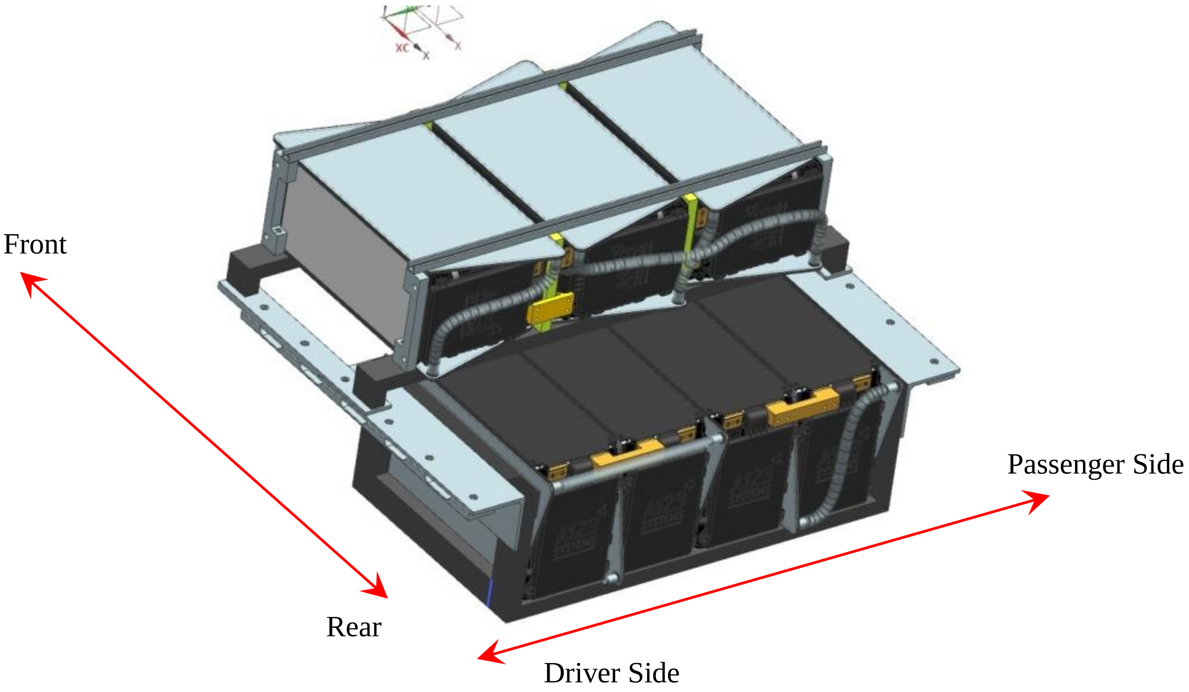


Figure 46 - Location of battery modules for final ESS design

Once the space claim was completed, the mounting structure was designed. This structure consisted of two metal attachment rails mounted to the vehicle. These rails connect to the frame holding the battery modules. The metal rails are welded to the frame rails of the vehicle, as show in Figure 47. This figure also shows the sheet metal removed to accommodate the battery modules.

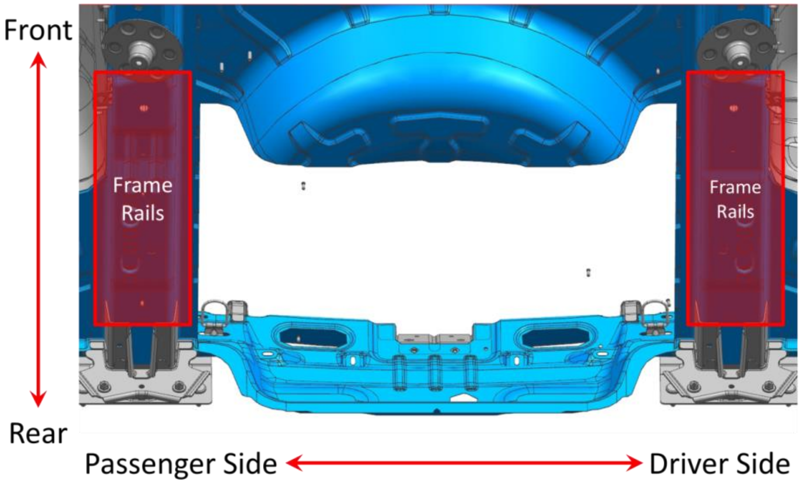


Figure 47 - Frame rails relative to area cut out of vehicle. View from under vehicle.

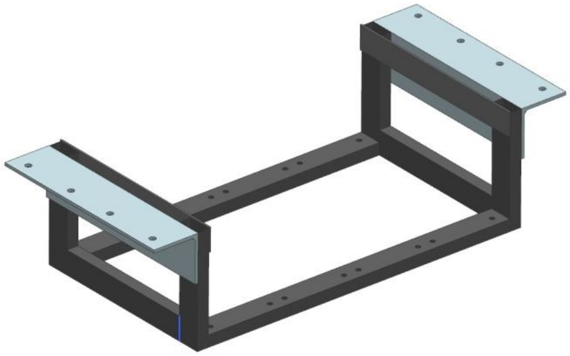


Figure 48 - Structure for lower section

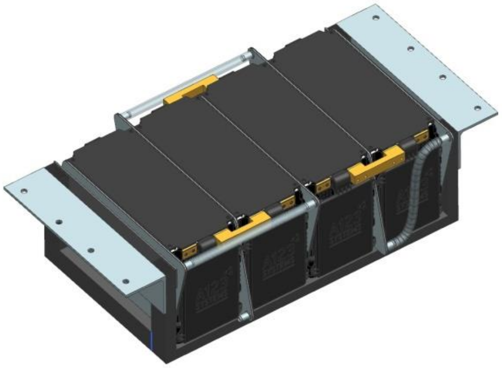


Figure 49 - Assembled lower section

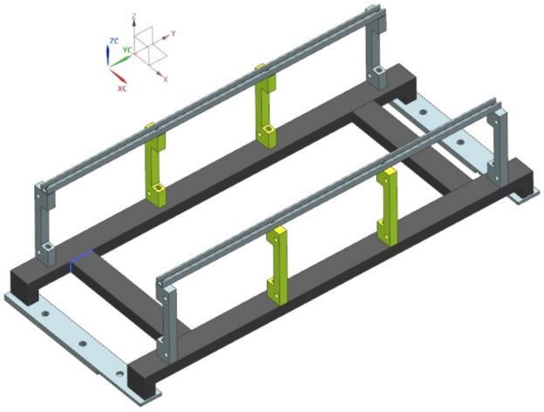


Figure 50 - Upper section structure

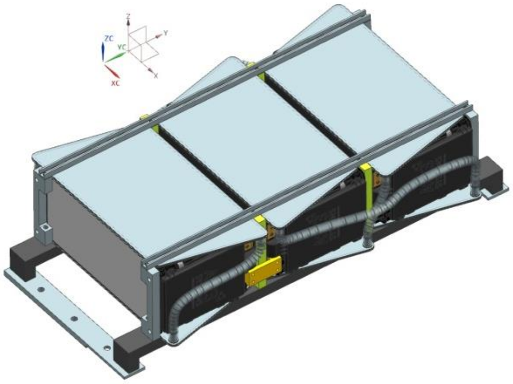


Figure 51 - Assembled upper section

The structure which holds the modules are made up of two parts; an upper and lower section, as shown in Figure 48 through Figure 51. The upper section houses three modules laying on their sides. The structure is made of 4130 rectangular tubes with 0.062" wall thickness. They are welded to two 1020 flat structure mounting plates. Both of these features are shown in Figure 52, labeled as 1 and 2 respectfully. Referring to the same figure, four Class 8.8 M10 threaded rods (3) run through all the modules. There are spacers (4) in-between each of the modules to space the modules, and hold them in place by allowing for a vertical Class 8.8 M10 bolt (5) through each spacer. There are two aluminum U channels (6) on top to hold down the cooling plates and stiffen the structure.

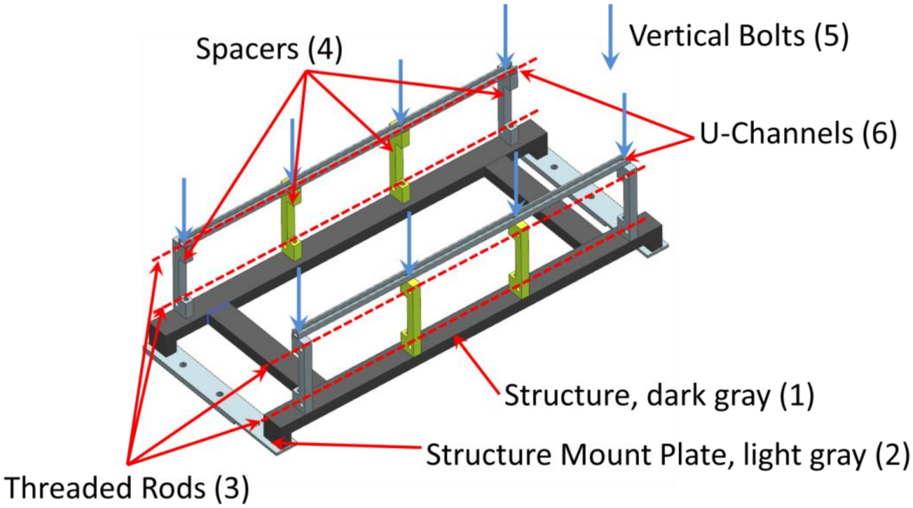


Figure 52 - Detailed breakdown of upper structure

The lower section is suspended from the frame rails and holds the remaining four modules. The modules are held in place with four Class 8.8 M10 vertical bolts through each module. The structure itself is once again made out of 4130 rectangular tubes with 0.062" wall thickness. The lower section is supported off a 1020 angle iron piece which is welded to the structural tubing. Both these elements are shown in Figure 53, labeled as (1) and (2), respectfully. Both the upper and lower sections use a rivet nut located on the top surface of the structural tubing to attach to the tubing. It was found in previous competitions that putting a nut on the other opposite side of the tubing presented issues, because it would cause the tube to be crushed when torqueing the bolt. These thread inserts are shown on in Figure 53, labeled as (3).

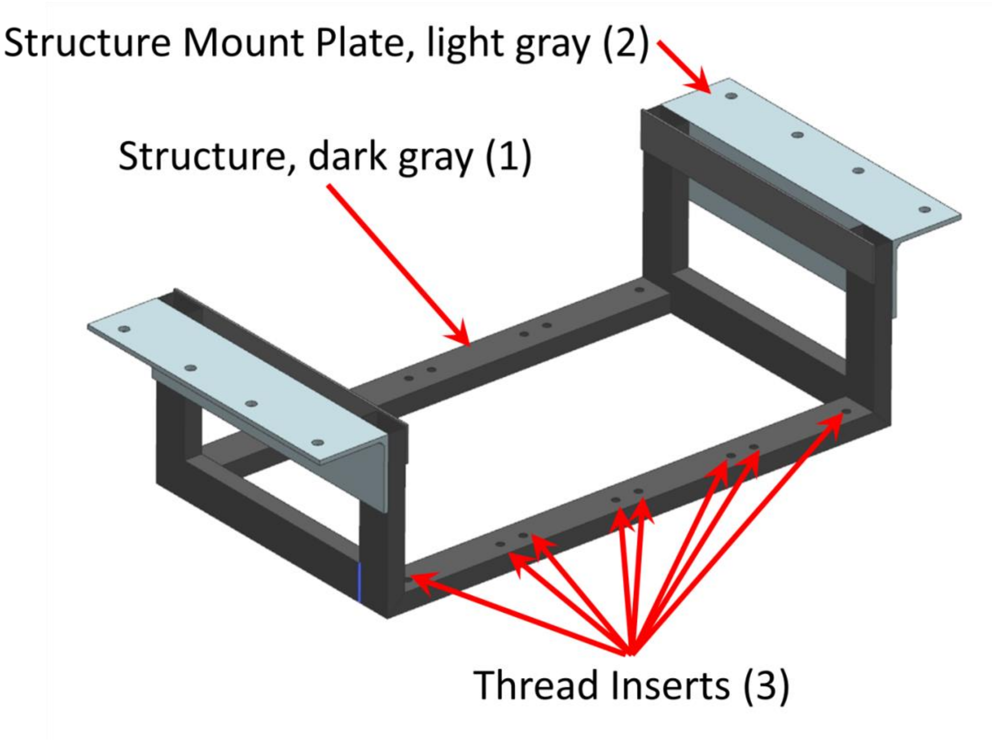


Figure 53 - Detail breakdown of lower structure

The final modification is the welding of two ‘Attachment Rails’, as shown in Figure 54. These rails will have six threaded holes each (12 total) for the upper and lower sections to bolt to as shown in Figure 54. Note that UWAFT wrapped the entire metal structure in Kapton tape to provide an electrical barrier against the conductive metallic frame.

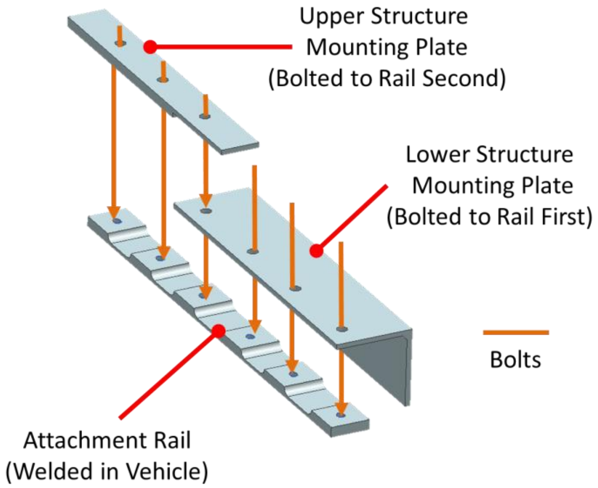


Figure 54 - Attachment rail, upper and lower structure mounting (driver side)

The entire proposed design underwent an extensive FEA analysis to ensure the battery mounting structure would hold in place during an accident. A static 20 G load was applied to the battery mass in the horizontal plane (front, rear, passenger and driver side), and an 8 G load in the vertical (up and down). The resulting stresses on the metal structures were analyzed; they were required to be half of the yield stress of the material selected. This analysis was carried out by Trevor Sabiston and documented extensively for GM [48] [27].

An issue that was raised was the impact the attachment rails and battery mounting frame would have on the overall crash absorption properties of the unibody. In modern cars, the unibody is shaped to deform in a certain way as to absorb the most amount of energy possible. This reduces the forces exposed to the passengers. The addition of battery changed the overall absorption properties. Initially the team attempted to model a 30 mph crash using LS-Dyna. LS-Dyna is a general-purpose FEA program that allows for highly nonlinear, transient dynamic finite element analysis using explicit time integration. The team quickly ran out of computational power to run a vehicle crash simulation. Also, properties representing the A123 structure were not available; they were simply modeled as hollow boxes. In the end, only the rear quarter of the vehicle was modeled, rather than the entire vehicle. The entire simulation was carried out by Kelvin Law [48] [27]. The results are shown in Table 9, with a comparison to the stock vehicle. Given the deformation was more or less the same as stock, the design was deemed safe.

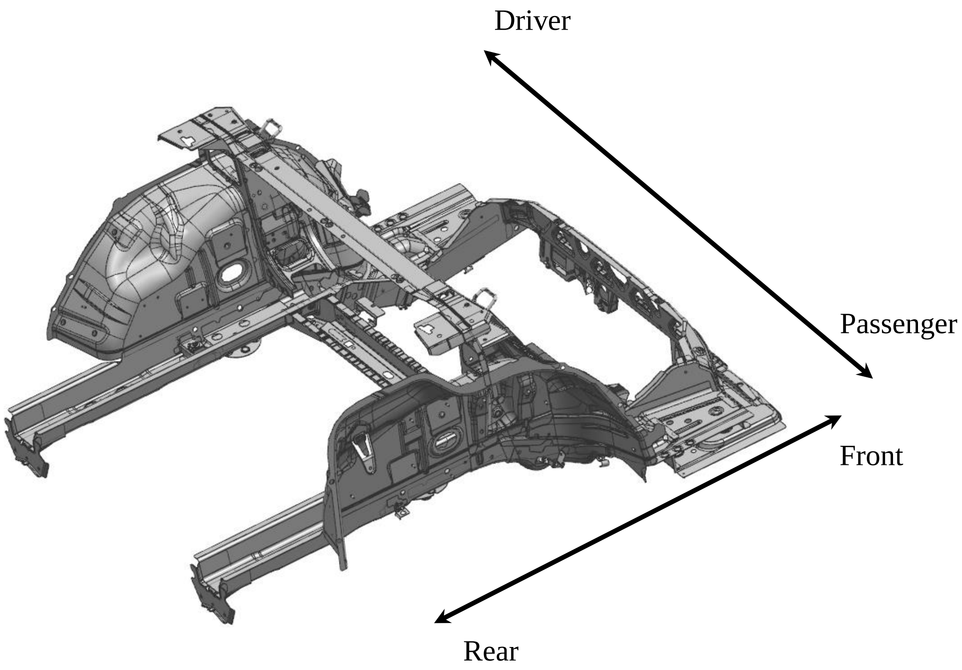


Figure 55 - Rear crash structure used for LS-Dyna analysis

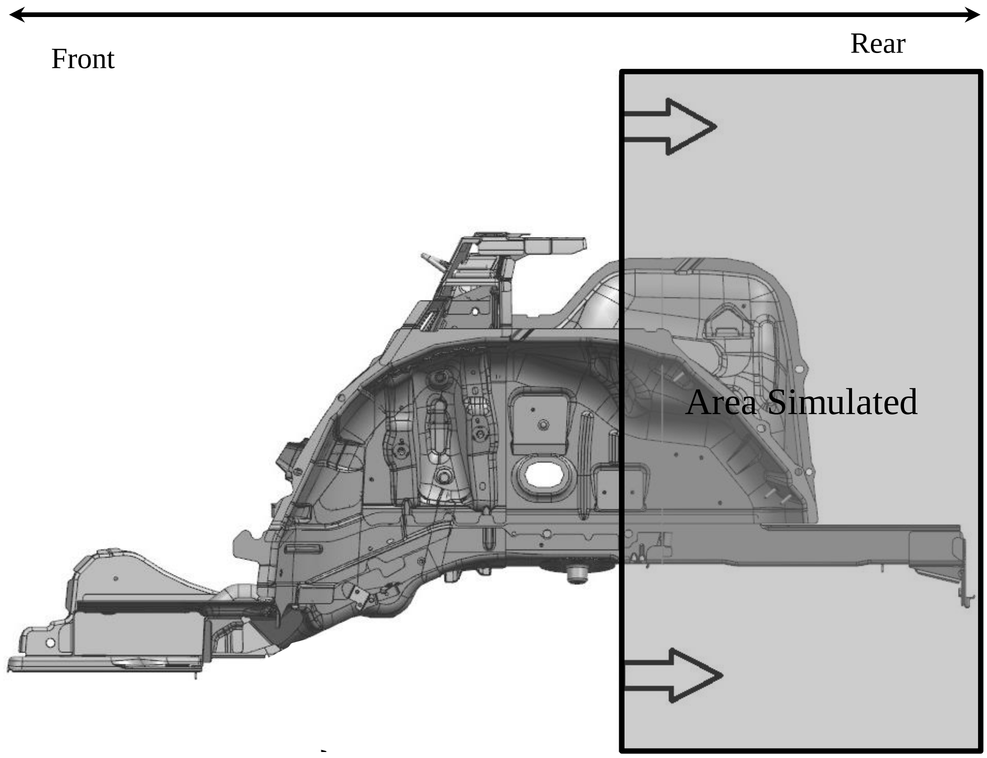
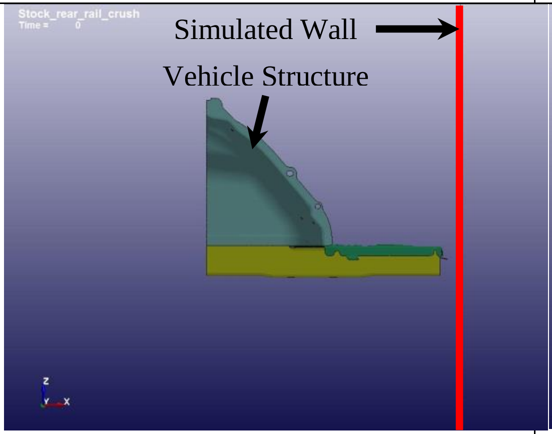
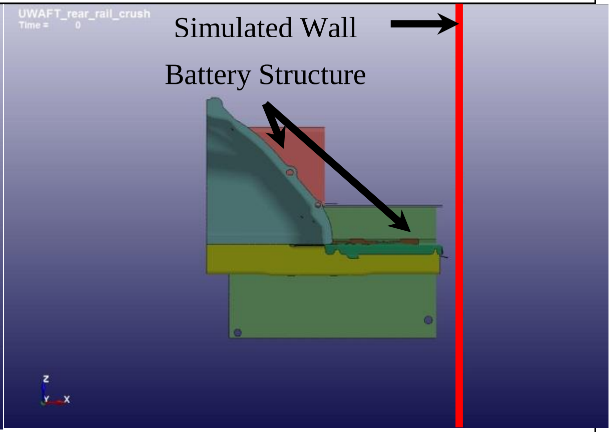
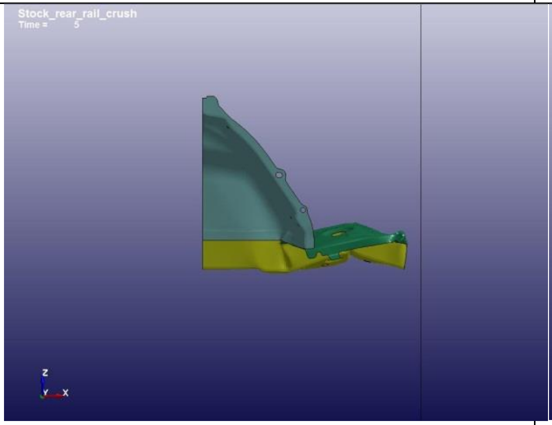
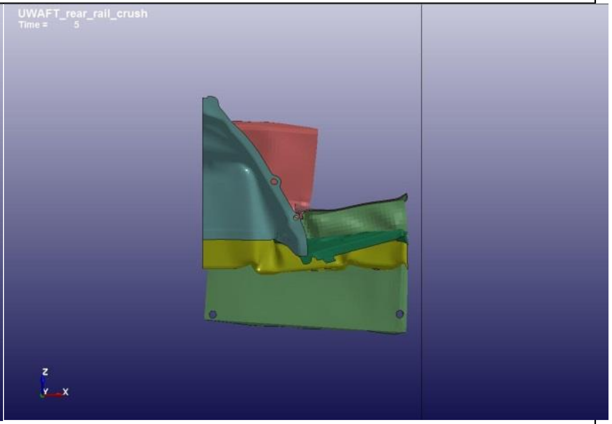
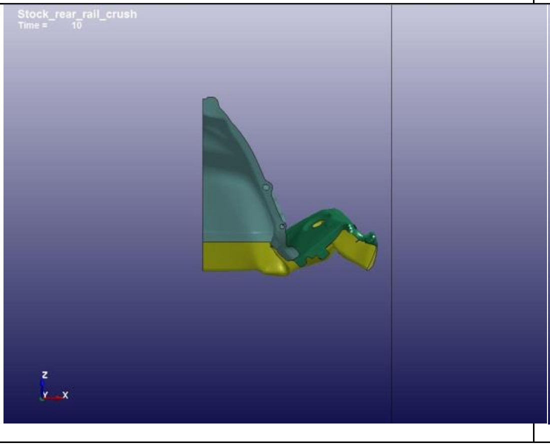
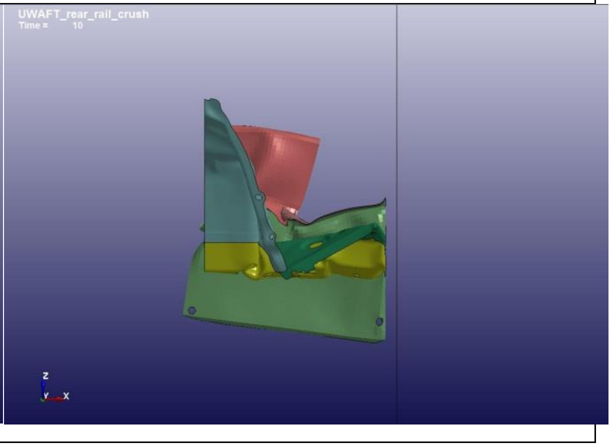
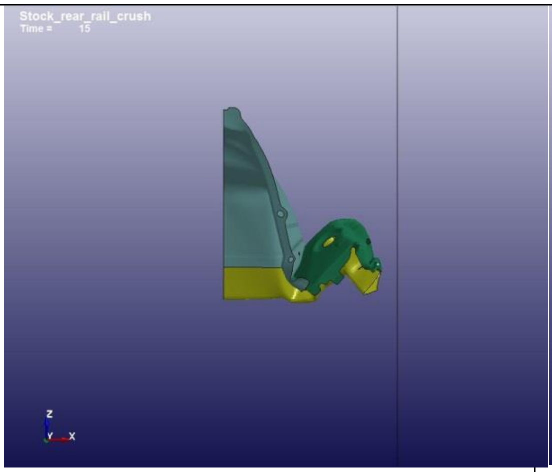
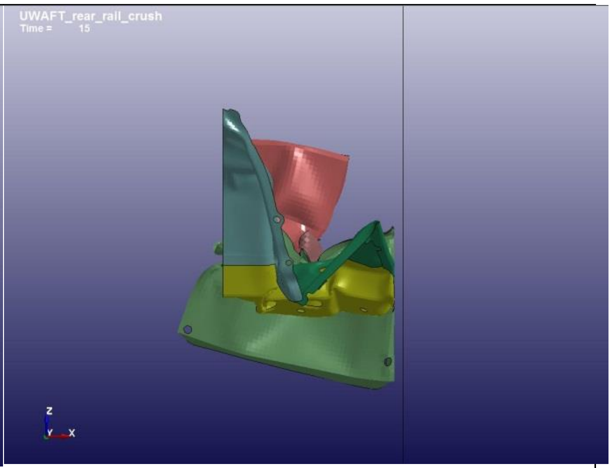
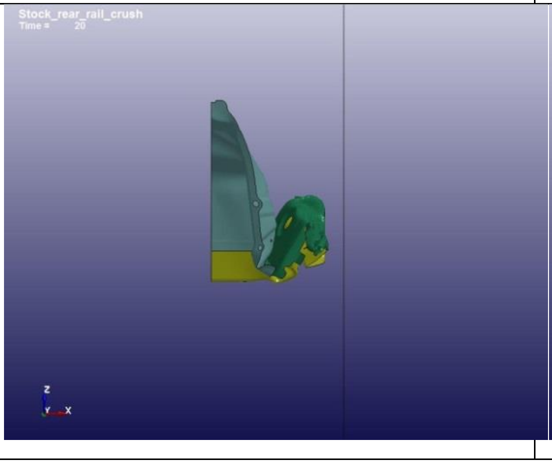
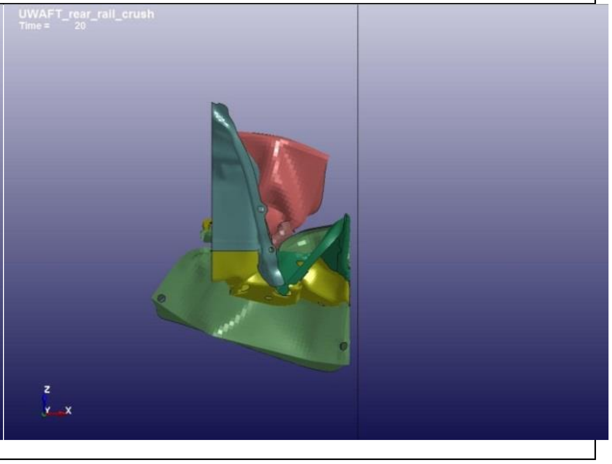


Figure 56 - Rear crash structure selected for final LS-Dyna simulation

Table 9 - LS-Dyna crash simulation in time step stock vs. modified

Time	Stock	UWAFT
0 ms		
5 ms		
10 ms		

15 ms		
20 ms		

4.6.7 Battery Enclosures

The battery enclosure has several requirements. It must protect the passengers and students working on the vehicle from the HV electrical systems within the battery. To do this the enclosure can be made from electrically insulating material such as plastics or metal lined with insulating materials such as Nomex. UWAFT used a carbon fiber/Kevlar enclosure, which was lined with Nomex paper and Kapton tape. The enclosure should also not have any metal bolts which pass through the inside of the enclosure, and are exposed to the outside of the enclosure. Flanges should be used instead, as shown in Figure 57. For HV connections to the battery, specially designed through-wall HV connectors should be used. These connectors are typically weather sealed as well and should be located in an easily accessible location.

As mentioned earlier in Section 4.6.1 Components of a Battery Pack, the MSD should be designed into the battery enclosure such that the enclosure cannot be opened until the MSD is removed. UWAFT achieved this by placing a plate behind the MSD. This plate blocked access to several bolts need to open the enclosure. By removing the MSD, the plate could be removed and the bolts made accessible.

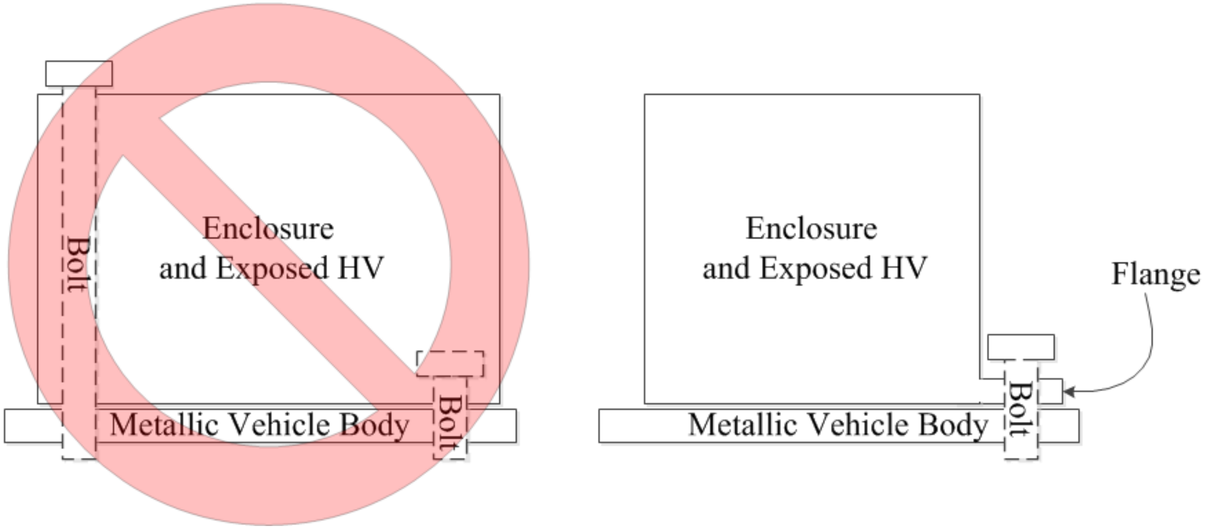


Figure 57 - Alternative to bolts passing through enclosures

Beyond electrical insulation, the enclosure must protect the batteries from moisture, road debris, and grit. The enclosure should be waterproof and contain a seal. In the event the battery cells experience overcharging, they can begin to vent gasses. The gases need to be vented outside of the vehicle. Pressure build-up within the enclosure can cause the enclosure to become a dangerous explosive vessel. UWAFT used two redundant pressure relief valves, set to 3 psig pointing to the outside of the enclosure to mitigate this risk.

Some battery suppliers also require having electromagnetic shielding (EMI). A metal case, or wire mesh will help provide EMI protection. If liquid coolant is used, a drain should be added to the bottom of the enclosure to allow for coolant to drain if there is a leak.

4.6.8 HV and LV Systems

The focus of this section is not the connection between cells within module, but rather the HV and LV wiring outside of a module. This wiring includes the HV bus bars or cabling between modules, MSDs, high voltage current sensors and connections to the outside of the pack. The LV wiring that will be discussed within this section will include the data connection between modules and the BCM, as well as any additional wiring sensor wiring.

When designing HV connection between modules, bus bars or HV cabling can be used. Bus bars are suite for connections too short for HV cabling. There is several design consideration when using bus bars:

- If possible, flexible bus bars should be used. Battery modules occasionally shift slightly during driving and can introduce fatigue stress on copper cell terminals. Flexible bus bars allow for movements among modules without introducing fatigue.
- Use flexible bus bars that have been rated for the relevant voltage and current. Typically suppliers will provide this information.
- If solid bus bars are being manufacturing, ensure there is sufficient cross-sectional area for the relative current. Unfortunately there is not set standard for cross-sectional area vs. ampacity. UWAFT consulted the EcoCAR 2 organizers for a recommended area, but ultimately it varies by application. Purchasing premade bus bars which have a rated ampacity and cutting them to length is an alternative option.
- All bus bars (both flexible and solid) should be covered in the appropriate rating of insulation. Combination of splicing tape, heat stink and outer anti-abrasion tape are ideal. A drop cover (a piece of non-conducive plastic or Nomex material) should cover all exposed module terminals to prevent tools or people from touching exposed high voltage.
- If possible, use tin plated copper bus bars to reduce corrosion on copper.
- There should be adequate spacing between the bus-bars and conductive materials. Generally half-an-inch or greater is desired.

If HV cables are being used, rather than bus bars, the following should be considered:

- Use an appropriate HV automotive orange cabling. Avoid using welding cable, which is typically rated on pulse basis, rather than on a continuous basis. UWAFT used Champlain Cable’s EXRAD HV cable products, which are specifically designed for automotive application. These cables are very flexible, are available in shielded or non-shielded versions, can be used in -70°C to 150°C temperatures, and can be exposed to oil or coolant without any damage to the insulation [49].

- The bend radius specifications provided by the cable manufacture should be respected.
- Loom should be used throughout the HV cables. Anti-shafting material should be used where needed.
- Cable/harness routing and retention should be used on both the low and high voltage systems.
- HV should be located at least 100 mm away from LV cables and parallel runs between HV and LV cable should be eliminated if possible. LV and HV cables should cross at 90°. This is done to reduce EMI on the LV cables.
- Tin-plated compression type lugs should be used to terminate HV cables. The appropriate hole size should be purchased for the lugs; they should not be modified to fit on a different sized hole (i.e. if the hole diameter is too small, do not make the hole bigger). The correct gauge (wire diameter) lug should also be selected. Heat shrink and splicing tape should be used to cover the exposed sections of the lug.
- The HV shielding should be isolated from the conductive cable. This is an issue near lugs because isolation and shielding needs to be removed to access the bare copper. Generally, the shielding should be cut back one inch from the bare copper.

The connections for both bus bars and HV cables require special attention:

- Always ensure the contact between lugs, bus bars or any other HV electrical interface is direct, without any washer or lock washers in the way; a direct mating surface ensures current is transferred with minimal interruptions. If secondary connections (such as voltage measurements) are needed, do not place the connection between the current paths.
- The quality and flatness of the mating surfaces of a connection are critical in high current applications. Increased resistance of the connection system caused by finish, flatness, or oxidation can lead to heating of the battery module terminal and limiting of the battery pack’s performance.

- All fasteners, including module interconnect fasteners, should have some form of torque retention (lock washers, nylon lock nuts, threadlock). Apply the correct torque to the bolts or nuts; HV connectors (specifically on contactors) can be made from copper bolts which break at much lower torque than steel bolts.

There are several additional considerations related to fusing, ground fault indication and bleed down systems; they fall in a gray area between pack design and electrical system design. This author has placed these concepts within the electrical design section.

4.7 Electrical Design Concepts

In general there are two different electrical systems in hybrid/electrical/plug-in (electrified) vehicles, a low voltage 12V system, and a high voltage system. The 12 V low voltage system is also used in conventional vehicles and operates most of the electrical systems, such as headlights, radios, instrument clusters, controllers, etc. A lead acid battery provides power when the vehicle is not on for both conventional and electrified vehicles. For a conventional vehicle, the alternator provides power during operation. In electrified vehicles, a 12 V DC-DC converter steps the high voltage potential down to 12 V providing power during operation. The following sections will discuss in detail the design of electrical systems for research vehicles. Note, designed should be reviewed by an expert in vehicle electrical systems; the advice provided below is simply a suggestion. UWAFT turned to Argonne National Laboratories to review the low and high voltage systems.

4.7.1 Low Voltage System

Within the context of research vehicles constructed at Universities, the low voltage electrical systems can be divided into two sections; the stock vehicle system and the university designed system. Hypothetically is possible to remove the stock vehicle’s system and build an entire electrical system from the ground-up, but this is challenging, time-consuming, and redundant work. If part of the stock system works and are not being changed, there is no point in removing these systems. The challenge therefore lies in what parts of the stock system should be modified/removed and what parts should remain the same.

Under the advice of GM, only the stock powertrain engine, transmission and hybrid controller were removed from the stock system (the donated vehicle was a mild hybrid system, hence the removal of the hybrid controller). The team had to devise control code to replicate the messages and signals normally sent by these devices to other devices (such as the instrument cluster) to ensure the remainder of the vehicle would operate normally. The only other part of the LV system changed was the throttle signals, which were sent to the supervisory controller. All other systems, including the air bags, brakes and body control systems were not changed.

The university designed LV system consisted of all of the wiring to the supervisory controller and the hybrid powertrain. The design of this system took place by listing all devices requiring control, and reviewing the electrical requirements these devices needed to operate. The LV fusing for these devices were also reviewed; all 12V electrical devices should be appropriately fused. An example of this review process is shown below. The devices and their electrical requirements are listed.

Table 10 - Sample 12 V electrical requirements

Device	**Electrical Requirements**	**Fusing (Amps)**
Cooling Fan (x2)	12V +, 12 V Ground	15
Coolant Pump	12V +, 12 V Ground	10
Supervisory Controller	12V +, 12 V Ground, Wake, Throttle Signal In (x2), CAN High/Low (x4), Analogue Out (x2), Analogue In (gear position)	7.5
Battery Control Module	12V +, 12 V Ground, Wake, CAN High/Low, Diagnostics CAN High/Low	15
Traction Motor Controllers (x3)	12V +, 12 V Ground, Wake, CAN High/Low, Diagnostics CAN High/Low	10
Battery Charger	12V +, 12 V Ground, Wake, CAN High/Low,	3
12V DC/DC	Wake, Crank, CAN High/Low,	N/A
HV AC Compressor	12V +, 12 V Ground, Wake, Crank, CAN High/Low,	3
Engine Controller	12V +, 12 V Ground, Wake, Crank, CAN High/Low, Throttle In (x2)	3
Parking Lock	12V +, 12 V Ground, Wake, Crank, CAN High/Low,	15

It should be noted the 12V DC/DC should also have a fuse on the 12 V output side and HV input side. A 12 V battery disconnect should also be added as a safety feature (preventing the vehicle from being accidently started) and to protect the battery from being drained.

Keeping the university LV and stock wiring harness separate allows for easier diagnostics of the 12V system. UWAFT used a ‘break-out’ board to accomplish this. A wooden board was mounted in the trunk; on this board were a series of DIN-rail terminal blocks. Each of the devices mentioned in Table 10 were connected to the terminal blocks. Connections that needed to be made between devices, for example CAN, were then ‘patched’ through the terminal blocks. The terminal blocks made it easy to directly measure voltage and switch connections between devices without soldering. The downside was the unappealing appearance and keeping track of all the connections.

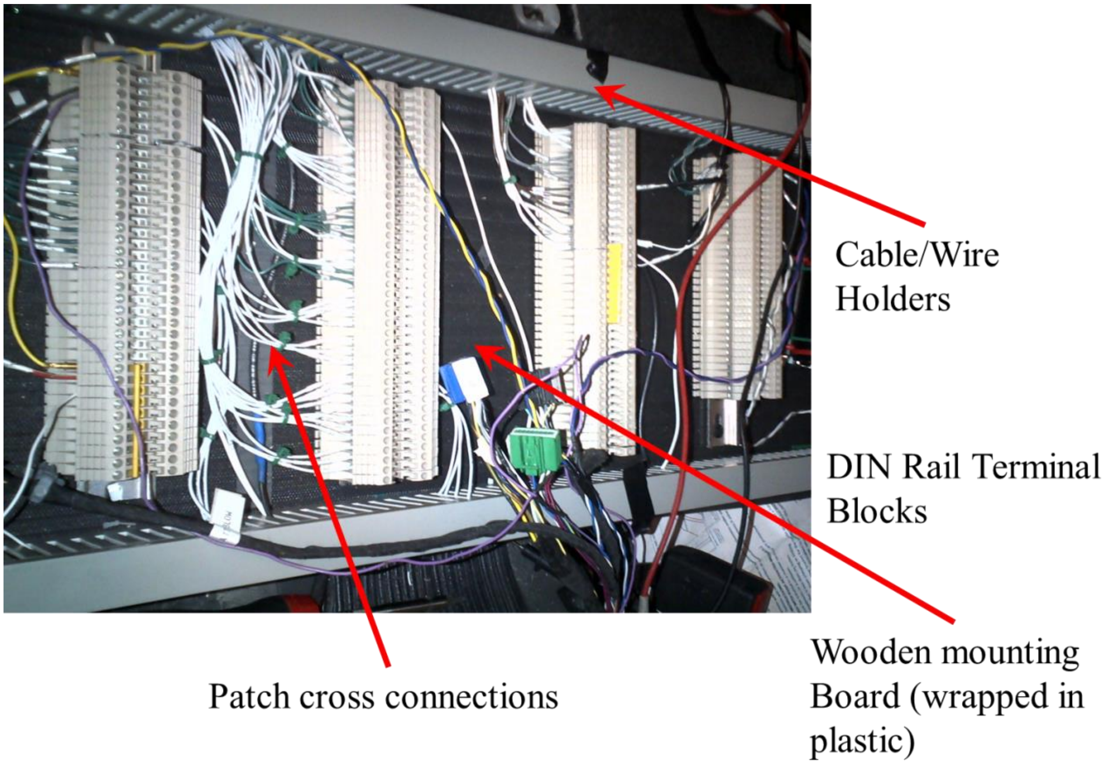


Figure 58 - Break-out board for university 12V system (during construction)

For fusing, automotive grade fuses should be used. These blade type fuses come in different ratings and physical sizes, yet are common for automotive purposes [50]. A fuse block holder can be used to group several fuses together. All devices should be automotive grade (i.e. operate on a 12 V system) and weather proofed accordingly. Wires used should be multi-stranded copper core wires that can operate between -60°C to 150°C. If the wires are being used under the hood, oil and UV resistant wires should be used. If connections for wires need to be made, there are three common methods to achieve this:

- Soldering: soldering works for high gauge (thin wire). These are typically signal wires. Ensure a soldering iron with temperature control and good tin solder is used.
- Butt Splice: used for low gauge (thicker) connections. These are typically power connections. Ensure a proper crimping tool is used and the entire connection is covered in heat shrink.

- Connector: use for devices that are frequently unplugged. These connections can be both signal and power wires, up to a certain ampacity. Select a weather proof connector which comes in a kit with various wire gauges. A kit typically allows for one crimper to cover a range of wire gauges.

Documentation of wiring is also important. Programs such as Altium Designer or other electronic design automation software work well for this task, but licenses can be expensive. UWAFT used a combination of Microsoft Visio and Altium Designer to document the 12 V system's wiring and fusing.

4.7.2 High Voltage Systems

Several of concepts related to high voltage systems are discussed in the preceding Section 4.6. The following sections will discuss HV isolation, ground fault indication (GFI), pre-charging, bleed down and fusing.

High voltage systems are typically isolated differently from low voltage systems. For a low voltage system the chassis or body of the car will be used as a ground. An isolated wire will carry the positive potential. This reduces the wiring complexity (and vehicle weight) significantly. For high voltage systems this is not possible due to safety reasons, thus the high voltage system is completely isolated from the chassis. Two separate cables are used to carry the positive and negative potential. This concept is shown in Figure 59. To further enhance safety, a GFI or HV isolation detection system is used. These systems send a 'piggy-back' signal on the positive/negative cables and chassis ground. If the signal is detected on a different path (i.e. a negative piggy-back signal is sensed on the chassis ground), a ground fault is raised. Several aftermarket companies offer a GFI detection system; in the past UWAFT used a Bender system [51]. UWAFT's current battery supplier, A123 Systems builds a GFI system within the BCM which broadcasts GFI faults via CAN messages.

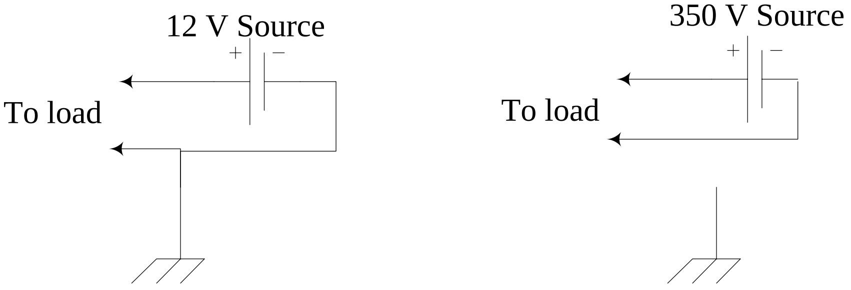


Figure 59 - Difference between LV and HV isolation

Correct automotive HV cables should be used for all HV systems. As mentioned in Section 4.6.8 for Battery Design Consideration, UWAFT uses used Champlain Cable’s EXRAD HV cable system. HV cables should also be fully enclosed in orange coloured solid conduit to protect against abrasion. If the cables pass through a bulkhead or near sharp edges, ensure the conduit passes through as well to protect the cables. The conduit should be labeled as high voltage along with the polarity (positive or negative). The cables should also be located away from the edges of the vehicle, as close to the center of the vehicle as possible, within the frame rails. They should be routed away from any heat sources and have sufficient bend radius. They should be secured to the vehicle every 12 inches.

Precharging refers to the process of voltage equalization across a contactor or other large difference in potential. It is important for systems with high capacitance; when voltage potential is introduced to a circuit with high capacitance, an in-rush of current will follow. This rush of current can be extremely high and can cause damage. As mentioned in Section 4.6.1, the circuitry can preside inside a battery’s HV system, or just outside of it. The precharge circuitry is made up of a contactor and high impedance resistor which controls the current and slowly allows for the voltage to build-up before the main contactors close. A diagram of this circuitry is shown in Figure 33.

A bleed down system brings the system voltage down to zero when main battery contactors close. This allows for the vehicle to safety be worked on. The bleed down is typically a power resistor located in parallel to the DC source. A switch is typically added to resistor; when the system is activated, the switch will close. Some battery or motor suppliers will integrate a bleed down system within their devices; for UWAFT, the motor supplier provided a build-in bleed down system.

Fusing for high voltage systems is critical to protect electrical systems such as motors, batteries and cabling. The general concept is to have the fuse fail first before anything else does. With this in mind cabling, bus bars and other components in the HV system should have a current rating higher than the fuse. Generally the peak power of the current sinks (motors for example) will dictate the fuse current rating. Fuses are typically rated using one of two standards:

- IEC standards, which can continuously operate at 100% of its rated current.
- UL standards, which can continuously operate at 75% of its rated current.

An additional specification for fuses is the breaking capacity, which describes the maximum short circuit current a fuse can safely blow without a failure such as a fire, breakage or explosion. Fuses also have different trip characteristics; they are either fast/quick acting or time-lag. Time-lag fuses trip at slower rates at high currents. UWAFT used fast acting fuses; technically time-lag fuses could have also worked, but given the high cost of the power electronics and experimental nature, the team decided to err on the side of caution. High temperatures can also derate fuses; suppliers typically provide a derating curve which can help compensate for higher temperature applications. Fuses themselves can generate heat; using information provided from suppliers an enclosure that can withstand the heat generated by fuses should be selected.

Another specification to consider is the amperes squared seconds (I^2t) rating. It is the amount of heat energy, in terms of current and time, required to open the fuse. For example, if a motor operates at 300 amps for 10 seconds (an acceleration event), the I^2t rating would be 900000; a fuse with an I^2t greater than this should be selected, otherwise the fuse will open. The I^2t rating is typically selected to protect components from heat during high current, continuous operation; cables are an example of HV components that should be protected this way. Pulsing of the fuses can also cause premature derating. To compensate for the cycling, the I^2t rating may be modified by a pulse derating curve (or fatigue factor) provided by the supplier. For example, the curve may state under 10^4 cycles, the fatigue factor is 29%, thus the new I^2t rating would be $I^2t_{fatigue} = \frac{I^2t_{old}}{0.29}$. The final factor affecting fuse selection is the packaging. Fusing come in different shapes and sizes; UWAFT used a stud style fuse which mounted the fuse with two bolts. These were FWP type fuses provided by Cooper-Bussmann. Further information about fusing selection is available online [52].

A final consideration for electrical system is electrical junction boxes or enclosures. These enclosures may house bus bars and fuses. Depending on where these boxes are located, they may need to be water tight. If so, NEMA 4X or IP64 are acceptable rating for water resistance. Cord grips should also be used to relief stress on cables entering or exiting the box. The location of these boxes is critical as well. They should be located in easily accessible locations for maintenance, and away from any heat sources. If they are located under the vehicle, they should be located as close to the center of the vehicle as possible; ideally within the frame rails. They should not be the lowest part of the vehicle. They should also be properly labeled as high voltage devices.

Chapter 5

Design Implementation Lessons Learned

The goal of this chapter is to highlight the changes that needed to be made when moving from the design phase to the deployment phase. This chapter highlights the benefits of student design teams and research vehicles; by allowing students to see design through to final product, students are exposed to a full design process. They learn about real-world challenges not discussed in the classroom, challenges such as lead-time, manufacturability, and resource management.

5.1 Controls Deployment

There were several challenges that faced the controls team during the design and deployment stage. During the development stage, data needed from suppliers to develop the plant models was difficult to get. Within the plant models, the team was able to estimate the physics of the model based on papers published on the matter; for example how a battery would react during discharging. The lack of data with plant models arise with the plant controllers. The motor suppliers, engine developers and battery suppliers did not supply sufficient information on how their controllers would behave. Generally, suppliers would provide a list of CAN message. With this and past experience UWAFT would have to estimate the control logic. Once the device was bench tested (tested in isolation outside of the vehicle), the team was able to validate the estimated control logic. This process was generally time consuming and if estimations were incorrect, lead to major issues. One such example was the speed control mode within the generator controller. The CAN message list stated the generator could be operated in speed control; hence the entire generator control code was designed around this concept. Once tested on the bench, it was realized speed control did not work as intended. The control code had to be revamped to allow for torque control.

Another example of suppliers not provided sufficient information includes mimicking the GM CAN bus. Due to the removal of the engine and transmission, signals normally sent by these devices needed to be provided to the rest of the vehicle. Again, only the CAN list was provided; the team had to guess the control logic and sequencing when the vehicle was bench tested. The team also had difficulty detecting the gear shifter position. In the stock vehicle, a cable connects the gear shifter to the gearbox, which in turn measures the position of the gear shifter. With the stock gearbox removed, the team needed to find a new way to measure the gear shifter position; the team opted for a sliding potentiometer. A 12 V supply signal was provided to the potentiometer and the change in voltage coordinated to gearshift position, which was sensed by the supervisory controller. The park-lock system, which does not allow for the driver to shift out of park unless the car is turned on and the brake pedal depressed, remained operational without the gearbox.

An issue that was not foreseen during the design phase was the current limitation on the controller. The controller' current output is limited to a maximum of 250 mA. The initial design called for the controller to activate relays for fans, pumps, and device wake-ups. The current required to drive these relays was above the 250 mA limit. The team reverted thus had to design a Darlington transistor which amplified a digital output signal from the controller. The team also investigated constructing a separate CAN controlled relay box, but the idea was discarded due to a lack of people able to design the device.

As mentioned in Section 4.4.2, updating the SIL/HIL models based on updated information from deployment of vehicle code is important. Up to date SIL/HIL model, control code can be updated in parallel and offline optimization can take place. Unfortunately for UWAFT keeping the SIL/HIL models up to date was challenging. The major issue due to this was licensing. The team was provided with unlimited MATLAB licenses, however there were only a limited number licenses for dSPACE controller software. This limitation meant only a handful of students could update the vehicle control code. To mitigate this issue in the future, UWAFT plans to designing a 'wrapper' for the control code. This allows for the kernel code to exist without any dSPACE block sets, allowing for anyone to update the control code. The dSPACE block sets can be added just before the code is deployed to an HIL or on the vehicle. This proposed 'wrapper' layout in shown in Figure 60 , an update to Figure 27

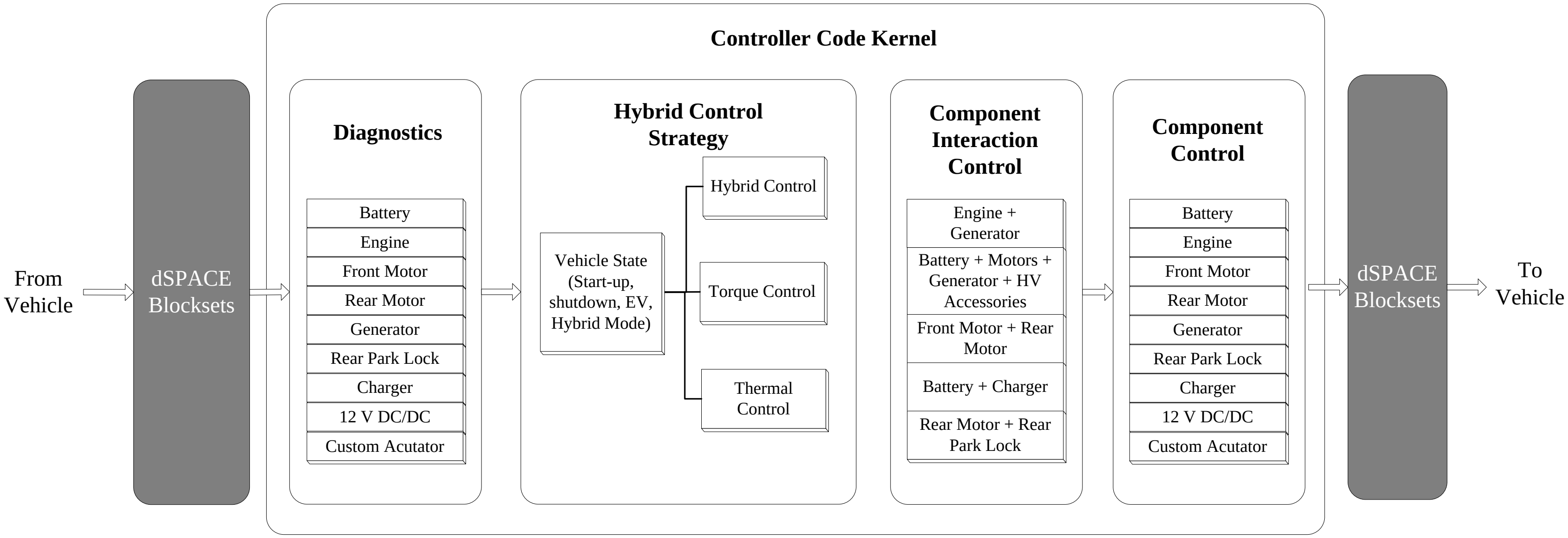


Figure 60 - Updated UWAFT control code with dSPACE wrappers

Beyond the technical challenges of code deployment, human capital was major issue for controls development. Human capital is a broad term, which includes the amount of students, the skills they possess, their commitment to the project, and creativity towards solving problems. For UWAFT, attracting students issues was not an issue; attracting students with the correct skill set was a challenge. Student in software, electrical or computer engineering, which is the required skills for controls development, did not see an automotive based project has having relevance to their field. These groups of students saw automotive design as a mechanical engineering task. The reality is most new cars (specifically EVs, HEVs and PHEVs) contain almost 50 embedded systems that are all within the domain of electrical, computer and software engineering. It is also challenging for the automotive industry to compete with software companies, which typically offer higher pay, better benefits, and better job locations.

Most students working on controls development were mechanical engineering students who learned controls development through self study. This worked well, however mechanical students lacked motivation to learn a new skill set, and many found controls more abstract than mechanical design. Mechanical design is easy to see, touch and hold; controls code is abstract and difficult to explain. Moving forward, UWAFT is working to engage more electrical/computer/software engineering by showcasing the need for their skill sets within the industry. Thanks to the success of Tesla Motors in California and the start-up like approach to operation, UWAFT also hopes to use their achievement to attract more students to the automotive industry.

5.2 Mechanical Changes

Within the scope of mechanical design implementation, there were three challenging aspects: design errors, manufacturing process, and materials selection.

5.2.1 Design Issues

The issues with the design propagated into issues of manufacturing and materials selection. One such issue with design was tolerance and parts alignment. The rear sub frame is made up of several parts, bolted together. M10 sized bolts were used, and with each bolt 1 mm of clearance on both sides (generating a 12 mm diameter hole). As the rear sub frame was constructed the 1 mm clearance began to add-up resulting in a sub frame which didn’t fit properly in the vehicle. This issue could have been resolved if dowels were used to align the parts, with bolts carrying the load. Another issue with the design was machinability; One part in particular was actually impossible to machine. If a machining technician was consulted during the design phase, this issue could have been addressed earlier in the development process.

Typically interference with other parts is not an issue as CAD drawing prevented conflicts, however this is only true if all parts are up to date and loaded into the software; the team learned the importance of revision tracking and keeping model up to date. The team did not include the routing of HV cables within the CAD, which made routing cables within the actual vehicle challenging. Generating shop drawings from the CAD was an issue as well; at times not enough dimensions or views were provided, so students had to go back to the computers to update their shop drawings.

Another design issue that the team faced was in the coupling between the generator and engine. The initial design used a chain, which would be soaked in oil during operation. A case was designed to hold the oil and apply oil to a bearing on the generator. Just before the chain was ordered it was discovered no chain could operate at the desired speed of the generator, which can reach 10000 rpm. The team had to revert to a belt system instead. While oil still needed to be sprayed onto the bearing for the generator, belts are typically not designed to operate in an oily environment. The team expects the belt will need to be replaced yearly, due to premature wear.

The battery pack had several issues with its design that were not realized until the final assembly. The team used cold plates between each of the modules; however this resulted in over 20 coolant connections, all of which pose a risk for leaking. The modules also didn’t match the exact dimensions in the CAD drawing; the mounting points were off by as far as 5 mm, which meant they did not line-up with the support structure exactly. Furthermore, the cold plates themselves are sandwiched between the modules, which made mounting the modules even more challenging. The bend radius of cables was not properly documented in the CAD, which made routing difficult. The enclosure was made from carbon, but the final product didn’t dimensionally match the CAD. This made the enclosure challenging to lineup and meet the mounting holes. The battery pack design required the final assembly to occur within the vehicle, which is a difficult process and can be unsafe if not carried out properly. It also makes servicing the battery pack difficult. In the future, the team will design the batteries to be constructed outside of the vehicle.

5.2.2 Manufacturing and Material Issues

There were several issues that arose during manufacturing. The first was lead-time due to complex design for some parts. Some parts required 5 axis machining; these machines are in short supply and once are open for use requires time to program and set-up. Complex parts also need multiple set-ups, which require even more time. Furthermore, the costs of booking 5-axis machines with multiple set-ups can reach well into thousands of dollars. Welding also affected lead time; typically booking a welder took several days. Parts that were welded also required jigs; these take additional time to design and machine. This was an issue for the rear sub-frame because it required very specific angles to fit ensures it would mount perfectly to the body of the car. Also, welding tends to warp metal and can push dimensional tolerance.

Beyond the manufacturing issues within the mechanical build phase, material selection presented issues. When students designed parts with non-standard sized steel, additional machining was needed. If students designed with common material sizes, costs and manufacturing time could have been reduced. Some students also designed with ‘exotic’ materials such as Aluminum 7075 or 4000 series steels. While these parts were stronger and lighter the costs were extremely high and lead-times long. The performance gains only nominal with these ‘exotic’ materials. In some cases students could have put in some extra effort the design the parts with more common materials any only had a slight gain in mass. Students also did not consider the manufacturability of materials as well. Some steels are much more difficult to machine that other, which increased lead-time and costs. Another mistake that was made was with welding aluminum. Certain types of aluminum, such as the 7000 series cannot be welded; a mistake which led to many delays.

5.3 Electrical Changes

There were a limited number of changes to the electrical system for the vehicle. On the high voltage system, one of UWAFT’s sponsors could only provide a 1000 V shielded cable, rather than the 600 V shielding required. While 1000 V protection is better, the thickness increase and therefore the bend radius of the cable were reduced. This made routing the cables more difficult. The competition organizers specified all HV cables must be protected by solid orange look. Finding loom that was flexible enough to fit within the vehicle, and the correct colour was difficult to find. Compression lugs for the ends of HV cables were also challenging to find, given they needed to have the exact hole diameter and gauging. They also required a long lead time. The HV cables and distribution boxes were not modeled in CAD; this meant the team had to look for any spot possible for the cables and distribution boxes. The result was a trunk full of cables, leaving little room for luggage.

Most of the issues for the LV system within the vehicle surrounded the break out board shown in Figure 58. There was not enough room on the board for all the connections, so the team had to use double stacked terminal blocks. There were occasionally issues with wires coming loose and incorrect connections. Documentation of all the connections on the board was also not always kept up to date. The team will have to remove the board eventually to allow for more room in the trunk.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

The challenge to reduce emissions and energy consumption within the transportation sector has challenged automakers management of human capital. To increase their hiring pool, automakers have collaborated with government and universities in North America to operate hands on student competitions such as EcoCAR 2: Plugging into the Future. The object of this thesis was to discuss how to design, construct and operate a vehicle for a student competition or research group. Various themes are discussed, including: model based design, parallelization of tasks, and required facilities. Examples and areas of possible improvement are drawn from UWAFT's participation in EcoCAR 2.

The facilities and resources needed to design construct and test a student team or research vehicle is are beyond traditional research projects. Universities need to provide insurance, financial and administrative support. A dedicate design and construction space is required large enough to fit a vehicle plus space for subsystems to be constructed and stored. Separate secure space is needed for battery construction. An extensive safety review is needed. Student with the correct skill sets need to be recruited and knowledge transferred between years.

The vehicle design can be carried out using a VDP and model based design with the first phase dedicated to design, the second to construction and the third to refinement. To support the VDP, the human capital can be broken down into three design groups: controls, mechanical and electrical. All three teams come together to outline the vehicle design goals, and use these goals to drive the vehicle' design. Model based design can then be used. The controls team can being to model the powertrain using Autonomie or AVL Drive. This thesis also goes over the controls development process and the benefits of DFMEA, FTAs and HILs for controls development. The mechanical team can then begin the design process using CAD and FEA. The electrical team can model the HV bus and select motors and 12V DC-DC converters, fuses and wiring. By employing a model based design approach, student can: (i) test a range of designs quickly, (ii) test the performance of these designs with a higher degree of confidence and, (iii) test designs without the need for expensive prototypes.

Finding sufficient qualified human capital within a university is challenging. There is a steep learning curve when it comes to working on green vehicles with electric powertrains. The difference between classroom knowledge and real-world engineering problems makes it difficult for new students to take on projects immediately. Co-op or internships tends to help with this, but only if the positions are similar to work being carried out on the vehicle. Furthermore, if many student teams are operating at the same time, there may be a lack of motivated, qualified students and/or competition for these students.

Correct information is critical to successfully carry out model based design. The entire premise of model based design is based on accurate information. Information such as: dimensions, materials properties, performance specifications, electrical specifications, control interfaces and control algorithms can be difficult to attain, even more so for academic environments. Finding sponsors/suppliers who understand the concepts of model based the design and the importance of correct information is critical. Suppliers/sponsors who have also worked with student design teams in the past are also beneficial.

Consulting with industry experts helps produce better products and better predict project management issues. Designs requires experience and given most students are new to designing complex mechanical, electrical and software systems, working with industry experts is essential. Most of the design issues UWAFT faced could have been resolved by consultation with industry subject matter experts. The manufacturability of designs should also be discussed with fabricators, welding, and machining experts. Industry experts can also help estimate lead times and better project costs.

Changes occur when transitioning from design to construction and serve as a reminder that design is an iterative process. While a mechanical design or software algorithm may look acceptable in a virtual environment, it is not uncommon to find issues during the manufacturing or operation of these designs when deployed. Learning and documenting these issues are critical to ensure these issues are mitigated in the future. UWAFT experienced these issues with the sub frame and battery pack. The project plan should also allow for additional time to resolve these issues.

6.2 Recommendations

As mentioned in the Conclusions, this thesis has following the vehicle design and construction focus through the UWAFT's team participation in EcoCAR 2. The recommendations for this thesis focus on methods possible future research work in the following areas: vehicle design processes, student team resources, collaboration, and quantification of student success through student teams.

Vehicle Design Process Recommendations: For many students, it is the first time they have been involved in hands on design project. This results in challenges predicting the time and budget allocations during the vehicle design process. Investigating methods to better predict timing and budgets is critical. Possible methods include documentation of previous projects, or consolation with industry. Generating an open platform, similar to a Wiki web-application maybe ideally suited for this information sharing.

Student Team Resources: This thesis gave a brief overview of the human capital needed. Additional research should be carried out to better quantify the number of undergraduate and graduate students needed to operate a student should be carried out. This research can be expanded to also investigate what types of students (i.e. mechanical, electrical, controls) are needed. Finally, methods to attract students to join teams can also be investigated.

Collaboration with Industry: Consulting with industry is critical to ensure correct information is fed into the model based design process. Working with industry who are familiar with student teams is also beneficial. Also, collaboration with industry to review designs and provide feedback on manufacturability will better predict lead-times, reduce mistakes and costs. Collaborations also benefits industries by providing HQP. A study should be carried out to monitor the relationship between industry and student teams and suggest methods encourage these relationships, perhaps through government incentives. Detailed lists of contacts should be maintained.

Quantification of Student Success: As mentioned throughout this thesis, student teams allow student to apply classroom knowledge to real-world industry related engineering problems. A study should be carried out to compare the academic success of these students versus students who are not involved in student teams. Metrics such as grades, graduation rate, post-graduation hiring, and post-graduation income can be evaluated.

Chapter 7

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