Mechanical Components Design and Optimization for an All-Wheel-Drive Series Plug-In Hybrid Electric Vehicle

by

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Author's Declaration

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

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

Abstract

The University of Waterloo Alternative Fuels Team (UWAFT) is a student team conceived in 1996, participating in numerous student competitions which aim to reduce emissions and improve fuel economy of passenger vehicles. UWAFT was led by faculty advisors Dr. Roydon Fraser and Dr. Michael Fowler in the EcoCAR 2 competition sponsored by the Department of Energy and General Motors. The team designed and competed with a 2013 Chevrolet Malibu, which was converted to an All-Wheel-Drive Series Plug-in Hybrid Electric Vehicle.

UWAFT was conceived with the primary goal of providing university students with an unparalleled level of hands-on experience through a project-based environment. Such projects build on the knowledge and skills learned in the classroom, and presents additional challenges that are not normally seen from the classroom alone. Such challenges include designing for manufacturability, sourcing components, solving problems with uncertainty, teamwork, project planning, and much more. Safety is a primary consideration with all the projects, and proper training are provided for the students, including high voltage training.

One particular topic that is receiving increasing attention is knowledge retention. It is a recurring issue due to the nature of student teams, as experienced team members eventually graduate and leave the team. Although there is usually an overlap of experienced and new team members, sometimes there is a large turnover rate and knowledge retention within the team becomes a problem as a large number of experienced team members graduate and leave at once. As such, detailed documentation of lessons learned is becoming a valuable tool in team knowledge retention as well as saving experienced team members the trouble of individually teaching each and every new volunteer that joins the team.

This thesis provides an outline of the general mechanical design processes as well as a focus on the mechanical design of major mechanical components that are required during a conversion of a vehicle to an Electric Vehicle (EV) or Hybrid Electric Vehicle (HEV). This thesis serves as part of the knowledge retention system for UWAFT such that new team members will have an easier time learning the design processes and understanding some of the things to look out for, with recommendations from the author based on his experiences from designing these components for UWAFT's EcoCAR 2 vehicle.

Acknowledgements

It is my belief that the start of my exciting career within the automotive engineering industry would not have been at all possible without the skills, experiences, and contacts I have gained through participation on the University of Waterloo Alternative Fuels Team and the EcoCAR 2 competition. To that I am extremely grateful for those who encouraged me to join the team.

I want to thank Dr. Roydon Fraser for his unwavering effort in encouraging students to participate in extra-curricular education through involvement with the UWAFT team. It was his ability to sell the never-ending list of benefits of participating on such a team within a very short introductory session that caught my interest and led me to join the team. I also want to thank Gurhari Singh, then Team Captain of the UWAFT team, for his efforts in teaching and guiding me through the all the technical aspects of the design competition as well as his leadership through demonstration of superb work ethics. I would like to thank Hung Nguyen, a past UWAFT leader, who not only taught me a lot of technical skills and encouraged me to work harder but was always there with advice, technical and personal. Without the help of Dr. Roydon Fraser, Gurhari Singh, and Hung Nguyen in getting me involved in the team and guiding me through it, I would not be where I am today with the technical skills I have developed through participating on the team.

I want to thank Dr. Michael Fowler for his support of my participation in the EcoCAR 2 competition. It is very special to see both Dr. Michael Fowler and Dr. Roydon Fraser with a very laid-back and hands-off approach to supervising the team, while providing extreme support towards the team's needs when needed.

I am very grateful for the support of all the EcoCAR 2 organizers and sponsors, as well as local team sponsors that dedicated their time and effort in making the competition happen. I would like to thank the engineering mentors from General Motors, Dan Mepham and Ben Beacock, who put countless hours into helping the team during the EcoCAR 2 competition. Your help was is much appreciated!

I would also like to thank Dr. Michael Fowler, Carol Li, Emily Soo, Erin Soo, and Michael Chow for lending an eye in editing my work and taking it to its current state of perfection.

Lastly, I would like to thank all of the UWAFT team members whom I had the pleasure of working with during the last three years. I would have preferred to put names down here, but I would really hate it if I accidentally missed someone. Without the extreme dedication of each and every single team member, the amazing final product would not have been possible. It has been a very memorable and fun-filled three years of late nights, and I was very fortunate to have spent it with such an amazing group who also shares the same interests as myself!

Dedication

To my Mother and Father.

Thank you for the extreme sacrifices you have made so that I had the opportunity to get to where I am now.

Table of Contents

List of Figures ix
List of Tables xii
List of Equations xiii
Chapter 1 Introduction 1
1.1 Thesis Objective 2
1.2 Thesis Outline 3
Chapter 2 Literature Review and Background 4
2.1 Motivation behind Alternative-Fuel Vehicles 4
2.2 Electrified Powertrain Architectures 6
2.2.1 Parallel Hybrid Electric Architecture 6
2.2.2 Series Hybrid Electric Architecture 7
2.2.3 Parallel-Split Hybrid Electric Architecture 9
2.2.4 Battery Electric Vehicle (BEV) Architecture 10
2.3 AVTC and EcoCAR 2: Plugging into the Future 11
2.3.1 Advanced Vehicle Technology Competitions (AVTC) 11
2.3.2 EcoCAR 2: Plugging into the Future 12
2.4 University of Waterloo Alternative Fuels Team (UWAFT) 18
Chapter 3 Overall Vehicle Design 20
3.1 Vehicle Hybrid Architecture 20
3.2 Mechanical Components 21
Chapter 4 Design Methodology and Information Retention Methodologies 24
Chapter 5 Half Shaft 30
5.1 Half Shaft Design Process 32
5.2 Barshaft Length Design 32
5.3 Welded Prototype Barshaft 35
5.4 Machined Prototype Barshaft 36
5.5 Production Barshaft 41
5.5.1 Material 41
5.5.2 Drawings 42
5.5.3 CNC Lathe Fabrication 42

5.5.4 Spline Rolling 42
5.5.5 Induction Hardening 42
Chapter 6 Rear Subframe 44
6.1 Rear Subframe Design Process 46
6.2 Rear Subframe Hard Points 51
6.3 Rear Subframe Optimization Process 52
6.4 Rear Subframe Design for Manufacturability 57
6.5 Rear Subframe Design for Assembly 58
6.6 Rear Subframe Jig Design 60
Chapter 7 Suspension 63
7.1 Spring and Damping Rates Design Process 63
7.2 Vehicle Data 64
7.3 Motion Ratio 64
7.4 Ride Frequencies 65
7.5 Ride Rate 67
7.6 Spring Rate 68
7.7 Critical Damping 69
7.8 Damping Ratio 70
7.9 Next Steps 71
Chapter 8 Generator Torque Coupling 74
8.1 Torque Coupling Design Process 74
8.2 Speed and Torque Ratio 74
8.3 Mechanical Design of Torque Coupling 76
8.3.1 Motor Bearing and Seal Lubrication 77
8.3.2 Torque Transfer Mechanism 78
8.3.3 Custom Sprockets 86
8.3.4 Generator Bearing Oil Enclosure 87
8.3.5 Expanded Enclosure 91
8.3.6 NVH 95
8.3.7 Failures 95
8.3.8 Lessons Learned 98
8.3.9 Future Improvements 98
Chapter 9 Other Mechanical Components 100

9.1 High Voltage Battery 100
9.1.1 Mechanical Mounting 102
9.1.2 Cooling of Battery Pack 107
9.1.3 Battery Pack Enclosure 107
9.2 Front Powertrain Component Mounting 110
9.3 High Voltage Distribution/Fuse Box 116
9.4 High Voltage AC Compressor Mounting 121
9.5 Powertrain Component Cooling Loops 122
9.6 Electrical Routing 123
9.6.1 Low Voltage Routing 123
9.6.2 High Voltage Routing 124
9.7 Exhaust 126
9.8 Heated Catalytic Converter 127
Chapter 10 Conclusion 130
Chapter 11 Recommendations 133
References 135
Appendix A – Design Methodology Instructional Materials 138
Appendix B – Drawings 141
Appendix C – Electrical Schematics 143
Appendix D – Cooling Loops 144

List of Figures

Figure 1 - Canada 2010 - Energy Use by Sector & Transportation Breakdown 4
Figure 2 - Canada 2010 - Transportation Energy Use by Energy Source 5
Figure 3 - Canada 2010 - Greenhouse Gas Emissions by Sector & Transportation Breakdown 5
Figure 4 - AWD Parallel Architecture (Parallel-Through-The Road) 7
Figure 5 - AWD Series Architecture 8
Figure 6 - AWD Parallel-Split Architecture 9
Figure 7 - Battery Electric Vehicle (BEV) Architecture 10
Figure 8 - EcoCAR 2 competition vehicles at General Motor's Milford Proving Ground 12
Figure 9 - EcoCAR 2 suggested team structure 13
Figure 10 - EcoCAR 2 swimlanes 14
Figure 11 - Team members working in the UWAFT garage 19
Figure 12 - UWAFT competition vehicles 19
Figure 13 - UWAFT EcoCAR 2 vehicle architecture 21
Figure 14 - Mechanical Design Process 27
Figure 15 - Assembled half shafts & exploded view of disassembled half shaft 30
Figure 16 - Gearbox/differential output offset to the left side of the vehicle 31
Figure 17 - Splined barshafts from the half shaft assembly with CV joints removed 33
Figure 18 - Half shaft length measurements from joint pivots 34
Figure 19 - Vehicle wheels rested on blocks for measurements of half shaft lengths 35
Figure 20 - Welded prototype barshaft 36
Figure 21 - Machined prototype barshafts 37
Figure 22 - Barshaft pre-roll diameter too small 38
Figure 23 - Tripod sliding past splines on barshaft due to improper spline run-off 39
Figure 24 - Barshaft with metal filler at end of splines to prevent tripod from sliding past splines 39
Figure 25 - Snap ring groove on torque transmitting portion of barshaft at the splines 40
Figure 26 - Stress concentration at snap ring groove causing a crack & barshaft snapping 40
Figure 27 - Snapped barshaft 40
Figure 28 - Barshaft only painted on portion outside of boots 41
Figure 29 - Front subframe 44
Figure 30 - Front subframe CAD holding front powertrain components 45
Figure 31 - Rear subframe redesign CAD 45
Figure 32 - Rear subframe with hard points (mounting locations) circled in red 46
Figure 33 - Rear subframe FEM showing loads and constraints applied 49
Figure 34 - Final optimized output of rear subframe from Optistruct 49
Figure 35 - Optimized subframe designed for manufacturability and assembly in CAD 50
Figure 36 - Rear subframe welding jig in CAD 51
Figure 37 - Rear subframe optimization process 52
Figure 38 - Rear subframe design space with hard points shown in red 53
Figure 39 - Subframe optimization at various element densities 55
Figure 40 - Final optimized output geometry exported to CAD using OSSmooth 56
Figure 41 - Rear subframe designed for manufacturability overlay on optimized geometry output 56
Figure 42 - Geometry simplification for increased manufacturability 1 57

Figure 43 - Geometry simplification for increased manufacturability 2 58
Figure 44 - Installed old rear subframe design, showing tilted gearbox 59
Figure 45 - Installed old rear subframe design, with half shaft interferences 59
Figure 46 - Old subframe design vs new optimized design 59
Figure 47 - Rear subframe jig with subframe shown 60
Figure 48 - Rear subframe welding jig showing peg board used for locating components 61
Figure 49 - New optimized rear subframe with suspension and powertrain components installed 62
Figure 50 - New optimized rear subframe installed in vehicle 62
Figure 51 - Calculation roadmap for tuning spring and damping rates 63
Figure 52 - Spring motion ratio 65
Figure 53 - Undesired vehicle pitch motion from having same ride frequency in front and rear 67
Figure 54 - Quarter car model simulation using Adams 68
Figure 55 - Critically damped, underdamped, and overdamped responses 70
Figure 56 - Damper FV curve regions 72
Figure 57 - TM4 Motive B 105 kW electric motor efficiency map 75
Figure 58 - GM LE9 Flex-Fuel engine estimated efficiency map 76
Figure 59 - TM4 generator showing exposed bearing at the output shaft 77
Figure 60 - TM4 Generator showing exposed bearing inside torque coupling system housing 77
Figure 61 - Belt-drive system designed in the Gates Design IQ software 79
Figure 62 - CAD of torque coupling belt-drive system 79
Figure 63 - Custom engine and generator Gates sprockets with Gates Poly Chain GT Carbon Belt 80
Figure 64 - Custom Gates sprockets and Gates Poly Chain GT Carbon Belt being test fitted 81
Figure 65 - Generator sprocket showing hub with specified smooth surface shaft seal 82
Figure 66 - Inside of oil dish showing shaft seal sitting on the generator sprocket hub 82
Figure 67 - Custom engine sprocket installed in vehicle showing bolt-on design and large fillet 83
Figure 68 - In-house designed and fabricated belt tensioner 84
Figure 69 - Tensioner installed showing threaded rod and nuts for tension adjustment 84
Figure 70 - Belt tensioning data as taken from Gates Design IQ software report 85
Figure 71 - Oil dish showing inlet directing oil stream into bearing and outlet 87
Figure 72 - Oil dish showing cut-out oil seal 88
Figure 73 - Shaft seal custom ordered for high rotational speed 89
Figure 74 - Old oil dish with small drain outlet installed in belt-drive housing 90
Figure 75 - Redesigned oil dish with larger oil drain outlet made of 3D printed ABS plastic 90
Figure 76 - CAD view of front traction inverter installed 92
Figure 77 - Belt-drive housing spacer installed on belt-drive housing 93
Figure 78 - Belt-drive housing spacer showing counter-bore through holes 94
Figure 79 - Belt-drive housing spacer with rubber seal glued on 94
Figure 80 - Flat lid installed on top of belt-drive housing spacer 95
Figure 81 - Sheared torque-coupling belt removed from vehicle 96
Figure 82 - Broken tensioner assembly showing snapped bolt 96
Figure 83 - Broken tensioner assembly disassembled 97
Figure 84 - Snapped tensioner bolt 97
Figure 85 - Idler pulley from tensioner assembly showing seized bearing 97
Figure 86 - Front of high voltage battery pack showing battery-related electronic components 102

Figure 87 - High voltage battery pack installed in vehicle with cover off 103
Figure 88 - High voltage battery pack showing tubular structure and modules in CAD 103
Figure 89 - Bottom structure for high voltage battery pack welded together 104
Figure 90 - Top structure for high voltage battery pack welded together 104
Figure 91 - Steel rails welded to trunk floor provide flat mounting surface for battery structure 105
Figure 92 - Bottom battery pack assembled 106
Figure 93 - High voltage battery pack showing aluminum cold plates installed 106
Figure 94 - High voltage battery pack carbon fiber enclosure (bottom) 108
Figure 95 - High voltage battery pack carbon fiber enclosure (top) 108
Figure 96 - High voltage battery pack CAD showing electronic components 109
Figure 97 - Bottom of high voltage battery pack enclosure 110
Figure 98 - Engine bay of stock 2013 Chevrolet Malibu 111
Figure 99 - Front powertrain assembly 112
Figure 100 - Engine bay showing 2 of 4 isolation mounts on the front powertrain component 112
Figure 101 - Stock powertrain rubber isolation mount showing hollow sections 113
Figure 102 - Liquid urethane mixtures 114
Figure 103 - Taping up the bottom of the isolation mounts 114
Figure 104 - Pouring of urethane mixture into the hollow parts of the isolation mounts 115
Figure 105 - Urethane mixture hardening 115
Figure 106 - Welded aluminum front powertrain mounting structure 116
Figure 107 - Rear high voltage distribution/fuse box 117
Figure 108 - Front high voltage distribution/fuse box 119
Figure 109 - NEMA 4X certified enclosure for high voltage distribution/fuse box 120
Figure 110 - Front engine bay of UWAFT EcoCAR 2 competition vehicle 120
Figure 111 - Mounting of high voltage AC compressor 121
Figure 112 - Design of AC compressor mounting in CAD 122
Figure 113 - Exhaust leak check fixture 126
Figure 114 - Heated catalytic converter 128
Figure 115 - Heated catalytic converter installed in vehicle 129
Figure 116 - Design IQ - Belt drive system sprocket and tensioner setup 139
Figure 117 - Design IQ - Belt drive system load condition setup 140
Figure 118 - Front motors cooling loop 144
Figure 119 - Rear motor cooling loop 144

List of Tables

Table 1 - EcoCAR 2 Year 1 competition scoring breakdown 15
Table 2 - EcoCAR 2 Year 2 competition scoring breakdown 16
Table 3 - EcoCAR 2 Year 3 competition scoring breakdown 17
Table 4 - Major powertrain components 21
Table 5 - Supporting major mechanical components 22
Table 6 - Flowchart block legend 28
Table 7 - Rear subframe FEM load cases as specified by General Motors 48
Table 8 - High voltage bus bar minimum cross-sectional area as mandated by EcoCAR 2 rules 118
Table 9 - Minimum spacing between exposed live high voltage components to opposite polarity 118

List of Equations

Equation 1 - Spring Motion Ratio 64
Equation 2 - Damper Motion Ratio 65
Equation 3 - Wheel Rate to Spring Rate Relation 65
Equation 4 - Damping Rate (@ wheel) to Damping Rate (@ damper) Relation 65
Equation 5 - Ride Rate 68
Equation 6 - Wheel Rate 69
Equation 7 - Spring Rate 69
Equation 8 - Critical Damping 69
Equation 9 - Damping Ratio 71
Equation 10 - Gear Ratio Relations 75

Chapter 1
Introduction

Energy security issues in North America and other parts of the world are an increasingly major concern. In 2012, energy consumption in the United States ranked second in the world at 79.195 Quadrillion Btu [1], while 28% of energy use in the United States attributes to the transportation sector [2]. With increasing global oil consumption and prices as well as stricter government standards and policies, automakers are searching for ways to reduce the fuel consumption of automobiles. Various methods of reduction in fuel consumption are being developed and utilized, such as the use of alternative energy, use of lightweight material, lighter vehicle architectures, more optimized control systems, among other initiatives. The hybridization and electrification of vehicles is a key initiative, firstly to capture energy with regenerative braking, but also to optimize the size of powertrain components in Battery Electric Vehicles (BEV), Mild Hybrid Vehicles, and Plug-in Hybrid Electric Vehicles (PHEV), reducing overall fuel consumption, emissions, and costs.

Hybrid vehicles refer to vehicles which consist of two or more energy sources. More specifically, Hybrid Electric Vehicles (HEV) are those that combine a conventional internal combustion engine utilizing fossil fuel with electric motors consuming electricity. This combination has the advantage of recapturing kinetic energy through regenerative braking, where energy which is usually lost as heat through conventional braking is recaptured and stored in a high voltage battery onboard the vehicle. Further, it opens up the possibility of utilizing electricity from the grid to power the vehicle through the addition of a charger, as well as vehicle to grid electricity flow with a bi-directional charger. Overall energy efficiency of the vehicle can be increased depending on the hybrid architecture, control strategy, as well as driving habits.

The focus on HEVs by automotive manufacturers is based on numerous reasons, but mostly due to the little to no additional infrastructure required for charging Plug-in Hybrid Electric Vehicles (PHEV), relatively low cost of electrification, and relatively high maturity and reliability of the technology. This is exemplified by the increasing population of production HEV and Battery Electric Vehicles (BEV) purchased and seen on the road today.

While hybridization and electrification of automobiles are increasing rapidly today within automotive manufacturers' portfolios, the need for highly trained personnel in designing, manufacturing, and servicing such vehicles and technology is even greater. Automotive manufacturers are scrambling to find people who are already trained to deal with technology unfamiliar with the conventional automobile such as high

voltage components. One of the ways automotive manufacturers address this issue is through educating post-secondary students through hands-on training programs and student competitions.

The University of Waterloo Alternative Fuels Team (UWAFT) is a student team created with the goal of providing world-class training and unparalleled hands-on experience for post-secondary students in the fields of engineering, business, and communications. The team aims to provide students with practical knowledge and experience through the design, integration, and refinement of the conversion of a production full-size road vehicle, following typical vehicle development processes that would be seen at an original equipment manufacturer (OEM) level. The team is a long-standing participant in the Advanced Vehicle Technology Competitions (AVTC) organized by Argonne National Laboratories (ANL), where regular training seminars and yearly competitions are held within North America, providing the framework for the hands-on training and vehicle development experiences required and sought after in the automotive industry [3].

1.1 Thesis Objective

This thesis outlines the design and analysis procedures of several major mechanical components common to a HEV, as well as documents the common mistakes, failures, and lessons learned in mechanical components design and analysis. These mechanical subsystems are specific to the University of Waterloo Alternative Fuels Team's (UWAFT) EcoCAR 2 competition vehicle: an All-Wheel-Drive Series Plug-in Hybrid Electric Vehicle based on the 2013 Chevrolet Malibu.

With the relatively high turnover of team members on a student team compared to automotive manufacturers, due to the 4-month rotation co-operative program at the University of Waterloo as well as graduating students, knowledge transfer and team knowledge retention is identified to be one of the challenges in this student training program. The examples used in this thesis outlines the author's work and lessons learned in the design and build process, and the intended purpose of this thesis is to create a "handbook" to present the aforementioned to newer students and team members in an organized fashion. This thesis is to facilitate knowledge transfer, team knowledge retention, and to provide a basis for which future design processes and lessons learned can be added to.

Over the course of the EcoCAR 2 project, the author of this work filled the following roles within UWAFT, participating on the vehicle design, integration, and refinement:

- Volunteer Team Member (May 2011 – Aug 2012)
- Mechanical Team Lead (Sept 2012 – May 2013)

- Team Captain (June 2013 – June 2014)

1.2 Thesis Outline

This thesis begins with an introduction outlining the motivation behind alternative-fuel vehicles today and an examination of various common electric and hybrid architectures. This provides a basic understanding and the ability to differentiate between different types of hybrid vehicles in the consumer market today. The advantages and disadvantages of each hybrid architecture are discussed. As this thesis is based upon the vehicle design, integration, and refinement process of the UWAFT EcoCAR 2 competition vehicle, which is an All-Wheel-Drive Series Plug-in Hybrid Electric Vehicle, many of the mechanical components designed are specific to this architecture and it is crucial for the reader to have an understanding of the basics of the Series architecture as well as being able to differentiate it against other common hybrid architectures.

The thesis continues by introducing the AVTC series as well as the EcoCAR 2 competition and a brief history of UWAFT. The EcoCAR 2 competition provides strict rules and guidelines on the design processes of every aspect of the vehicle during the conversion to a custom-built hybrid vehicle, with a heavy emphasis on safety. As such, all components designed are heavily influenced by the competition rules which reflect standards within the automotive industry.

With a technical background of hybrid vehicles and an understanding of the competition governing the design of UWAFT's vehicle, the design of major components required in the hybridization of a vehicle is examined in detail, starting with the basic mechanical design process which is followed for the design of all components. The designs of the major mechanical components are explained with insights, recommendations, and lessons learned by the author through his experience in the participation of these designs, and the assembly and use of the designed components and systems. This thesis ends with conclusions and recommendations by the author on the mechanical design processes involved in the hybridization of a vehicle.

This thesis is a tool for those looking to learn the best practices and design methodology in the conversion of a vehicle to an electric or hybrid vehicle. Safety is of utmost importance, while reliability of components designed is crucial to the success of the vehicle conversion. Although the author believes there should not be any shortcuts taken when designing, fabricating, or assembling vehicle components, this thesis shall serve as a shortcut to the learning process for the designer on his or her quest to designing a safe and reliable HEV or Electric Vehicle (EV).

Chapter 2
Literature Review and Background

2.1 Motivation behind Alternative-Fuel Vehicles

There are an increasing number of vehicle models offered by manufacturers which incorporate some type of electrification and/or hybridization in its powertrain. There are a number of motivations behind the increased research in alternative fuels specifically for automotive use. As of 2013, the estimated total world proved oil reserves reached 1687.9 billion barrels [4], while the world consumption of oil was 33.33 billion barrels [4]. This implies that if the consumption of oil stays at 2013 levels and no new oil reserves are discovered, the current world proved oil reserves will be depleted in 50 years. Note that this is an unrealistic projection as more oil reserves will almost certainly be discovered in the future, while oil consumption will most certainly not remain constant at 2013 levels.

It is worth taking a further look at the consumption of energy by sector as shown in Figure 1. In 2010 in Canada, 2,595 PJ of energy consumption was attributed to the transportation sector [5], of which 1,390.3 PJ belonged to passenger transportation [5]. Further, the majority of the transportation sector's energy consumption consisted of motor gasoline (1,406.9 PJ) and diesel fuel oil (812.4 PJ) as shown in Figure 2.

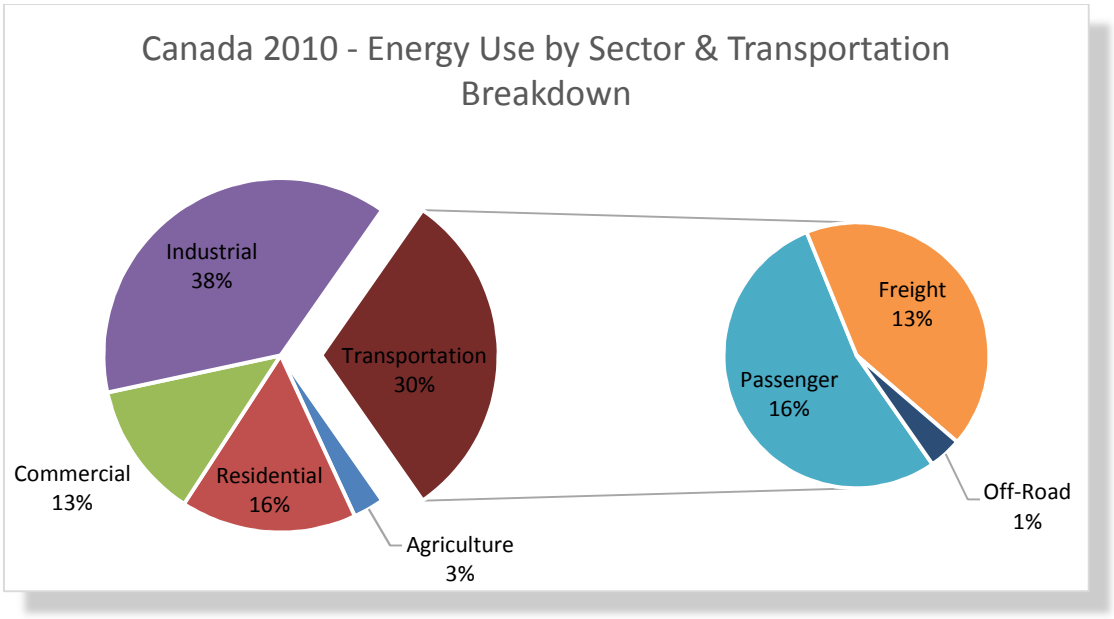


Figure 1 - Canada 2010 - Energy Use by Sector & Transportation Breakdown [6]

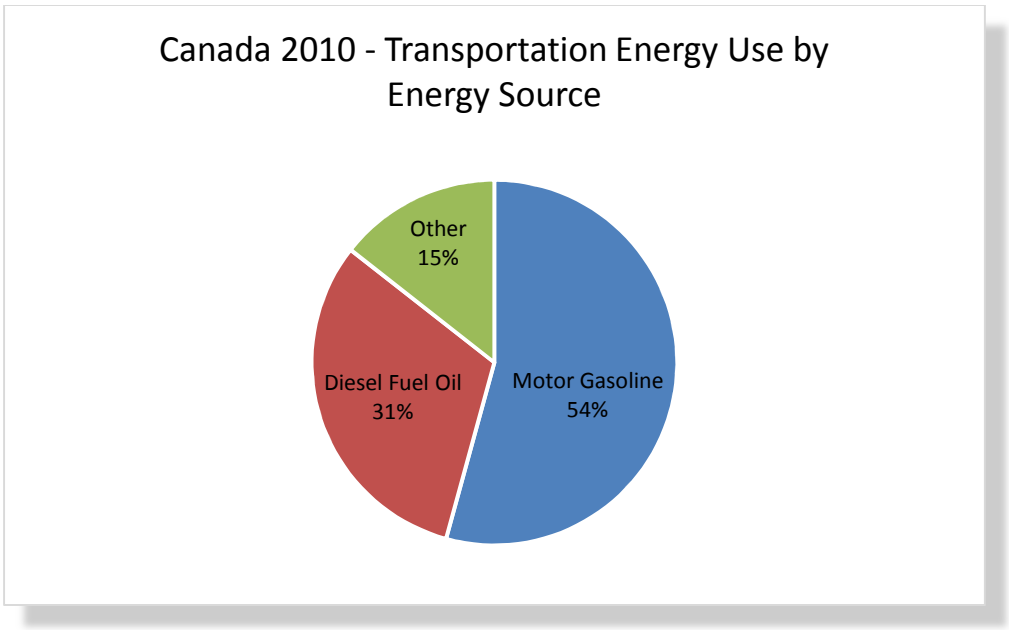


Figure 2 - Canada 2010 - Transportation Energy Use by Energy Source [6]

Another factor that must be taken into account is the greenhouse gas emissions from the use of oil. In 2010 in Canada, the transportation sector contributed to 179.2 Mt of CO_2 [5] as shown in Figure 3.

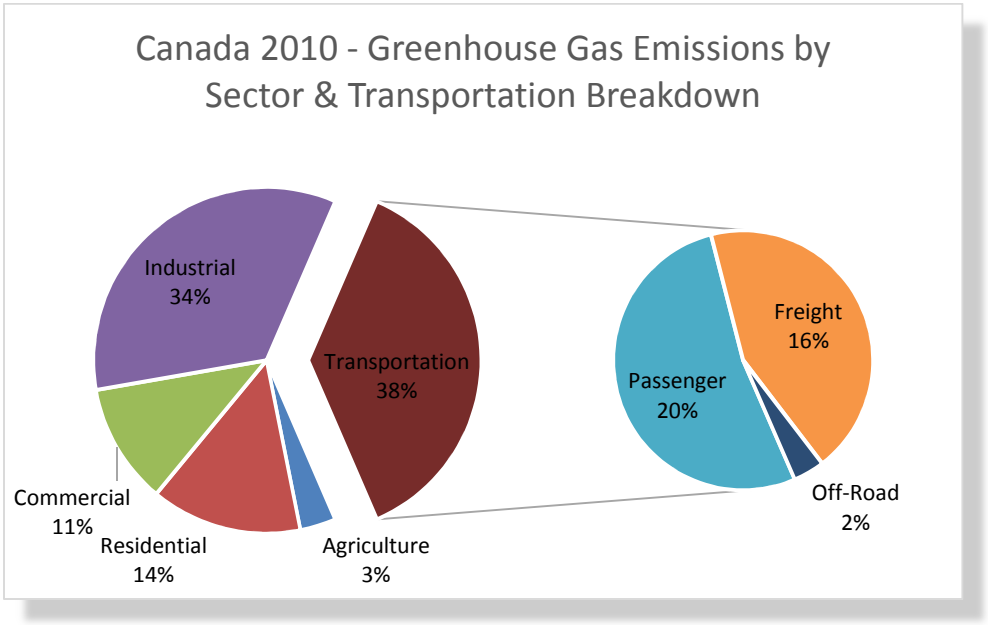


Figure 3 - Canada 2010 - Greenhouse Gas Emissions by Sector & Transportation Breakdown [6]

Greenhouse gas emissions and the supply and demand of oil are not within the scope of this thesis, but rather these figures are presented here to establish the idea that the world's oil reserves are limited and that new technologies as well as a shift in alternative fuels is inevitable. Naturally one of the areas that should

be targeted is the transportation sector, specifically for ground vehicles as they are a major contributor to the country and the world's oil consumption as well as greenhouse gas emissions.

2.2 Electrified Powertrain Architectures

Although electrification and other alternative-fuel vehicles have been experimented with since the beginning of the automotive industry, the widespread acceptance and offering of electrified vehicles or alternative-fuel vehicles only started in the recent decades, due to various factors such as cost, perceived performance, and other factors that are all outside the scope of this thesis. As electrified vehicles are a relatively new product, there is a rapid growth in this field and various electrified powertrain architecture have emerged, each with their own benefits and disadvantages. This section will explore the common electrified powertrain architectures [7] [8].

2.2.1 Parallel Hybrid Electric Architecture

A hybrid vehicle refers to a vehicle that uses two or more main energy sources to power the vehicle. In this case, a Parallel Hybrid Electric Vehicle implies the use of electricity and one other energy source, such as conventional gasoline, diesel, E85 ethanol-gasoline mix, or others. This architecture allows for the vehicle to be propelled directly by both energy sources, hence the name Parallel. An example of a Parallel Hybrid Electric architecture would be a vehicle which has its front wheels powered by an internal combustion engine, which is connected to the gas tank, while the rear wheels are powered by an electric motor connected to the high voltage battery. In this example, both gasoline and electricity has a direct path to the wheels providing propulsion, and is referred to as the All-Wheel-Drive (AWD) "Parallel-Through-The-Road" architecture and illustrated in Figure 4. One can also have a parallel path from the engine and electric motor to the transmission, with clutches to mechanically disengage the electric or the gasoline path. Such arrangement is referred to as the "Pre-Transmission" Parallel architecture. "Post-Transmission" Parallel architecture is possible as well.

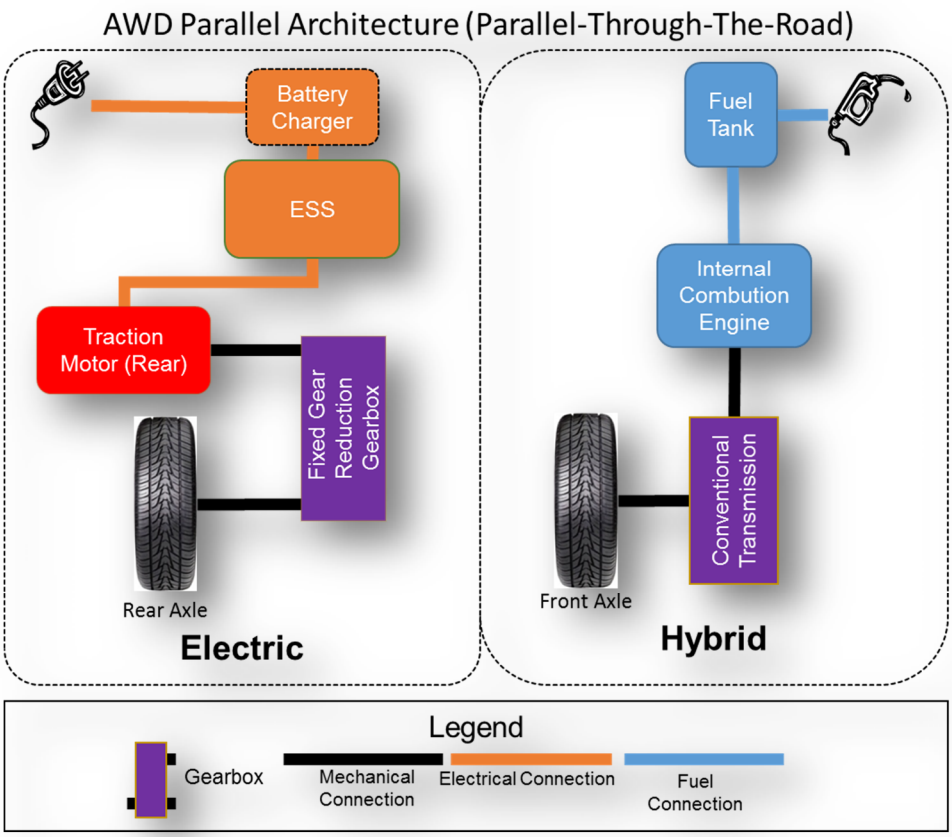


Figure 4 - AWD Parallel Architecture (Parallel-Through-The Road)

This type of architecture is one of the most simplistic of the hybrid architectures, and has several advantages including easy integration, low cost and mass due to less components, and minimal energy conversion losses due to the direct path of each energy source.

However, one drawback is that both the electric motor and the internal combustion engine are coupled directly to road loads through the gearbox, hence maximum efficiency of these components are seldom achieved. This is a big shortcoming particularly for the engine, in that the engine is relatively inefficient during operation in the low power region. Hence in scenarios such as low speed city driving, idling, and deceleration, the low vehicle demand from decreased road load does not allow the engine to reach peak efficiency, ultimately wasting more fuel.

2.2.2 Series Hybrid Electric Architecture

The Series Hybrid Electric architecture has only one path for vehicle propulsion energy. Typically the vehicle is driven solely by one or more electric motors while an internal combustion engine powers a generator. The engine is not mechanically connected to the wheels and as such does not directly provide

propulsion energy. Instead the engine acts as a range extender, charging the high voltage battery through the generator and providing electrical energy directly to the traction motors. This architecture is illustrated in Figure 5.

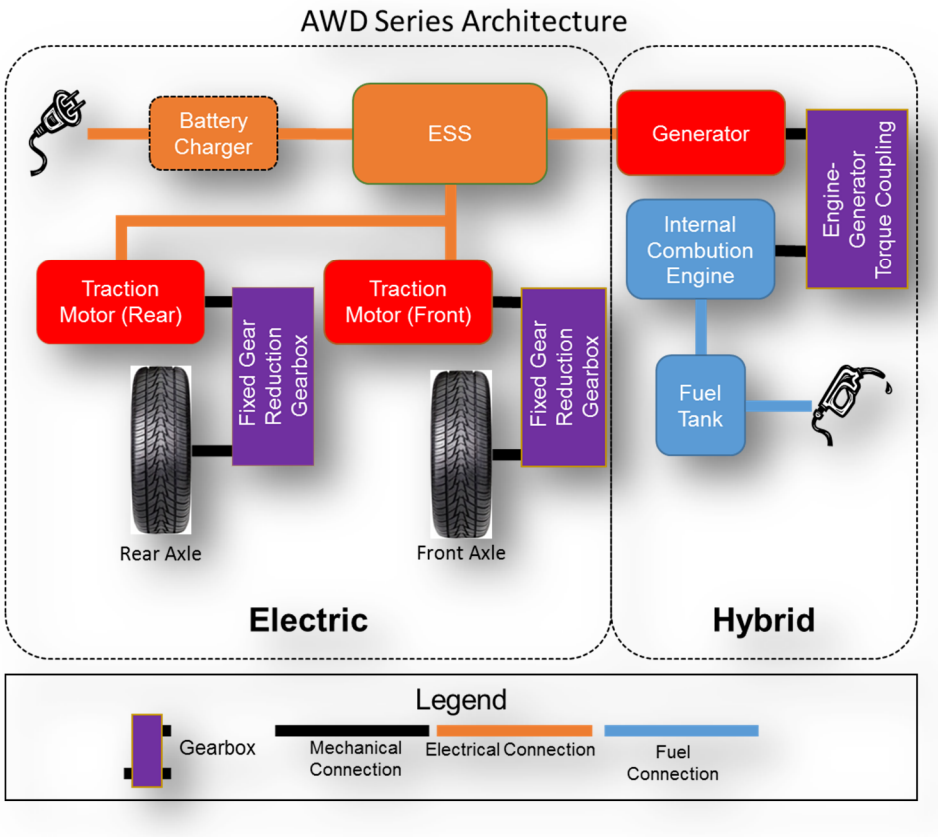


Figure 5 - AWD Series Architecture

The advantage with this hybrid arrangement is that the engine may be controlled to run at its optimal operating point, through careful control of its speed and torque output combination, as the engine is uncoupled from the wheels and road load. This condition allows the engine to run at its highest efficiency.

However, there are several drawbacks to this arrangement. The Series architecture requires more components in its powertrain, driving the cost and mass of the vehicle up as well as introducing packaging challenges for design engineers. Further, as kinetic energy from the engine must convert to electrical energy before converting back to kinetic energy to provide vehicle propulsion, there is a double conversion loss as supposed to an engine that is directly coupled to the wheels through a gearbox. However, this double conversion loss can be offset by efficiency gained through operating the engine near its peak efficiency.

2.2.3 Parallel-Split Hybrid Electric Architecture

A Parallel-Split Hybrid arrangement consists of at least one electric motor along with an internal combustion engine. All power sources can provide propulsion energy to the wheels through a power split device, which is usually a planetary gear set. The ratio of the vehicle propulsion energy from the engine and motors can be altered by controlling the speed of the motors. Furthermore, clutches in the power split device allow the engine and motors to be decoupled and operate independent of the wheels and road load. Depending on where the power split is located, the system can be classified as an input-split, output-split, or compound-split. The All-Wheel-Drive Parallel-Split Architecture is shown in Figure 6.

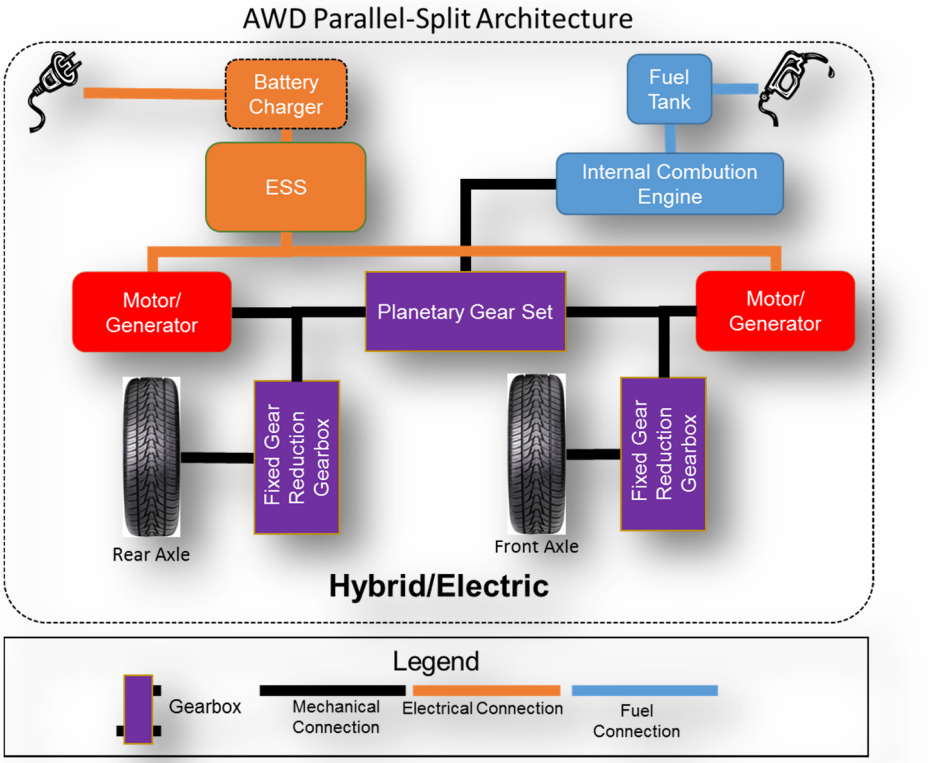


Figure 6 - AWD Parallel-Split Architecture

The Parallel-Split arrangement combines the advantages of both a Series and Parallel Hybrid architecture, in that the engine has decoupling capabilities from road loads, allowing optimal operating conditions and can be downsized. This arrangement also allows for an optimized energy pathway as well as other benefits of a hybrid such as regenerative braking and engine start-stop technology. The Parallel-Split is the most efficient hybrid powertrain architecture, at the expense of increased complexity in the power split device. This is the most common hybrid powertrain in the market today and examples include Toyota's Synergy Drive used in the Toyota Prius, Lexus RX 400h, as well as others from the Toyota/Lexus hybrid line-up.

2.2.4 Battery Electric Vehicle (BEV) Architecture

Battery Electric Vehicles (BEV), or Electric Vehicles (EV) for short, are vehicles that employ a purely electric architecture, consisting of a high-voltage battery and at least one electric motor for propulsion. There are no other sources of energy such as gasoline in the engine and as such is not considered a hybrid. These vehicles do not directly produce any emissions as the powertrain is purely electric. However they may have upstream emissions, and this amount varies depending on the geographic location, as all, if not most, of the electrical energy comes from charging from the electrical grid. This electricity must be generated upstream, and depending on the energy source which could be a coal plant, hydro-electricity, solar, or others, there can be upstream emissions. Only vehicles equipped with equipment such as solar panels may have a portion of its onboard electrical energy obtained from outside of the grid, although the proportion of energy from the solar panels will be minimal compared to that from charging from the grid. It is important to note that electrical energy obtained from regenerative braking still originates from the vehicle's propulsion energy source, as the vehicle must be propelled before there is kinetic energy to be absorbed by regenerative braking. In the case of a BEV, the energy from regenerative braking will still originate from the high voltage battery. The BEV architecture is illustrated in Figure 7.

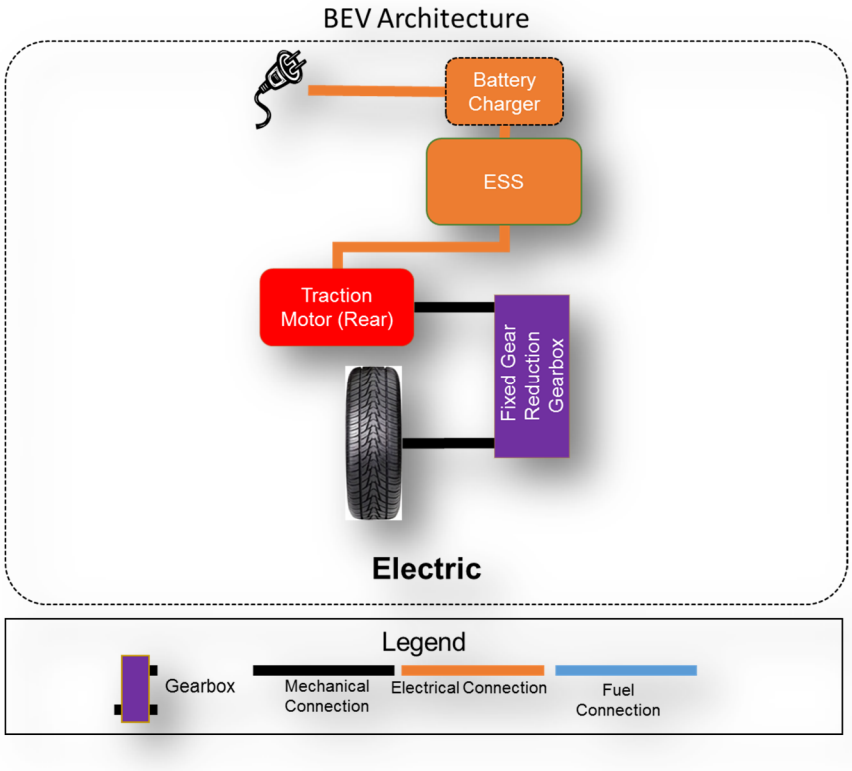


Figure 7 - Battery Electric Vehicle (BEV) Architecture

BEVs are becoming more available in the market today, however they suffer from limited range as well as "range anxiety". "Range anxiety" refers to the psychological concern that the vehicle may run out of charge and become stranded. This is because there is no other energy source onboard other than the high-voltage battery, and when the battery is completely discharged, there is no method of charging the battery immediately and conveniently, compared to filling up an empty gas tank at the nearest gas station. There are more and more charge stations being installed in public, however the charge times are significantly longer than that of filling up a tank, and there are much less charge stations than there are gas stations. There are also battery swap technologies that exist in which the high-voltage battery can be swapped out rapidly and replaced with a fully charged battery [9]. However, there are lots of issues yet to be solved with this alternative such as infrastructure issues and dealing with different state-of-health (SOH) of the different batteries as they degrade over time [10] [11].

Examples of BEVs include the Tesla Model S, Nissan Leaf, Toyota RAV 4 EV, and the Mitsubishi i-MiEV. These vehicles have a maximum electric range of 265 miles [12], 73 miles, 100 miles, and 62 miles on the EPA cycle respectively [8].

2.3 AVTC and EcoCAR 2: Plugging into the Future

2.3.1 Advanced Vehicle Technology Competitions (AVTC)

The Advanced Vehicle Technology Competitions (AVTC) are part of a series of competitions sponsored by the U.S. Department of Energy (DOE) and managed by Argonne National Laboratory (ANL), dedicated to accelerating the development of sustainable vehicle technologies of interest to the DOE and the automotive industry. The AVTC started in 1988 with the Methanol Marathon competition, and have since focused on various different alternative fuels or green car technologies, including propane, ethanol, methane, hybrid, and plug-in technologies. These competitions have each involved one of the "big three" American automotive manufacturers, which would donate a vehicle to each of the teams along with engineering support. The competitions also rely heavily on industry sponsors which include part suppliers, instrumentation companies, consulting organizations, and software companies.

The latest competition of the series is EcoCAR 3: An Advanced Vehicle Technology Competition. It is a 4-year competition focused on reducing the environmental impact of a Chevrolet Camaro while "maintaining the muscle and performance expected from this iconic American car" [3]. However, the author of this thesis was a participant in the previous EcoCAR 2: Plugging into the Future competition, and as such this thesis focuses on the University of Waterloo's entry vehicle in the EcoCAR 2 competition.

2.3.2 EcoCAR 2: Plugging into the Future

EcoCAR 2 was a 3-year competition challenging 15 universities across North America to re-engineer a 2013 Chevrolet Malibu, with the goal of reducing environmental impact without compromising safety, performance, or consumer acceptability. The official technical goals of the competition are to:

- Reduce fuel consumption
- Reduce well-to-wheel greenhouse gas emissions
- Reduce criteria tailpipe emissions
- Maintain consumer acceptability in the areas of performance, utility, and safety [3]

Figure 8 shows the competition vehicles from various universities across North America competing at General Motor's Milford Proving Ground.



Figure 8 - EcoCAR 2 competition vehicles at General Motor's Milford Proving Ground

General Motors was a headline sponsor to the EcoCAR 2 competition, and as such has donated to each team a Chevrolet Malibu and provided engineering support and mentorship. Further, the competition's 3 year duration was based around GM's Vehicle Development Process (VDP), in which the first year of the competition was focused on designing the vehicle, including architecture selection, design of mechanical, electrical, and controls systems, as well as analysis. The second year of the competition focused on the integration of the designs from Year 1 into the vehicle, which included mechanical fabrication and

installation, electrical installation, and control strategy implementation. The third and final year of the competition focused on refinement, where teams were to bring the vehicle to a 99% showroom ready condition. Consumer acceptability of the vehicle was weighed heavily.

The EcoCAR 2 competition had a recommended structure provided by the competition organizers from Argonne, which consisted of three main teams for each competing universities: a technical team, a business team, and a communications team, as shown in Figure 9. The technical team's area of focus was in the design, analysis, integration, and refinement of the vehicle. The business team focused on financial aspects, project planning, human resources, and purchasing. The communications team focused on outreach events such as school visits and tradeshows, handling the media, social media, and more. Within the technical team, it was recommended to be divided into three sections: a mechanical team, an electrical team, and a controls, modeling, and simulations team, where responsibilities are shown in Figure 10.

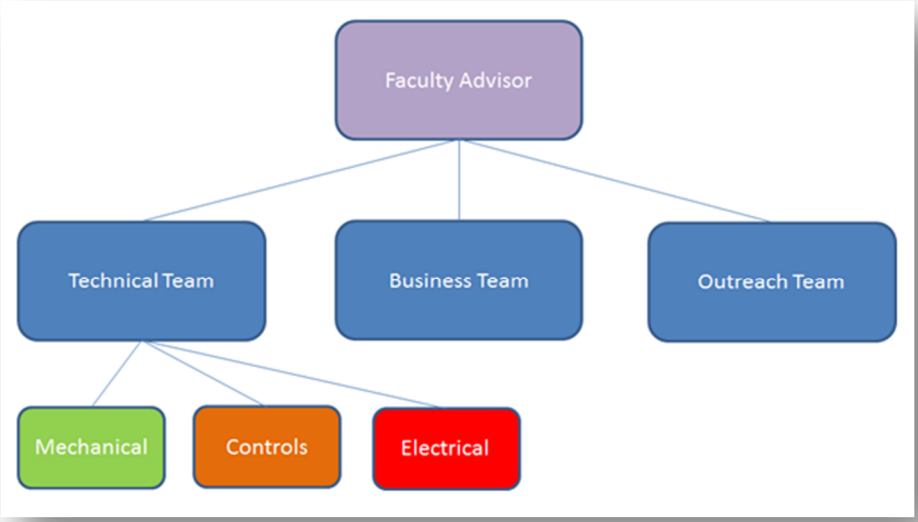


Figure 9 - EcoCAR 2 suggested team structure

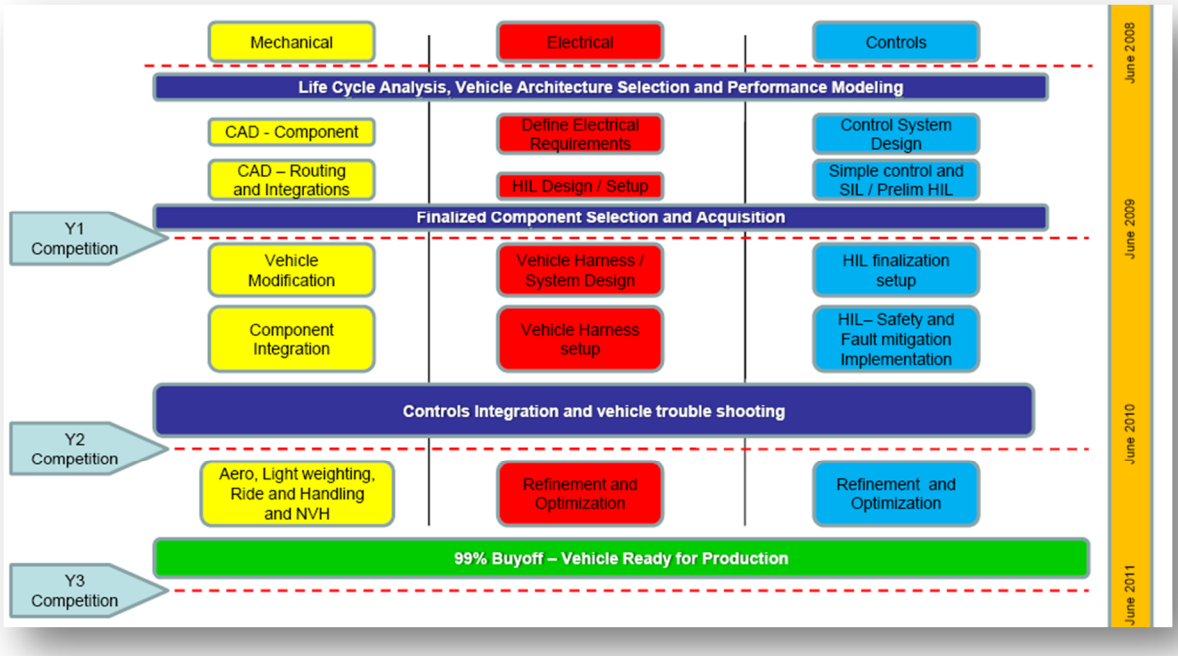


Figure 10 - EcoCAR 2 swimlanes [13]

Throughout each year, there were a number of scored deliverables required from each team which includes engineering progress reports, business-related reports, communications-related reports, and others which vary from competition years. At the end of each competition year, there was a final competition which consisted of a static and a dynamic portion. Since the vehicles were constructed in Year 2, there was no dynamic portion to the Year 1 final competition.

The dynamic portion of the Year 2 and Year 3 final competitions involved taking the competition vehicles to GM's proving grounds and running various dynamic vehicle events after a vigorous safety inspection. These dynamic events included acceleration, braking, skid pad, gradeability, autocross, emissions, fuel consumption, and more. The static portion of each year's final competition included presentations by students on the design process, analysis, and others, followed by questioning by a panel of judges who were selected for their expertise in the specific fields. The presentation topics included: mechanical, electrical, controls, business, outreach, and more. Scoring distribution for the three competition years for EcoCAR2 are shown in Table 1 to Table 3.

Table 1 - EcoCAR 2 Year 1 competition scoring breakdown [14]

Event	Points	Due Date
Pre-Competition Deliverables		
Report 1 – Production Vehicle Modeling	30	9/29/2011
Report 2 – Vehicle Architecture Selection Proposal	80	11/3/2011
Report 3 – Controller HIL Development	20	12/8/2011
Draft Business Plan	5	12/15/2011
Communications Plan	3	1/17/2012
Website	5	1/31/2012
Youth Education Presentation	2	Winter workshop 2/2-5/2012
Business Progress Presentation	5	
Controller HIL Presentation	30	
Report 4 – Subsystem and High Voltage Design	100	2/27/2012
Final Business Plan	5	3/13/2012
Pre-competition Facility Inspection	60	March 2012
Report 5 – HIL System Development and Vehicle Integration Refinement	85	4/5/2012
Sponsor Collaboration Final Video	2	4/17/2012
Final Outreach Report	2	4/24/2012
Final Design Report Draft	0	4/26/2012
Final Design Report	85	5/10/2012
Competition Events		
Mechanical Presentation	85	Year 1 Competition May, 2012
Electrical Presentation	85	
Controls Presentation	85	
Project Initiation Approval	80	
Final Outreach Presentation	6	
HIL Evaluation	90	
Business Presentation	10	
Trade Show	40	
TOTAL SCORE	1000	

Table 2 - EcoCAR 2 Year 2 competition scoring breakdown [15]

Event	Points	Due Date
Pre-Competition Deliverables		
Communications Plan	8	Oct. 30, 2012
Business Plan	5	Nov. 1, 2012
Progress Report 1	20	Nov.8, 2012
Sponsor Collaboration Video and Blog Post	8	Jan. 15, 2013
Winter Workshop Modeling and Simulation Event	50	Winter Workshop
Sponsorship Pitch & Table Top Exhibit	5	Jan. 2013
Progress Report 2	20	Feb. 7, 2013
Pre-Competition Safety and Technical Inspection	40	March 2013
Business Plan Results Report	10	March 25, 2013
Progress Report 3	20	March 28, 2013
Draft Final Technical Report	0	April 18, 2013
Media Report	12	April 30, 2013
Final Technical Report	35	May 2, 2013
Competition Events		
0-60 and 50-70 mph Acceleration	50	Year Two Final Competition Yuma, AZ May 2013
Braking	20	
Autocross	30	
Maximum Lateral Acceleration	20	
Energy Consumption	75	
Petroleum Energy Use	75	
Criteria Emissions	75	
Well-to-Wheel (WTW) Greenhouse Gas (GHG) Emissions	75	
Dynamic Consumer Acceptability	30	
AVL Drive Quality	40	
Gradeability	0	
Static Consumer Acceptability	60	
Vehicle Design Review	50	

Controls Presentation	50	Year Two Final Competition San Diego, CA May 2013
Mechanical Presentation	50	
Electrical Presentation	50	
Business Presentation	5	
Outreach Event Presentation	12	
TOTAL SCORE	1000	

Table 3 - EcoCAR 2 Year 3 competition scoring breakdown [16]

Event	Points	Due Date
Pre-Competition Deliverables		
Progress Report	20	Oct. 24, 2013
Year Three Communications Plan	8	Oct. 31, 2013
Year Three Business Plan	5	Oct. 31, 2013
Year Three Implementation Plan	8	Jan. 16, 2014
Chassis Dynamometer Test Plan	10	Jan. 16, 2014
Sponsor Collaboration Video and Blog	8	Feb. 6, 2014
Progress Report 2	20	Feb. 6, 2014
Draft Impact Report	5	Feb. 27, 2014
Pre-Competition Safety and Technical Inspection	30	March 2014
Progress Report 3	20	April 10, 2014
Influencer Campaign and Report	12	April 24, 2014
Final Technical Report Draft	0	April 24, 2014
Final Impact Report	10	May 8, 2014
Cumulative Modeling and Simulation White Paper	20	May 1, 2014
Final Technical Report	40	May 8, 2014
Media Relations Report	12	May 15, 2014
Competition Events		
0-60 mph Acceleration	25	Year Three Final Competition Milford, Michigan June 2014
50-70 mph Acceleration	25	
Braking	25	

Gradeability	0	
Autocross	25	
Maximum Lateral Acceleration	20	
Energy Consumption	75	
Petroleum Energy Use	75	
Tailpipe Emissions	75	
Well-to-Wheel (WTW) Greenhouse Gas (GHG) Emissions	75	
Dynamic Consumer Acceptability	50	
AVL Drive Quality	50	
Static Consumer Acceptability	75	
Vehicle Testing Complete Presentation	50	
Mechanical Presentation	35	Year Three Final Competition Washington, D.C. June 2014
Electrical Presentation	35	
Controls Presentation	35	
Business Presentation	10	
Outreach Event Presentation	12	
TOTAL SCORE	1000	

2.4 University of Waterloo Alternative Fuels Team (UWAFT)

The University of Waterloo Alternative Fuels Team (UWAFT) is a student team in the University of Waterloo's Engineering department, and has been participating in the AVTC since 1996 in the Ethanol Vehicle Challenge. The team was founded by Dr. Roydon Fraser with the goals of providing a platform for students to obtain real world automotive experiences in the areas of engineering, business, and communications. Figure 11 shows students working in one of the UWAFT work bays.



Figure 11 - Team members working in the UWAFT garage

UWAFT has in the past converted stock vehicles to work on alternative fuels such as propane, natural gas, ethanol, hydrogen, and more recently has worked with hybrids and plug-in technology. Some of the past UWAFT competition vehicles are shown in Figure 12.

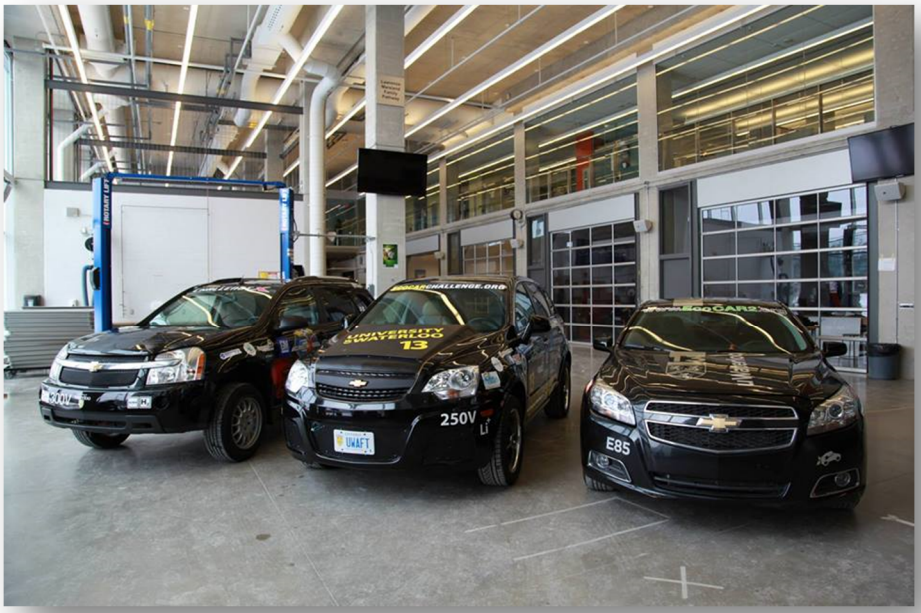


Figure 12 - UWAFT competition vehicles (from left: ChallengeX, EcoCAR, EcoCAR 2)

Chapter 3
Overall Vehicle Design

3.1 Vehicle Hybrid Architecture

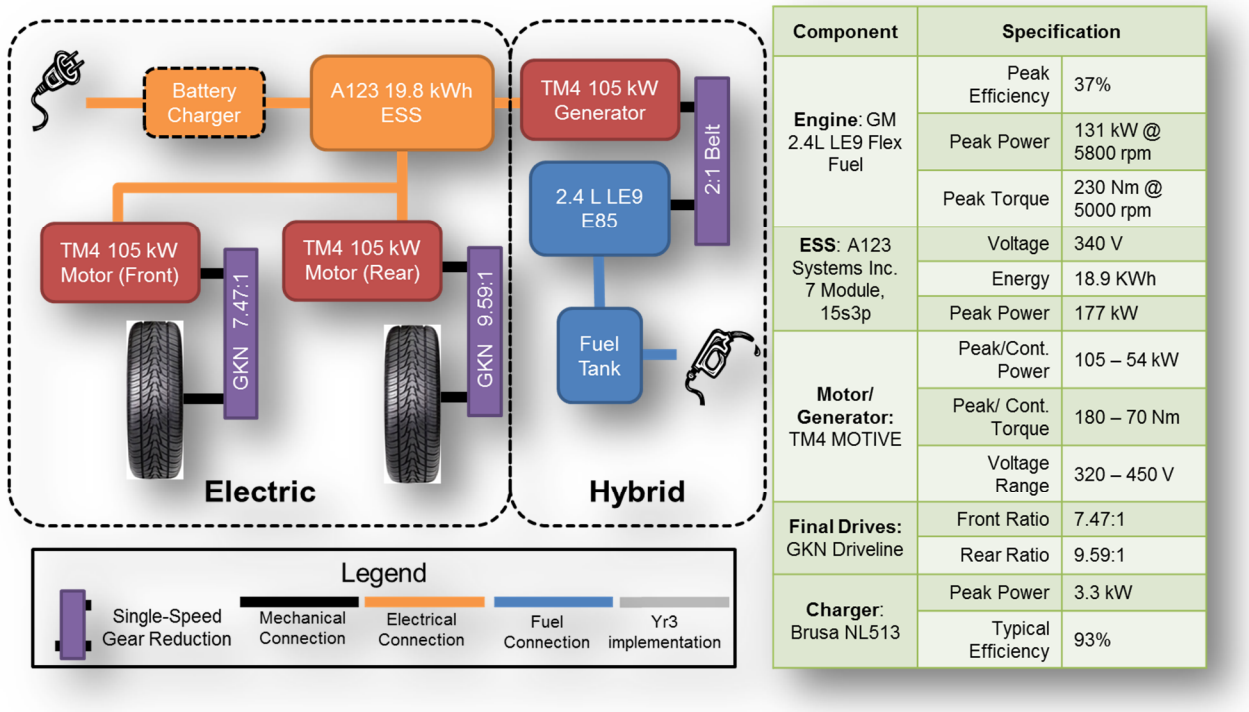
The design and analysis procedures in this thesis are drawn from the University of Waterloo Alternative Fuels Team's (UWAFT) EcoCAR 2 entry vehicle: a 2013 Chevrolet Malibu. This vehicle was donated by the headline competition sponsor, General Motors. Through modeling and simulation in Year 1 of the 3-year competition, UWAFT selected an All-Wheel-Drive Series Plug-in Hybrid Electric Vehicle as the hybrid architecture of the vehicle and has since completed the conversion. The UWAFT vehicle architecture is illustrated in Figure 13.

This hybrid architecture consists of a TM4 105 kW AC induction electric motor paired to a GKN eTransmission fixed gear reduction gearbox in the rear axle, and an identical electric motor paired to a GKN eAxle fixed gear reduction gearbox in the front axle, providing all-wheel-drive traction in the vehicle. These motors are the vehicle's traction motors, and provide a theoretical total vehicle peak traction power of 210 kW (281 horsepower).

A GM LE9 2.4L Flex-Fuel engine is located in the engine bay, which does not provide traction power to the wheels. Rather, this E85-capable engine is coupled to a third identical motor acting as a generator through a custom designed belt-drive system, which provides the "extended-range" capability of the vehicle should the driver take it on a long-distance trip. This defines the "Series" architecture of the vehicle, as the engine's power cannot be directly transferred to the wheels for traction, but must convert into electrical energy first through the generator, before converting back to kinetic energy through the front or rear traction motors for propulsion.

The vehicle has an on-board charger from Brusa which allows plugging the vehicle into the grid through a level 1 or level 2 vehicle charger, drawing power from the grid at a maximum of 3.3 kW.

Lastly, the vehicle consists of an A123 19.8 kWh Li-ion high voltage battery pack located in the trunk, which provides approximately 60 km of electric range for this particular vehicle.



Component	Specification	
Engine: GM 2.4L LE9 Flex Fuel	Peak Efficiency	37%
	Peak Power	131 kW @ 5800 rpm
	Peak Torque	230 Nm @ 5000 rpm
ESS: A123 Systems Inc. 7 Module, 15s3p	Voltage	340 V
	Energy	18.9 KWh
	Peak Power	177 kW
Motor/ Generator: TM4 MOTIVE	Peak/Cont. Power	105 – 54 kW
	Peak/ Cont. Torque	180 – 70 Nm
	Voltage Range	320 – 450 V
Final Drives: GKN Driveline	Front Ratio	7.47:1
	Rear Ratio	9.59:1
Charger: Brusa NL513	Peak Power	3.3 kW
	Typical Efficiency	93%

Figure 13 - UWAFT EcoCAR 2 vehicle architecture

3.2 Mechanical Components

The hybridization and electrification of a vehicle requires the addition of many mechanical components along with the aforementioned major powertrain components for core operation of the vehicle. The components used for UWAFT's EcoCAR 2 vehicle are listed below in Table 4 and Table 5.

Table 4 - Major powertrain components

Component	Model
Front Traction Motor	TM4 105 kW AC induction electric motor
Rear Traction Motor	TM4 105 kW AC induction electric motor
Generator	TM4 105 kW AC induction electric motor
Front Gearbox	GKN eAxle fixed gear reduction
Rear Gearbox	GKN eTransmission fixed gear reduction
High Voltage Battery Pack	A123 19.8 kWh 346 V Li-ion
DC-DC Converter	Brusa
On-board Charger	Brusa 3.3 kW
Supervisory Controller	dSPACE MicroAutoBoxII

Table 5 - Supporting major mechanical components

Component	Description	Critical to Minimal Vehicle Operation
Rear High Voltage Distribution/Fuse Box	Acts as "splitter" from the high voltage bus to individual high voltage components at rear of vehicle. Fuses integrated.	Yes
Front High Voltage Distribution/Fuse Box	Acts as "splitter" from the high voltage bus to individual high voltage components at front of vehicle. Fuses integrated.	Yes
High Voltage Battery Pack Structure	The structure for the high voltage battery modules and all supporting electronic modules for the high voltage battery.	Yes
Air Intake	Inlet routing for the internal combustion engine's throttle body. Contains mass airflow sensor to measure inflow.	Not required for EV
Engine-Generator Torque Coupling	Mechanism to physically connect and transmit torque from engine to electric generator. (e.g. belt-drive, chain-drive, gears, etc.).	Not required for EV
Rear Subframe	Rear structural frame which holds all the rear suspension components to the vehicle as well as and rear powertrain components (e.g. differential, gearbox, traction motors).	Not required for front-wheel-drive (FWD)
Half Shafts	Rods with splined ends and constant velocity (CV) joints which transmits torque from the gearbox/differential to the wheels. CV joints allow for movement of wheels relative to chassis (e.g. wheels turning left/right, suspension travel).	Yes
Suspension (Springs/Dampers)	Springs and dampers for all four corners. Should be redesigned with new spring rates and damping rates to account for increased mass and altered mass distribution. Directly affects vehicle ride height.	Not a requirement, but will significantly impact vehicle ride and handling.
Front Powertrain Mounting Structure	Mounting structure and adapters which connects the front powertrain components (e.g. motor, generator, engine) to the chassis through vibration-isolation mounts.	Not require for RWD
E85-Compatible Fuel Tank	Stainless-steel tank to hold E85 (normal plastic tank cannot hold ethanol).	Not required for EV

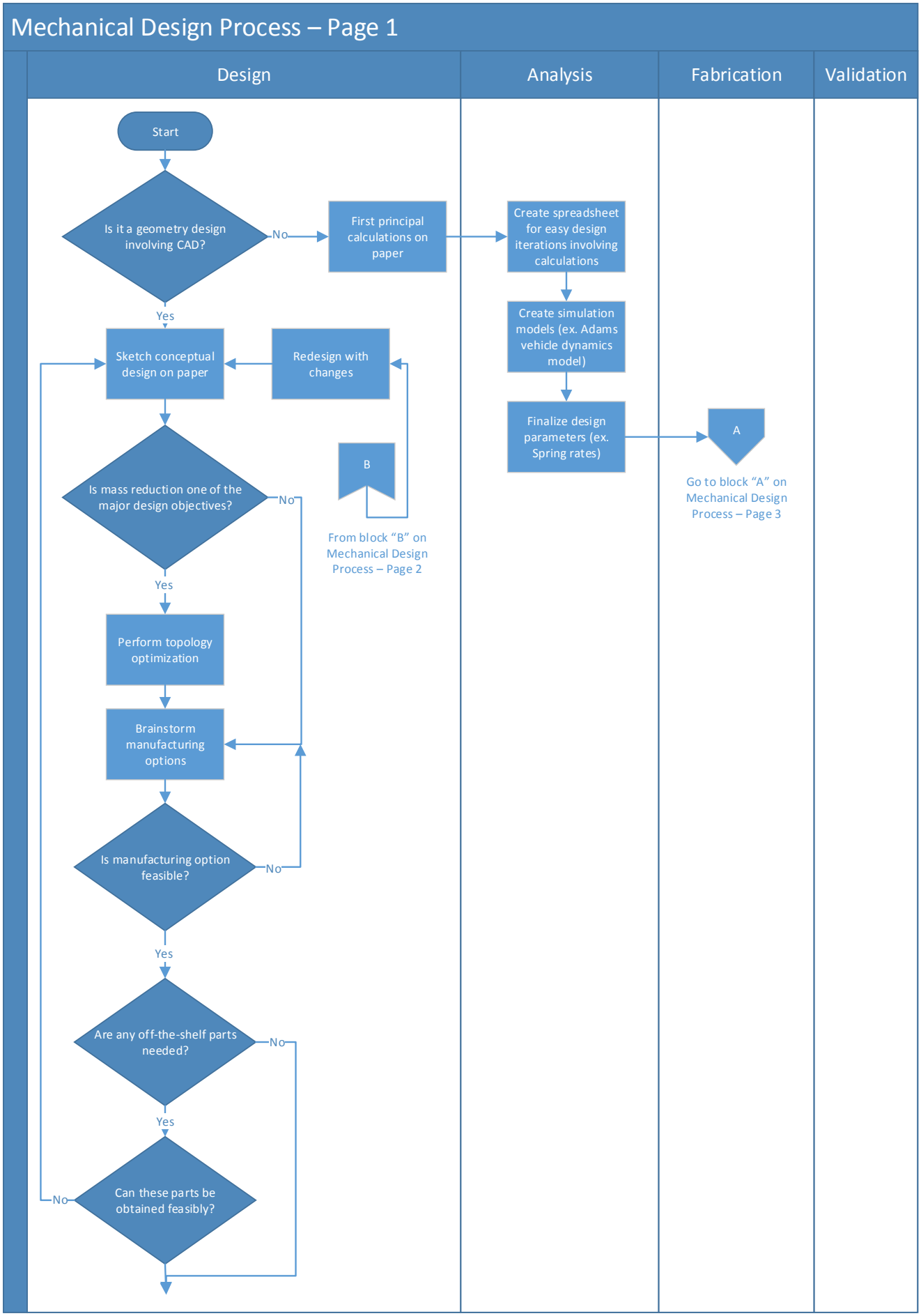
The above list outlines the major supporting mechanical components to the hybridization or electrification of a conventional vehicle. The third column outlines whether the components are critical to vehicle operation. For example, springs and dampers, although are important for vehicle ride height as well as ride and handling of the vehicle, are not critical to vehicle operation as the car will still run with improper spring and damping rates. Some components are only required in certain scenarios, such any engine-related items are not required for a full EV.

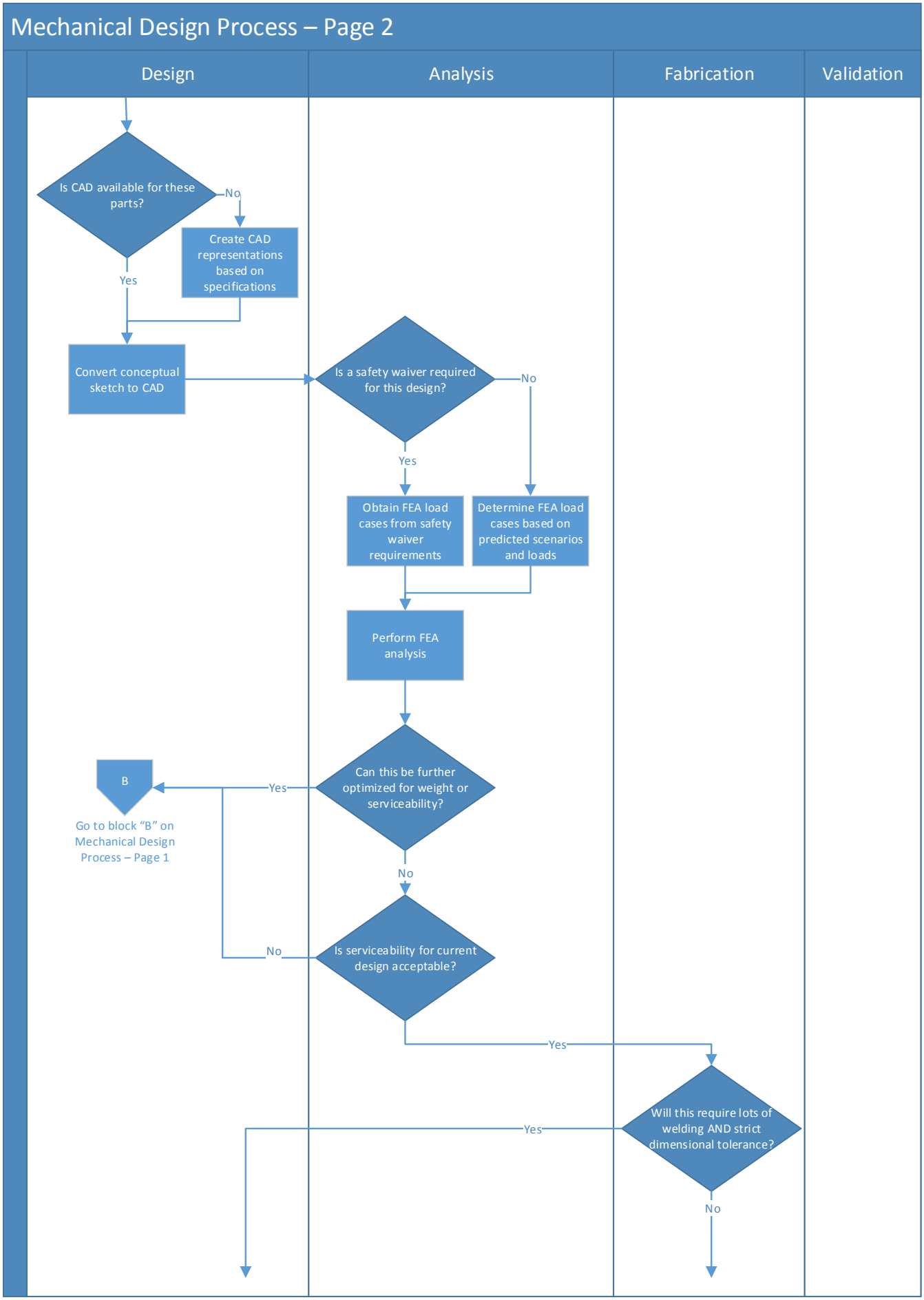
Chapter 4
Design Methodology and Information Retention Methodologies

The design methodology varies from different mechanical components throughout the vehicle, taking into account numerous factors such as complexity of component, design objective, fabrication technique, constraints, and requirements. For instance, the structural rear subframe which supports the rear suspension and rear powertrain components of the vehicle has various strength and stiffness requirements, limited fabrication processes available, and is designed with the objective of overall vehicle mass reduction. This is a relatively more complex design which requires additional steps such as topology optimization for mass reduction, finite element method (FEM) for verification of strength and stiffness requirements, design for manufacturability, design for serviceability, sourcing of available components, material selection, welding jig design, and more. Comparing to a simpler component such as the high voltage distribution/fuse box, this only has spacing requirements between opposite electrical polarities and is required to be waterproof. The design of this component requires only sourcing of off-the-shelf components and careful placement of these parts.

The general design methodology used in the design of supporting mechanical components in a custom All-Wheel-Drive Series Plug-in Hybrid Electric Vehicle is outlined in Figure 14 on the next three pages, with Table 6 showing the legend for the flowchart blocks. The methodology is the result of the author's design experiences, and aims to simplify and outline the design steps for new students as well as provide an organized outline for student teams to aid in splitting the work within the organization, namely design, analysis, fabrication, and validation.

The flow chart is split into four swim-lanes to aid in categorizing steps within the Mechanical Design Process into the areas of design, analysis, fabrication, and validation. This is intended to visually organize the various steps within the design process such that student teams may more easily delegate work within various sub-groups within the mechanical team.


Mechanical Design Process – Page 1
Design
Analysis
Fabrication
Validation
Start
Is it a geometry design involving CAD?
No
First principal calculations on paper
Create spreadsheet for easy design iterations involving calculations
Create simulation models (ex. Adams vehicle dynamics model)
Finalize design parameters (ex. Spring rates)
A
Go to block "A" on Mechanical Design Process – Page 3
Yes
Sketch conceptual design on paper
Redesign with changes
B
From block "B" on Mechanical Design Process – Page 2
Is mass reduction one of the major design objectives?
No
Yes
Perform topology optimization
Brainstorm manufacturing options
Is manufacturing option feasible?
No
Yes
Are any off-the-shelf parts needed?
No
Yes
Can these parts be obtained feasibly?
No


Mechanical Design Process – Page 2
Design
Analysis
Fabrication
Validation
Is CAD available for these parts?
No
Create CAD representations based on specifications
Yes
Convert conceptual sketch to CAD
Is a safety waiver required for this design?
No
Yes
Obtain FEA load cases from safety waiver requirements
Determine FEA load cases based on predicted scenarios and loads
Perform FEA analysis
Can this be further optimized for weight or serviceability?
Yes
B
Go to block "B" on Mechanical Design Process – Page 1
No
Is serviceability for current design acceptable?
No
Yes
Will this require lots of welding AND strict dimensional tolerance?
Yes
No

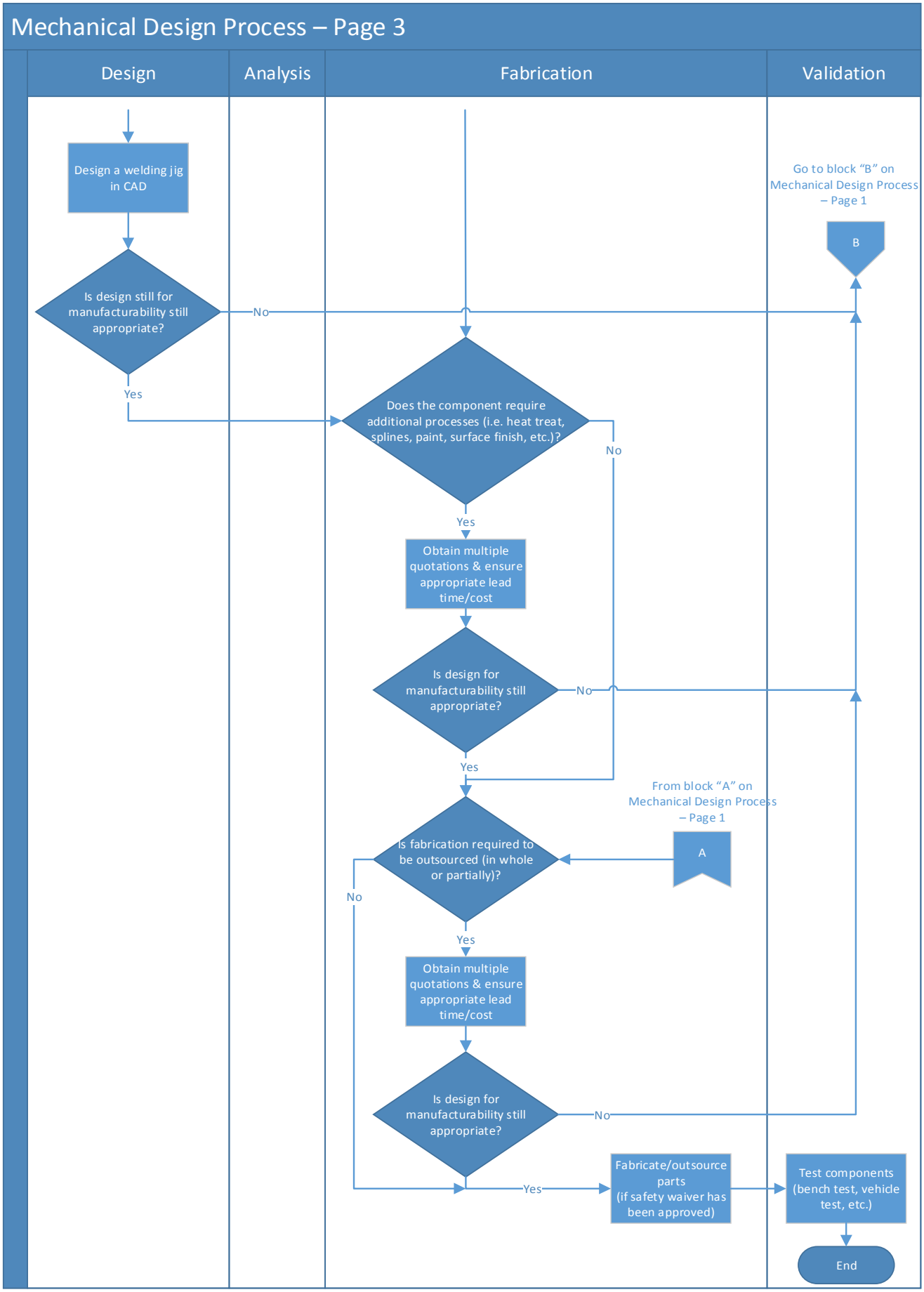


Figure 14 - Mechanical Design Process

Table 6 - Flowchart block legend

Shape	Description
	Start/End block
	Decision block
	Process block
	Go-To block (off-page reference)
	From block (off-page reference)

Seen above in the Mechanical Design Process flow chart, the trend is that the process moves in chronological order from design, analysis, fabrication, to validation. This natural trend is a result of logical design steps; that is the design process begins with a conceptual design, evolving into a concrete design either designed in CAD or on a spreadsheet with numerical parameters specified and finalized. The design is then supported by analysis which may include FEM or other simulations, which in many cases are required in a report in the form of a safety waiver by the student competition organizers. With a proven design through simulation, the design is realized through various fabrication methods and additional processes such as heat treatment, spline rolling, and painting. Lastly, the physical product is tested either on a bench or in vehicle, depending on application and the appropriateness of each test.

The first decision block asks “Is it a geometry design involving CAD?” The answer yes leads to a process that involves CAD design, FEM analysis, fabrication, and validation. The answer no leads to a similar process with the exception that CAD design and FEM analysis are replaced with spreadsheet calculations for parameters finalization and other forms of computer simulation, respectively. For instance, in the design of the spring and damping rates, a spreadsheet calculation and a vehicle dynamics model is suffice while CAD and FEM will not be required if the suspension geometry will remain the same. However, there are scenarios when the process may involve both CAD design and spreadsheet calculations, in which case both processes are applicable and both should be used. The reader should be aware and use common sense when utilizing the process outlined in the flow chart.

Note that throughout the design process, there are several decision blocks which help identify if the design is still valid and appropriate to move forward. This is similar to a sanity check, often performed in the area of controls to ensure that the design is still on track and not violating anything major. Any time the design is deemed infeasible or inappropriate by these decision blocks, the design process loops back to either a simple redesign to rectify the problem, or a complete redesign. For instance, a structural rear subframe may

be designed and optimized to save a significant amount of weight. However, if it is realized that the geometry cannot be manufactured feasibly, for instance, due to limitations imposed by stamping as costs would be prohibitive on such low volume, then the designer must go back and completely redesign the structure such that an appropriate manufacturing process may be used. However, if the subframe is only found to not provide an acceptable level of serviceability, such as in the case a bolt cannot be removed unless the entire structure is taken apart outside of the vehicle, then perhaps a simple redesign and movement of the bolt may suffice.

It must be noted that depending on the student team and the resources that it has, the organization may differ. In some larger organizations, a project manager may exist and take on tasks such as procurement, finding suppliers, quotations, pickup and delivery of parts, scheduling, and more. However, many of the tasks in the design process may be combined and result in being the responsibilities of a single person. For instance, often a single person will be carrying out CAD design as well as FEM simulations. In some cases, a single person may take on the entire design process from start to finish. Various factors play into the distribution of tasks including team resources and timing, and the allocation of tasks should be done in such a way that balances the overall efficiency of the team and the learning of students.

In the following chapters, several specific mechanical design projects specific to the UWAFT EcoCAR 2 competition vehicle will be discussed in details. The Mechanical Design Process will be used and tailored towards each individual project.

Chapter 5
Half Shaft

The half shaft is a component which transmits torque and power from the output of the differential to the wheel hub, as shown disassembled in Figure 15. It is most commonly a steel rod which consists of a constant velocity (CV) joint on both ends that pivot, allowing for movement of the wheels when they encounters a bump or during steering. Depending on the design, there may also be an intermediate shaft between the differential and the in-board CV joint which offsets the pivot point in the outboard direction. Shaft material can also be made of alternative material including carbon fibre in high performance racing applications, although this is beyond the scope of this thesis. Here the focus will be on half shafts that are designed out of steel.



Figure 15 - Assembled half shafts (top left) & exploded view of disassembled half shaft

In a typical conversion and electrification of a conventional vehicle, the stock gearbox is typically replaced to one more suitable for the application, depending on the hybrid architecture. Two immediate problems arise from this switch in gearbox:

- the output location of the differential will most likely have changed, which alters the length of the half shafts needed

- the physical attributes of the differential output in the new gearbox will likely be different from that of the stock gearbox, requiring different shaft profile and splines on the in-board CV joint or intermediate shaft going into the differential

The simplest way to solve both of these problems is by using a set of inboard CV joints or intermediate shaft that is designed for the new gearbox, re-using the original outboard CV joints going into the wheel hubs, and finally fabricating a new barshaft with splines that will fit into the inboard CV joint on one end

and the outboard CV joint on the other end. The new barshaft requires the proper length to account for the new position of the differential output as well as wheel movement from bumps and steering. This will typically need to be done for each wheel as the lengths will likely not be identical from left to right side due to asymmetrical positioning of the differential output from packaging constraints, as shown in Figure 16.



Figure 16 - Gearbox/differential output offset to the left side of the vehicle

The UWAFT EcoCAR 2 Malibu is an All-Wheel-Drive Series Plug-in Hybrid Electric Vehicle, and electric motors are the sole source of propulsion. Hence fixed gear reduction gearboxes designed specifically for the high speed and high torque of electric motors are used at each axle. There is a TM4 105 kW electric motor paired with a GKN eAxle fixed gear reduction gearbox in the front axle, and an identical motor paired to a GKN eTransmission fixed gear reduction gearbox in the rear axle. Further, the rear hubs are from a Buick Lacrosse as the entire rear suspension and subframe was taken from the Lacrosse to allow for the all-wheel-drive architecture. Therefore, the front and rear half shafts are completely different in terms of splines and shaft profile, while the shafts are similar from left to right, the only exception being barshaft length due to an offset of the differential output.

5.1 Half Shaft Design Process

Referring back to the Mechanical Design Process flow chart, the half shaft design process is one which requires both CAD design and calculations, taking both paths from the first decision block. Assuming that off-the-shelf CV joints will be used, that is the outboard CV joints will match the wheel hub and the inboard CV joints will match the differential output, the only thing that needs to be designed is the barshaft connecting the two CV joints together. This is essentially taking the barshaft which matches the outboard CV joint, cutting it in half, and then welding to it the end of the barshaft which matches the inboard CV joint. In fact, this will be the method in which a prototype shaft will be fabricated and used to verify the lengths of the newly designed barshafts.

5.2 Barshaft Length Design

In general the outboard CV joints have a fixed pivot point with respect to the wheel hub, while the inner CV joints allow for linear translation for the pivot point in the cross-car direction. The linear translation in the inner CV joint is referred to as plunge, and this exists because the distance between the inboard and outboard CV joints changes as the wheel moves during bump or steering; the rigid half shaft is allowed to plunge slightly in the cross-car direction to allow for the changing distance between CV joints. Note that a barshaft which is designed too long will bottom out when plunging into the CV joint, causing damage to the tripod mechanism inside the CV joint. On the other hand a barshaft that is too short will become partially or fully unseated when plunging out of the CV joint, again causing damage to the tripod mechanism or mechanically disconnecting the differential from the wheels completely. Figure 17 shows machined and splined barshafts awaiting induction hardening.



Figure 17 - Splined barshafts from the half shaft assembly with CV joints removed

The lengths of the barshafts can theoretically be determined in CAD, as the locations of the wheel hubs which dictates location of outboard CV pivot, and differential output which dictates range of locations of inboard CV pivot, are known. However, from past experiences this can lead to a very inaccurate measurement mostly due to the fabrication tolerances by students on the mounting structure for the gearbox, ultimately causing the differential output to be located several centimeters away from its design position. The barshaft design length should be obtained from CAD, but this should only be used as a reference, complimenting actual physical measurements. Figure 18 shows the length measurements to be taken from differential side CV pivot to wheel hub side CV pivot.

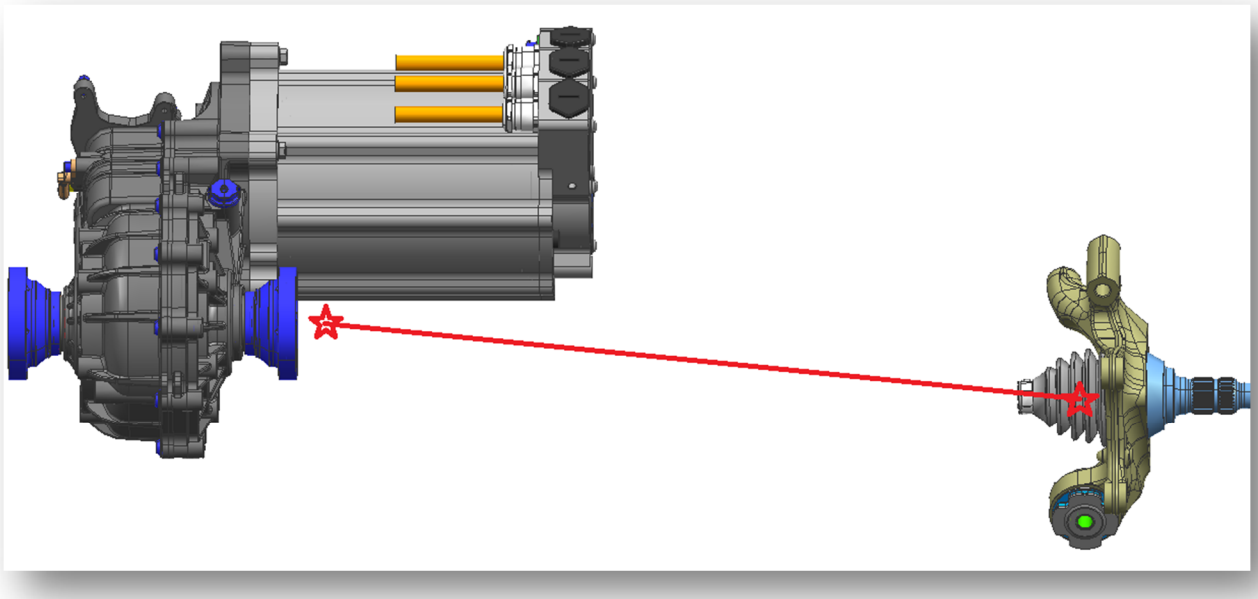


Figure 18 - Half shaft length measurements from joint pivots

If the physical vehicle is available with at least the wheel hub and gearbox installed, a physical measurement can be carried out using a string held from the outboard pivot point to the range of inboard pivot points, as shown in Figure 19. Two measurements are to be taken at each vehicle position: shortest distance from the outboard pivot to the inboard pivot (which is the most outboard position on the range of inboard pivot positions), and the longest distance from the outboard pivot to the inboard pivot (which is the most inboard position on the range of inboard pivot positions).

The above measurement process is then taken with the vehicle in the air, with suspension unloaded, at three positions: with the wheels straight, with the wheels fully turned to the left, and with the wheels fully turned to the right. Only one measurement will be required at the rear assuming the rear wheels do not steer.

This process is to be repeated with the vehicle sitting on blocks, where suspension is loaded with weight of vehicle. Ensure that the vehicle sits safely on the blocks, and that the blocks are able to support the weight of the vehicle. A person should also be in the driver's seat holding the brakes as a safety precaution as there will be someone measuring the CV joints underneath the vehicle. Ensure that the vehicle is lifted off the blocks before turning the wheels to a different position. The measured values will either increase or decrease from before as the distance between the inner and outer CV pivots have now changed. Based on this change, it can be determined whether the distance between inboard and outboard CV pivots will continue to increase or decrease if the suspension was loaded further until it is fully compressed.

The goal is to design the barshaft such that the inner pivot will always be within the full range of inner CV pivot plunge depth during the full range of suspension travel and steering.



Figure 19 - Vehicle wheels rested on blocks for measurements of half shaft lengths

5.3 Welded Prototype Barshaft

With barshaft lengths designed, a first set of prototype barshafts can now be fabricated to confirm the lengths. This requires the procurement of the original barshafts which came with both the outer CV joints and the inner CV joints at each corner of the vehicle. Only the one end of each barshaft which matches the CV joint being used on the prototype vehicle will be used. The matching end of the barshafts is to be cut near the middle section such that when the two ends are welded together they form a new prototype barshaft with the appropriate design length for each wheel. This is shown in Figure 20.

With the ends cut as perpendicular to the longitudinal axis of the shaft as possible, they are to be welded together as straight as possible. Confirm that the lengths are still within the previously designed specifications after welding.



Figure 20 - Welded prototype barshaft

Assemble the new prototype shafts back into the CV joints using the original hardware and ensure that the right snap rings and retaining clips are used; otherwise there is a risk of the CV joints being permanently stuck to the barshaft due to an oversized retaining clip from past experience. Leave the CV boots out so that the inner tripods can be inspected, and install the half shaft assembly back into the vehicle.

With the half shaft assembly installed on the vehicle, measure the distance of the tripod assembly from the CV joint at each of the positions used previously in designing the barshaft lengths, and ensure that the inner tripod sits within the full range of plunge depth of the inner CV joint.

Do not drive the vehicle with the welded prototype barshafts as the welds will not be able to take the torque transmitted from the gearbox to the wheels and can result in catastrophic failure.

5.4 Machined Prototype Barshaft

A second set of prototype barshafts can now be fabricated from solid steel round stock which will give the strength required in driving the vehicle temporarily, as shown in Figure 21. This is a cost effective way to ensure that the design lengths are in fact appropriate even under severe road conditions, such as a big pot hole, big bump, hard cornering, or combination of the above.



Figure 21 - Machined prototype barshafts

Typically using pre-heat-treated 4340 steel for the prototype half shafts is adequate for short testing. The material should be able to provide the strength required, however the problem lies in fatigue. From past experience, prototype half shafts made using this material have failed after a few hundred kilometers of testing through the form of a small crack initiating at the weakest point, such as a snap ring groove, which eventually propagates into shearing of the entire solid shaft. Lifetime of the prototype shaft will depend heavily on driving conditions as well as output torque rating of the engine or electric motor.

Machined prototype barshafts can be splined by any local gear and spline suppliers. By simply providing the welded prototype barshafts with the original splines, the suppliers should be able to find something that will fit. Note that this is not necessarily a perfect fit and tolerances may be slightly off, but for the purposes of fitment testing this should be adequate. An important note in this step is that high attention should be paid to the tolerance of the pre-roll diameter of the shaft, where the splines will be rolled or cut. From previous experience, shafts that are fabricated with pre-roll diameters that are slightly too large or small can create significant fitment problems, and if such problems are found it is highly recommended to fabricate a replacement shaft. Pre-roll diameters that are fraction of a millimeter too large will not fit into the tripod assembly, while pre-roll diameters that are slightly too small could cause the splines to "slip" and grind in the tripod during high torque applications, causing irreversible damages to the costly tripod assembly which costs roughly $200-300. Figure 22 shows the result of a shaft with its pre-roll diameter turned too small.



Figure 22 - Barshaft pre-roll diameter too small

It is also likely that depending on the splining supplier and the processes that are used for rolling/cutting splines, they may not have the right tools to give the proper spline run-offs. This may cause issues such as the tripod sliding past the splines into the center of the barshaft, as some stock barshafts rely upon the spline run-off as a hard stop to the tripod, as shown in Figure 23. If the tripod slides past the splines while in the vehicle, it can cause the tripod to become uncoupled from the barshaft, rendering the vehicle inoperable. Several techniques can be used to remediate the issue on the prototype shafts, however a proper spline run-off should be used on the production barshaft to avoid further issues caused by these temporary fixes. One can remediate the run-off issue by tack welding onto the end of the splines, applying metal filler which hardens onto the end of the splines, or machining a snap ring groove at the end of the splines and installing a snap ring there. These methods all provide an alternate hard stop to the tripod, however each of these solutions have their respective weaknesses. Welding onto this material can cause it to become very brittle and crack, causing fatigue issues. Metal filler can crack or fall off completely from the shaft if not adhered well, causing the debris to be ground up in the CV joint assembly. The introduction of a snap ring groove in the torque path of the barshaft, as shown in Figure 25, creates stress concentration and can create cracks and fatigue issues, and has resulted in a completely sheared barshaft without warning after months of operation from past experience, as shown in Figure 26 and Figure 27. Figure 24 shows filler material applied to the end of splines as a temporary fix.



Figure 23 - Tripod sliding past splines on barshaft due to improper spline run-off

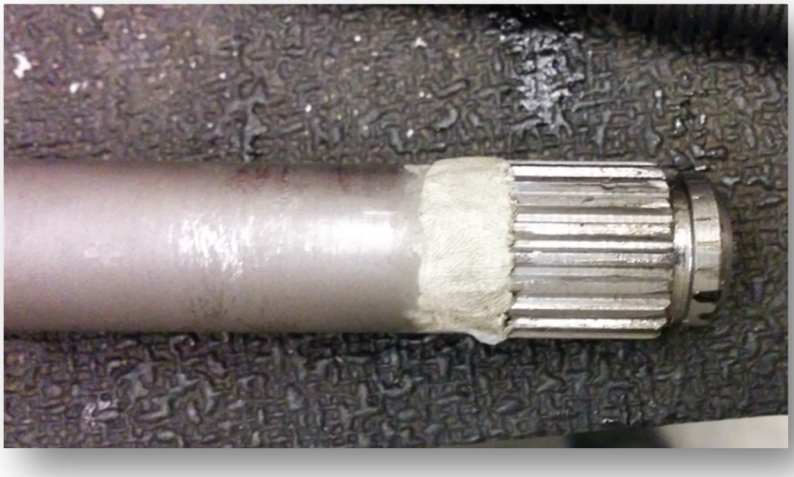


Figure 24 - Barshaft with metal filler at end of splines to prevent tripod from sliding past splines

Ensure tight tolerances for the retaining ring groove at the outboard splined section of the shaft, and inboard if it exists, and ensure that the correct retaining clip is used at these locations. From past experiences, if the groove diameter on the shaft is slightly too large or a slightly larger retaining ring is used, disassembly of the shaft from the tripod assembly may not be possible after installation. If the shaft is found to be stuck on the tripod and cannot be disassembled, the shaft can be cut near the tripod assembly and drilled out carefully, hence saving the cost of purchasing another costly tripod assembly. Further, pay careful attention to the handling of the tripod assembly and related parts, as these parts will crack easily when dropped and if they experience impact forces.



Figure 25 - Snap ring groove on torque transmitting portion of barshaft at the splines



Figure 26 - Stress concentration at the snap ring groove caused a crack, resulting in the barshaft snapping at the groove from fatigue



Figure 27 - Snapped barshaft

If the machined prototype barshafts will be left on the vehicle for extended periods of time, they should be painted in the areas that are exposed to the environment, such as center of shaft outside of the boots. This will provide added protection from oxidation of the steel. Do not paint the portion inside the boot and especially the splines, as the paint will chip and come loose, causing added friction and increased heat from the CV joints during high speed and/or high torque operation. Figure 28 shows a painted shaft.



Figure 28 - Barshaft only painted on portion outside of boots

5.5 Production Barshaft

As this guide is intended for prototype vehicles, parts on this vehicle will not be made at a high volume "production" level and hence will usually cost significantly more than production vehicles. Some manufacturing processes are meant for high production runs such as metal stamping and induction hardening, and hence may not be cost effective or efficient for one-off or very low production parts. The fabrication of production barshafts require them to be properly induction hardened, providing the high strength and hardness of the outer shell, while keeping a soft inner core which provides the fatigue life from the cyclic loading through years of use. It is challenging to find suppliers that are willing to do small batches of induction hardening and it is usually very costly, however this method of post-machining process is highly recommended as shafts have sheared in half completely with no prior warning from past experience due to fatigue.

5.5.1 Material

The production shafts should be fabricated from a mild steel with enough carbon content for induction hardening to the proper shell hardness, and it is suggested to use SAE1045 or SAE1050. SAE1050 is harder to get a hold of but is ideal in obtaining the shell hardness, while good quality SAE1045 from a reputable supplier should suffice. Note that suppliers will sell SAE1050 as 1045 sometimes as it is of higher quality.

Spline suppliers as well as CNC lathe fabrication suppliers should be able to provide quotations with material included. This may sometimes result in reduced cost.

5.5.2 Drawings

Proper drawings with all dimensions as well as tolerances called out are required, as well as the 3D .STP and 2D .DXF files. Further, spline specification callout along with spline run-off must be present in order for the shafts to splined properly. Lastly, induction hardening details outlining shell hardness, core hardness, and case depths must be present. It is recommended that the splined area of the shaft not be dimensioned for its diameter to avoid confusion, as the spline supplier will be able to advise on proper pre-roll diameter based on the spline specifications. See Appendix B – Drawings for a sample of such drawing.

5.5.3 CNC Lathe Fabrication

It is recommended to have the barshafts machined precisely on a CNC lathe for accurate pre-roll diameters and retaining ring grooves, as well as other features. The machining cost for barshafts is very reasonable at roughly $70-$80 for machining including material each, versus $30 for material alone, although outsourcing to a CNC lathe is not absolutely necessary.

Spline suppliers should also be able to provide quotations of the CNC lathe fabrication of the barshafts along with splining operation and material, resulting in a reduced cost. Ensure to obtain multiple quotes from several suppliers for comparison.

5.5.4 Spline Rolling

Most splines on barshafts are designed to be rolled using a certain pre-roll diameter. The spline company will be able to advise on proper pre-roll diameters based on the spline specifications. It is recommended that a supplier be found such that the splines are rolled not cut, and that they have the right tooling given the spline specifications as well as spline run-off, to ensure proper fitment into the tripod as well as to ensure that the tripod does not slide past the splines, uncoupling the barshaft from the CV joint. The spline supplier should be able to provide a quotation with the material and the CNC-lathe operation of the shaft, reducing overall cost.

5.5.5 Induction Hardening

Due to the high torque application along with the cyclic loading nature of the barshafts, it is strongly recommended that the shafts be induction hardened to provide the proper surface hardness for high strength while retaining a soft inner core for fatigue properties. This will ensure that the barshafts can handle the high instantaneous torque of the electric motors while lasting hundreds of thousands of kilometers and years of use.

The induction hardening process is meant for high volume runs, and as such it will be more challenging to find suppliers that will provide this service to a small batch of parts as in this scenario. Some suppliers will provide small batch services, but this is quite costly. The high cost comes from the setup of such process, where each design must be hardened, cut open, and tested. Several pieces are needed as the setup process requires destructive testing to ensure the correct case depth and core hardness. Additional cost will incur if special equipment or setup is required – however this is unlikely in this scenario. In a typical prototype automotive application, the four corners of the car will likely have a slightly different design. In the case of the EcoCAR 2 vehicle, the front and rear barshafts are completely different, while the left and right designs only differ by length. This will require 4 different setups. Further, for most automotive barshaft applications, 2 to 3 pieces of each design should be expected to be cut for destructive testing, hence at least 4 to 5 pieces of each design should be fabricated. Be sure to contact the induction hardening supplier to inquiry as to how many pieces are required for destructive testing for the specific application and plan accordingly.

For more details on the induction hardening profile of the shaft, refer to the book "Multiaxial Fatigue of an Induction Hardened Shaft" http://books.sae.org/ae-28/, the gearbox supplier which was GKN Driveline in the case of EcoCAR 2, and the induction hardening supplier [17].

Chapter 6
Rear Subframe

Modern passenger vehicles as well as an increasing amount of trucks utilize a unibody construction, where there is no discrete "frame" holding the components of the vehicle. Rather, the entire vehicle is structural, including its various outer sheet metal and roof. The unibody structure is favored as it reduces vehicle mass and cost by optimizing the structure of the vehicle, versus the older body-on-frame structure where the entire body of the vehicle can be disassembled, leaving the frame of the vehicle where the suspension components as well as powertrain components are attached. Most modern pick-up trucks and heavy duty sports utility vehicles (SUV) utilize the body-on-frame construction as it provides a stronger chassis and increased towing capacity, with the trade-off of increased vehicle mass and cost.

In a unibody passenger vehicle, such as the 2013 Chevrolet Malibu from which UWAFT's EcoCAR 2 vehicle is based on, front and rear subframes exist as shown in Figure 29 and Figure 30. The subframes are also referred to as the front and rear cradle. The subframes are structural and are used to hold all of the suspension components, as well as support parts of the major powertrain components. For example, the engine/transmission combination is usually held by two load-bearing mounts on the left and right sides which are fixed to the frame rails from above, while two torque mounts are located in the front and rear of the engine/transmission combination fixed to the front subframe from below.



Figure 29 - Front subframe (yellow frame on table) which holds the front suspension and front powertrain components together

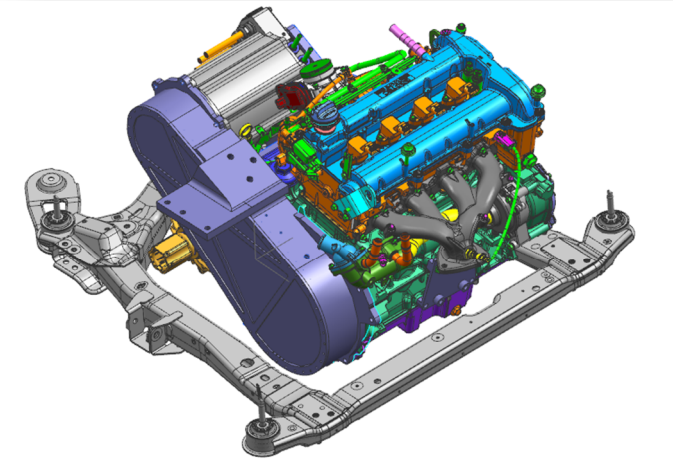


Figure 30 - Front subframe CAD (shown in gray at the bottom) holding front powertrain components

During the hybrid conversion of the EcoCAR 2 vehicle, the rear subframe needed to be modified in order to create space to house the rear traction motor and gearbox. This process is usually required in order to convert a front-wheel-drive (FWD) vehicle to an AWD vehicle, as the stock rear subframe will not have been designed for packaging of the powertrain components in the rear, as shown in Figure 31. The modified rear subframe will also need to be stronger as it now needs to hold the weight of the added rear powertrain components, as well as the high torque output of the electric motor.

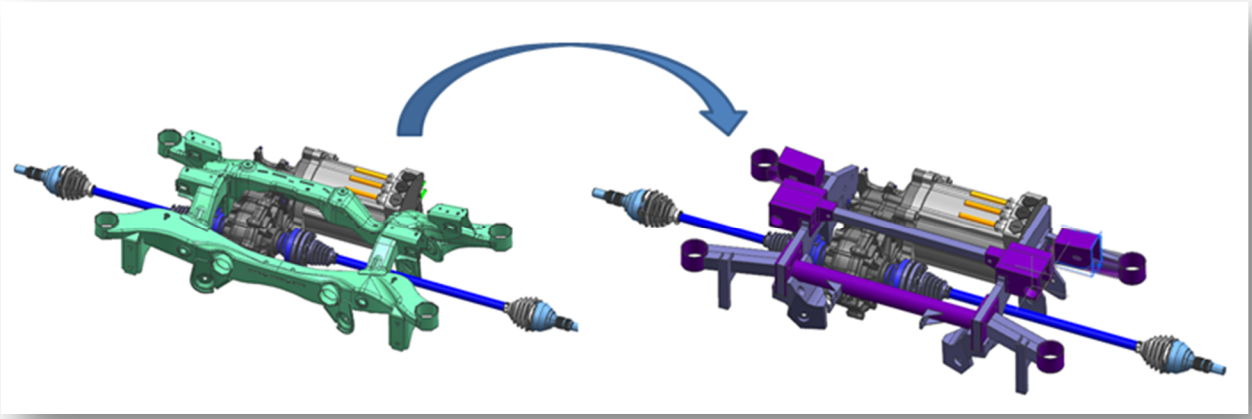


Figure 31 - Rear subframe redesign CAD (Left: stock rear subframe unable to accommodate added rear motor and gearbox, showing interferences. Right: redesigned rear subframe holding rear powertrain components)

There are two methods of modifying the rear subframe in order to house the added rear powertrain components: 1) cut and weld to the stock subframe, or 2) design a rear subframe completely from scratch. While the first option requires less design and fabrication as parts of the stock subframe are reused, this does not necessarily yield the lightest and most efficient structure as the design may not be the most optimized due to the fact that reused stock parts become limitations in the design geometry – the stock subframe was optimized but not for the modified load paths. Designing a completely new subframe from scratch means more components need to be designed and fabricated as well as needing tight tolerances on more parts in order to facilitate easy assembly; this can yield a much more optimized structure as there are minimal limitations on geometry. In the case of the UWAFT EcoCAR 2 vehicle, the method of completely redesigning the rear subframe from scratch was chosen in order to yield the high mass savings.

6.1 Rear Subframe Design Process

The first step to the rear subframe design process requires specifying the hard points to the structure; that is all the geometry constraints as required by mounting locations of all suspension and powertrain components, as well as the mounting locations of the rear subframe to the body of the vehicle. The hard points are shown in Figure 32.

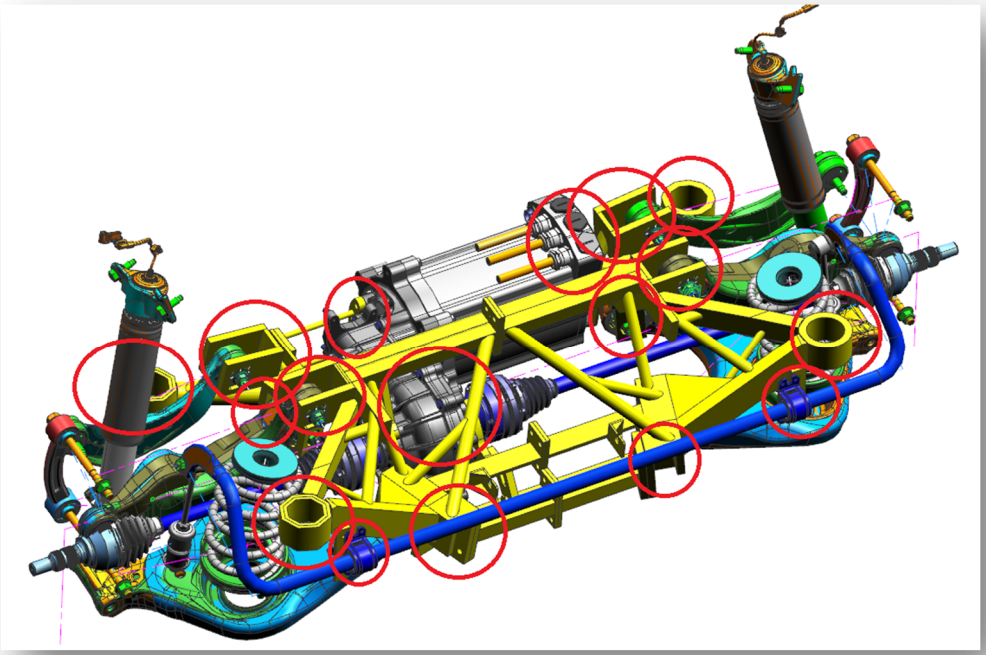


Figure 32 - Rear subframe with hard points (mounting locations) circled in red

With all the hard points of the rear subframe optimization set, requirements of the rear subframe design are to be determined, which are strength and stiffness in established load cases. Load cases of the rear subframe consist of various scenarios that the vehicle will experience, such as one-wheel bump, two-wheel bump, cornering left, rear impact, and more, which are shown in Table 7 and applied to the FEM model in Figure 33. Loads are obtained through vehicle dynamic simulations or in-vehicle measurements, containing the forces and moments applied at all the suspension mounting points. In the case of EcoCAR 2, these load cases were provided by General Motors. Typically the strength and stiffness requirements of the redesigned subframe should be as strong and stiff as the stock design. In EcoCAR 2, it was required that the displacement of all the suspension mounting locations as well as the peak stress of each load case must be equal to or less than that the stock rear subframe experiences in the identical load case.

Table 7 - Rear subframe FEM load cases as specified by General Motors

Load Cases
Two-Wheel Bump
One-Wheel Bump – LHS
One-Wheel Bump – RHS
Twist – LHS jounce, RHS rebound
Twist – LHS rebound, RHS jounce
Forward Braking
Reverse Braking
Cornering – Left Turn
Cornering – Right Turn
Forward Acceleration
Reverse Acceleration
Max Torque – Forward
Max Torque – Reverse
Reverse Bump
Forward Impact

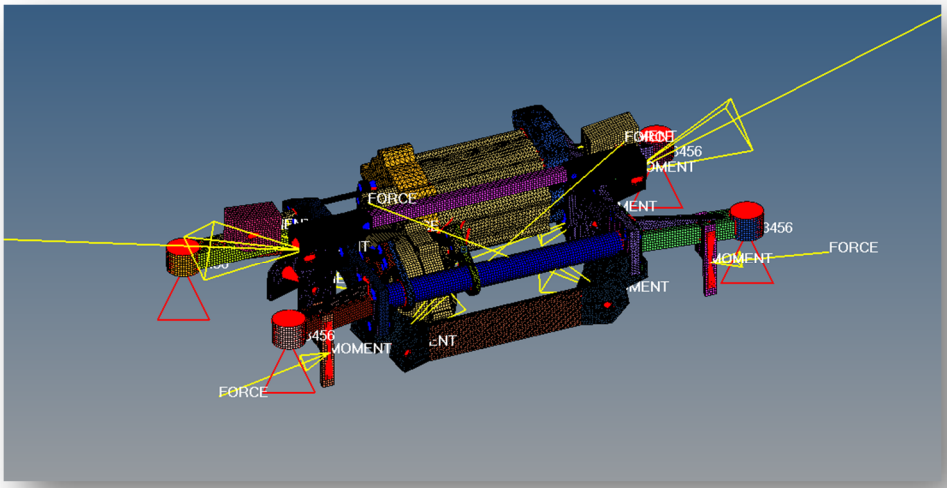


Figure 33 - Rear subframe FEM showing loads and constraints applied as per General Motors specified load cases

The next step is to set up the optimization using FEM software packages. UWAFT has chosen to use Altair's Hyperworks suite for this task for two reasons: 1) it is widely used in the automotive industry for this type of work, and 2) the software package comes with all required solvers in order to perform optimization and static analysis on the subframe. Figure 34 shows the resultant optimized geometry from the optimization analysis done in Optistruct.

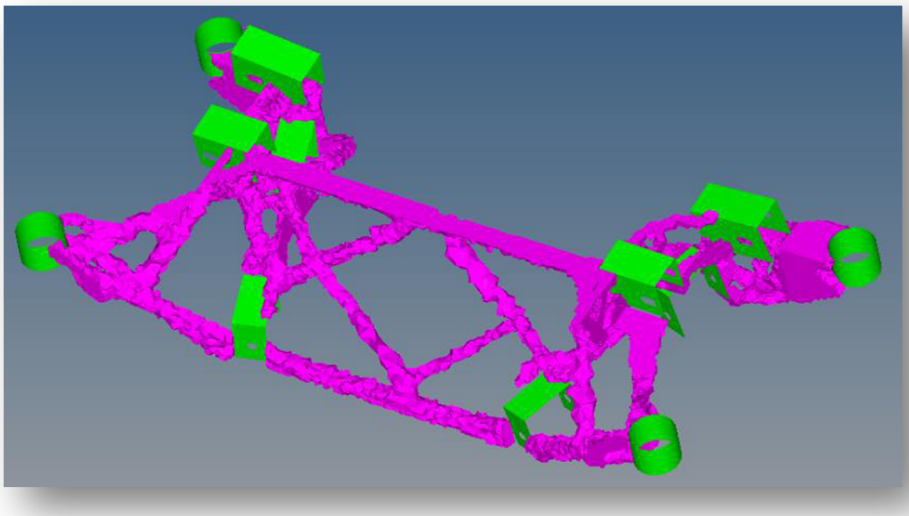


Figure 34 - Final optimized output of rear subframe from Optistruct

Using the optimized structure obtained from the FEM software, one can import the geometry into a 3D CAD software and design on top of it, using it as an underlay. The design should utilize components that can be easily obtained, and should resemble the optimized geometry as close as possible in order to retain the optimized load paths as calculated from the FEM software. The redesigned CAD geometry should be imported back into the FEM software in order to validate its strength and stiffness, and any changes required must be made in order to obtain a final structure which is as strong and stiff as the stock subframe. Figure 35 shows UWAFT's redesigned subframe based on the optimized geometry from FEM.

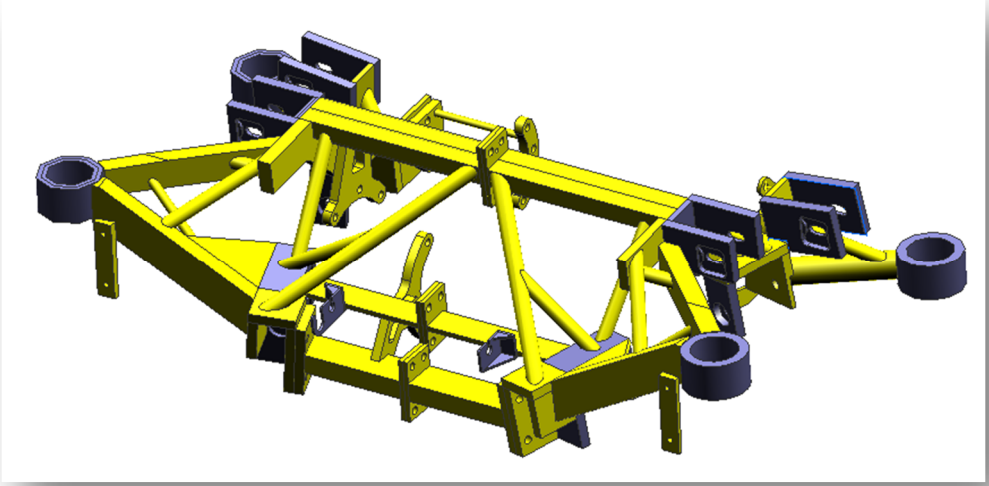


Figure 35 - Optimized subframe designed for manufacturability and assembly in CAD

Lastly, in order to facilitate the manufacturing of the rear subframe, a jig should also be designed from CAD and manufactured out of steel in order to maintain high geometry accuracy with special attention paid to all critical locations, namely the hard points from the optimization problem. As the rear subframe is a critical structural component, a safety waiver was required to be submitted to the organizers and General Motors in the EcoCAR 2 competition, outlining the entire design process as well as FEM results in order to prove the safety of the newly designed rear subframe. Figure 36 shows the welding jig for UWAFT's subframe in CAD.

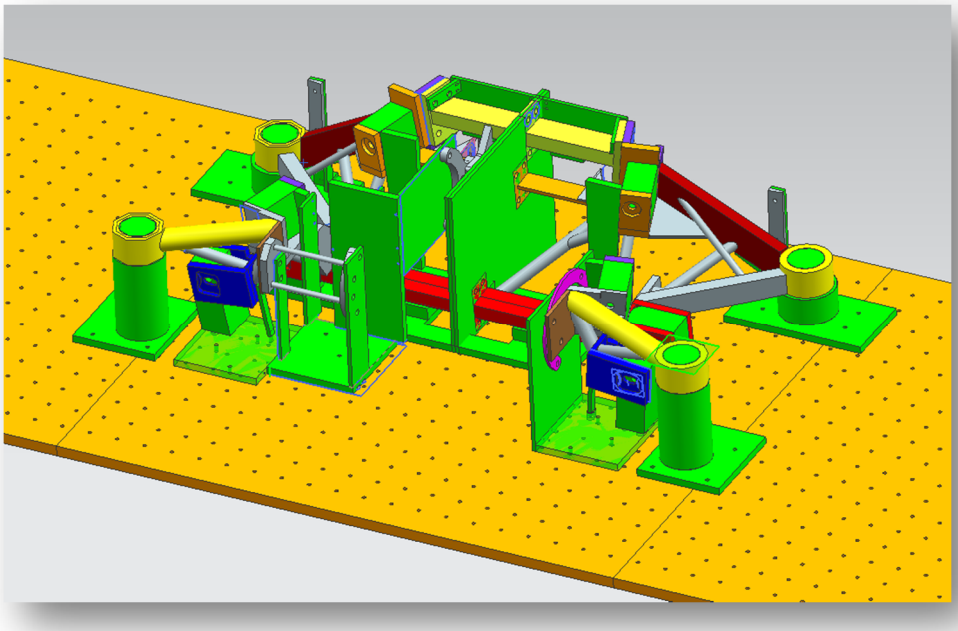


Figure 36 - Rear subframe welding jig in CAD

6.2 Rear Subframe Hard Points

In order to design a rear subframe from scratch, it must be realized that the geometric constraints are as follows:

- Rear subframe to body mounting locations
- Suspension components mounting locations
- Motor and gearbox mounting locations*
- Half shaft range of movement*

The locations of the rear subframe to body mounts as well as suspension mounting locations are fixed; these will dictate hard points on the initial optimization problem. Note the asterisks on motor and gearbox mounting locations and half shaft range of movement. The locations of the motor and gearbox mounting locations, and hence the half shaft range of movement, are also hard points on the optimization problem, and the optimized structure should be calculated based on these hard points. However, the motor and gearbox locations are not constrained and may be moved for clearance requirements, as well as to best suit the position of the differential output and hence the CV joint angles and half shaft range of movement. Note that although the motor and gearbox locations may be moved, this should be positioned to optimize CV joint angles and half shaft movement first, and then fixed as “hard points” for the optimization problem.

They should only be moved if it is absolutely necessary in order to facilitate manufacturability, assembly, or clearance of the rear subframe.

The mounting locations of the rear suspension components as well as the rear subframe to body mounts may be obtained from CAD if available; otherwise CAD must be obtained from 3D scanning of the physical vehicle. This ensures accuracy in the subframe design.

6.3 Rear Subframe Optimization Process

Figure 37 illustrates the basic process of the rear subframe optimization problem.

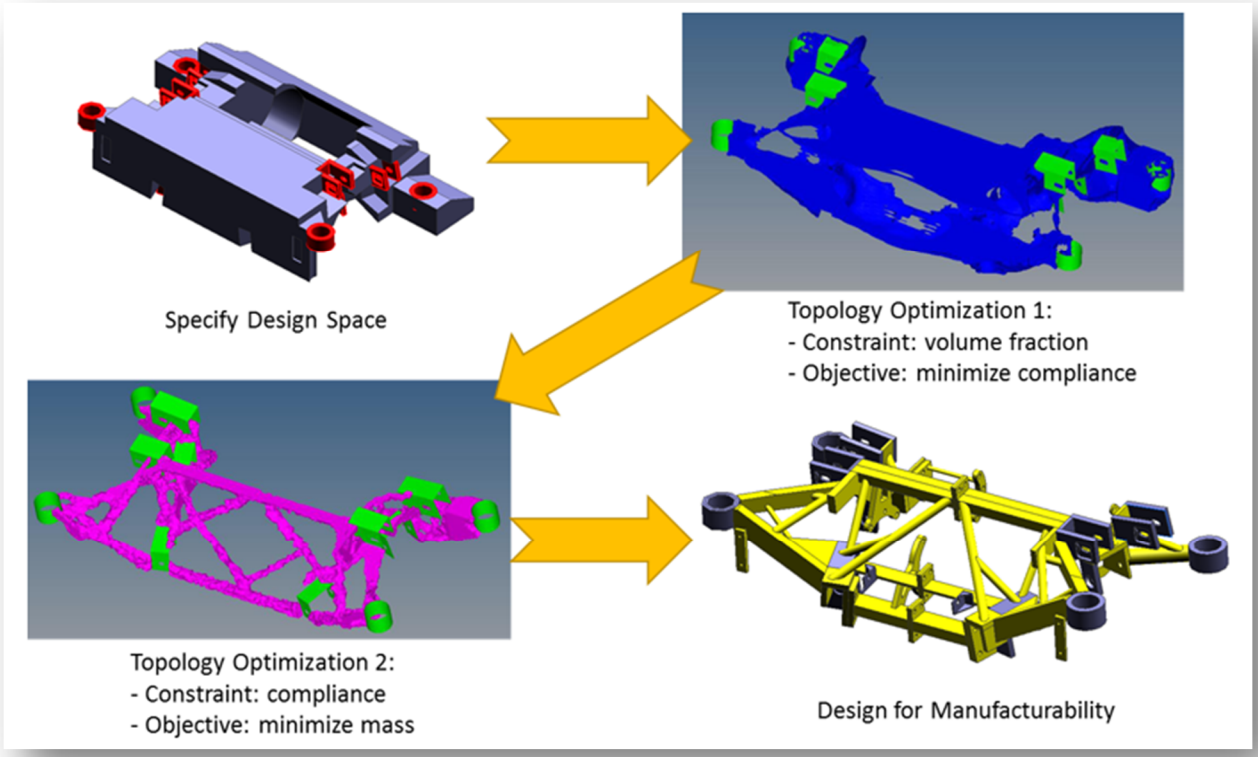


Figure 37 - Rear subframe optimization process

The rear subframe optimization process begins with identifying and specifying the hard points of the optimization problem as well as the design space. The hard points have been described in Section 6.2. The design space is the available space in which the optimized structure can be in, taking into account interference with surrounding objects such as suspension components, gas tanks, half shafts, and the range of travel of these components if they move. The design space should also account for interference with the assembly process of both the optimized structure as well as surrounding components. This is the special envelope in which the optimization software will use to optimize the geometry of the subframe.

Figure 38 shows the design space and hardpoints of the UWAFT subframe optimization problem. The structure around the hard points colored in red is not part of the design space and hence will not be optimized; this is the final shape of the parts. These parts are usually designed before the optimization process as a very specific geometry is likely required for mounting, such as a bored out cylinder to hold round bushings. These pre-designed parts along with the optimized structure will later go through FEM verification to ensure strength and stiffness of the structure as a whole, and changes may then be made to strengthen or stiffen the structure.

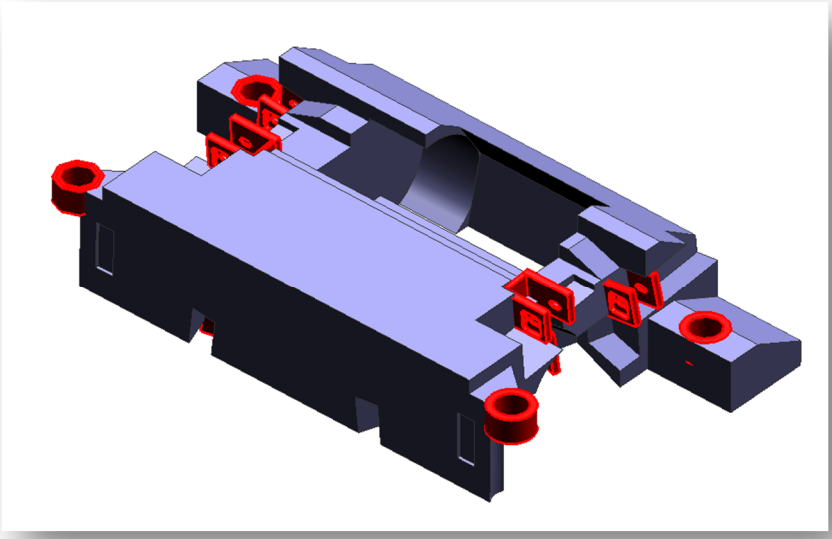


Figure 38 - Rear subframe design space with hard points shown in red

The Optistruct solver was used by UWAFT in EcoCAR 2 as this comes as a bundle with Altair's Hyperworks suite. Optistruct is a powerful solver which can perform various types of optimization as well as FEM analysis on structural components. The user must specify the following:

- Design constraints (for example: displacement of a certain point must be < 1 mm); and,
- Design objective (for example: mass must be < 50 kg).

In order to specify the design constraints and design objectives in Hypermesh for Optistruct, the optimization responses (for example: displacement, mass) must be specified beforehand.

Topology optimization is most suitable for the rear subframe optimization problem as it yields an optimized geometry based on the load paths of the FEM load cases that the user must specify, which may include forces and moments applied to the subframe from wheel bump, rear collision, etc. The design space must

be specified in Hypermesh for Optistruct by creating a design variable which points to the property assigned to the design space. Material selection should also take place during the optimization in order to engineer an optimized structure based on the material properties of the selected material(s).

Following the advice from Altair, in the case of the rear subframe the optimization problem should be broken down into two steps:

Step 1:

- Design constraint: volume fraction < 0.3
- Design objective: minimize compliance

Step 2:

- Design constraint: compliance
- Design objective: minimize mass

From each optimization step, a meshed geometry will result showing the optimized geometry based on the load paths from the load cases. The amount of material on the output geometry can change by adjusting the element density, and one should adjust the element density such that the output geometry makes sense, such as ensure no floating parts. This is illustrated in Figure 39.

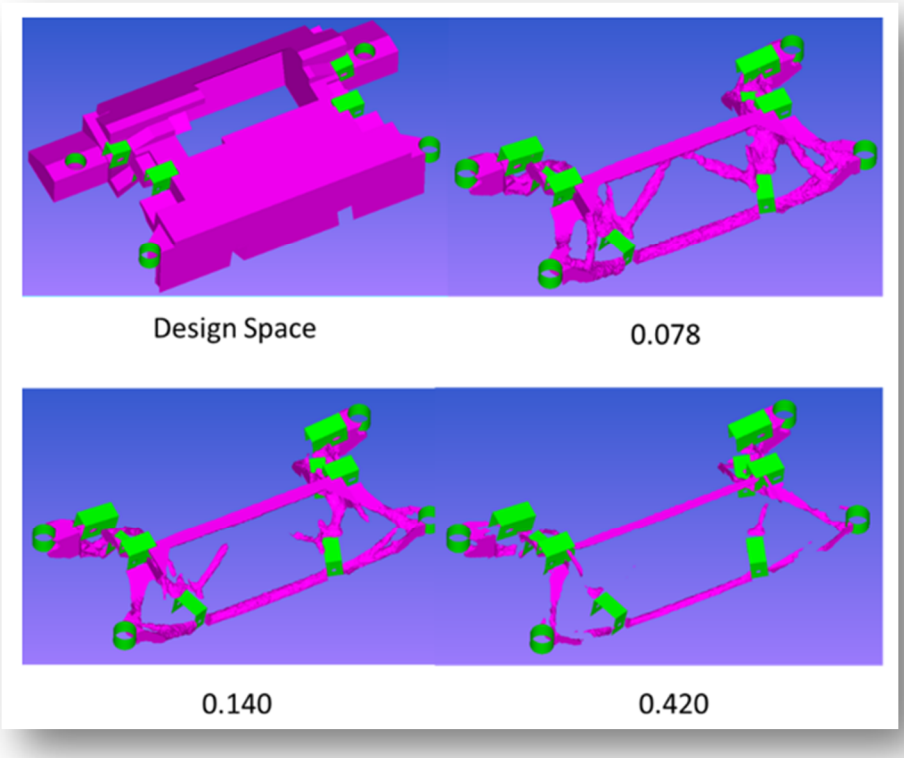


Figure 39 - Subframe optimization at various element densities

The output of the first optimization step should be fed into the second optimization step as the design space. Finally, the output of the second step should be exported into CAD to be used as an underlay in order to design an optimized structure with the optimized geometry. Figure 40 shows the optimized geometry output for UWAFT's subframe, while Figure 41 shows the subframe designed for manufacturability overlaying the optimized geometry from FEM from which it was designed from.

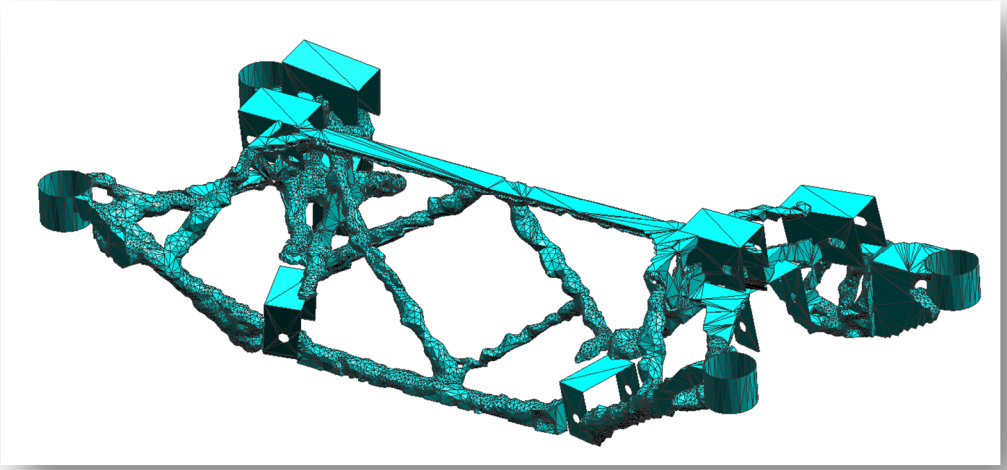


Figure 40 - Final optimized output geometry exported to CAD using OSSmooth function in Hypermesh

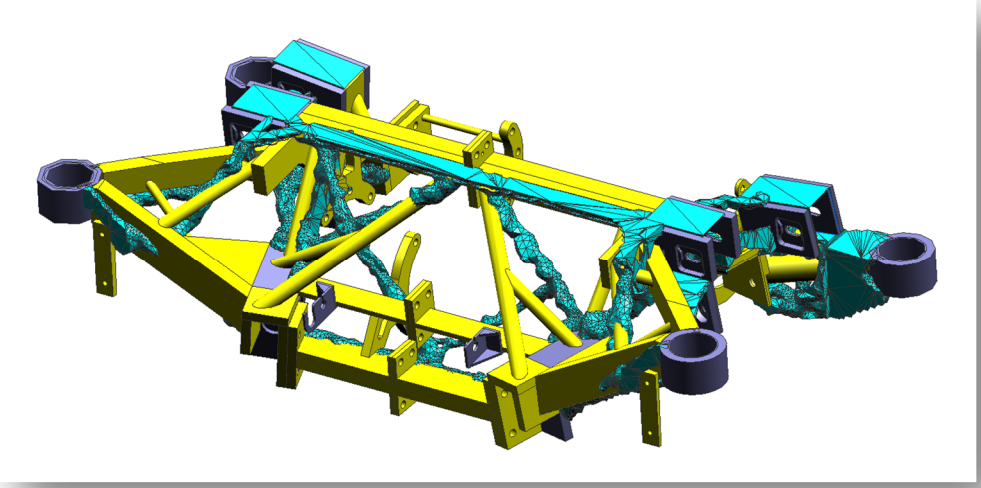


Figure 41 - Rear subframe designed for manufacturability and assembly overlay on optimized geometry output (Teal: optimized geometry output. Yellow/violet: Designed for manufacturability and assembly)

It should be noted that the optimization process should be applied with care. There are limitations with the optimization process, and material can only be removed during the process, hence starting off with the design space or maximum material. The results of the optimization requires a large amount of human intervention and processing in order to transform an optimized geometry to a product that can be manufactured at the present state of optimization routines. Further, the final result should always be fed

back and re-analyzed and physically tested to ensure that the product can withstand the expected loading conditions.

6.4 Rear Subframe Design for Manufacturability

With an optimized geometry in CAD, it can be seen that such geometry cannot be easily manufactured. One must now design, using the optimized structure as an underlay, a manufacturable product using raw material or parts which can easily be obtained in a cost effective manner. Such material or parts can include sheet metal, angle iron, square or round tubes, solid or hollow tubes, etc. Note that one should also consider the difficulty and cost of obtaining these raw materials when designing, and account for the standard sizes that these components come in, such as using a standard 1" diameter tube versus a nonstandard size of 26.5 mm diameter. Consider how the parts will be fixed to each other (e.g. welding, bolting), and what manufacturing processes are available (e.g. water jet cut parts, CNC mill, lathe, etc.) It is highly recommended to avoid unnecessarily complicated geometry which will increase cost and lead time significantly. Figure 42 and Figure 43 shows examples of unnecessarily complicated geometry which were simplified to reduce cost and manufacturing lead time.

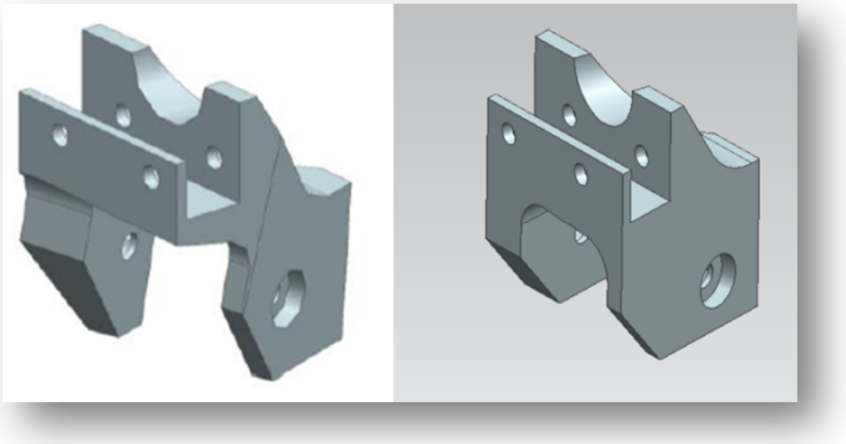


Figure 42 - Geometry simplification for increased manufacturability 1 (Left: complicated geometry with angled planes requiring a 6-axis CNC to fabricate. Right: simplified geometry with faces in perpendicular planes, several cuts removed, increased radii)

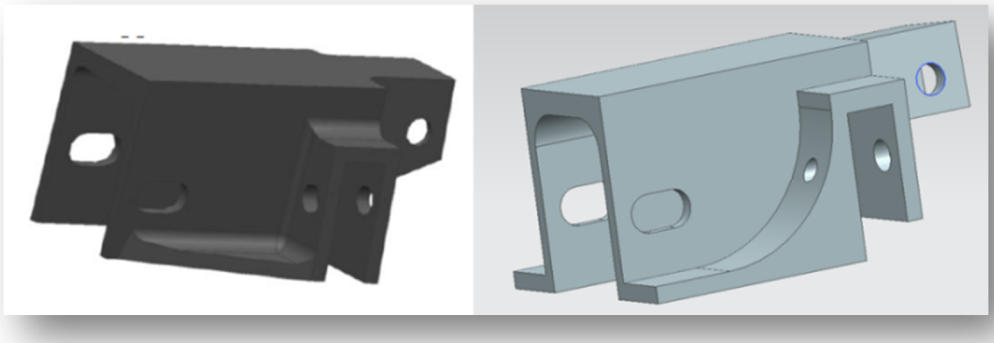


Figure 43 - Geometry simplification for increased manufacturability 2 (Left: complicated geometry with unnecessary cuts. Right: simplified geometry with larger radii allowing for larger end mill bits)

6.5 Rear Subframe Design for Assembly

The design of the subframe should be considered for assembly, as this important step will save countless hours down the road during assembly and installation. In EcoCAR 2, it was decided that the rear subframe is to be constructed from two halves that are bolted together in the middle, in order to avoid tolerance stack from one side to the other from a high number of bolt clearance holes. The two halves are composed of smaller parts which are all welded together. This design ensures that the subframe to body mounting points are accurate which eases installation into the vehicle, while all gearbox and motor mounting locations are accurate in order to facilitate easy installation. From past experience, a subframe design with a high number of bolted parts causes high tolerance stack up which results in very inaccurate critical mounting locations. This causes installation of the motor and gearbox into the subframe and the installation of the subframe to vehicle very difficult, while the end result had the motor and gearbox sitting centimeters away from its design position and at an angle, causing further issues such as half shaft interferences as shown in Figure 44 and Figure 45. UWAFT's Year 2 rear subframe design versus Year 3 design is shown in Figure 46.



Figure 44 - Installed old rear subframe design, showing tilted gearbox due to tolerance issues from bolt clearance holes

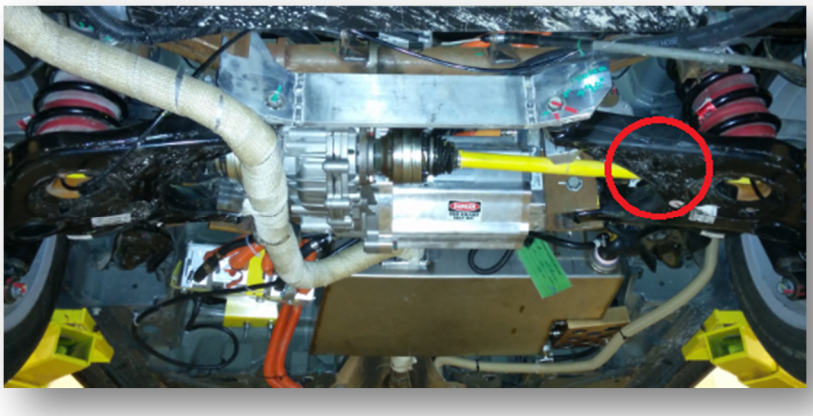


Figure 45 - Installed old rear subframe design, with half shaft interferences on the control arm shown by red circle during full suspension travel range



Figure 46 - Old subframe design vs new optimized design (Left: old design not optimized for mass, manufacturability, or assembly, weighing 100 lbs. Right: optimized design weighing 39 lbs)

6.6 Rear Subframe Jig Design

The geometric tolerance of the rear subframe is fairly critical; specifically the mounting locations of both the subframe to body mount points as well as the motor, gearbox, and suspension mount points. The accuracy of these hard points will ensure easy assembly, as well as the ability to maintain proper vehicle alignment. The design and use of a proper welding jig facilitates the needed accuracy.

The welding jig should be designed from the critical hard points outward; that is, all the motor, gearbox, suspension mounting locations, and subframe to body mounting locations should be properly secured by the jig. The UWAFT rear subframe and welding jig in CAD is shown in Figure 47.

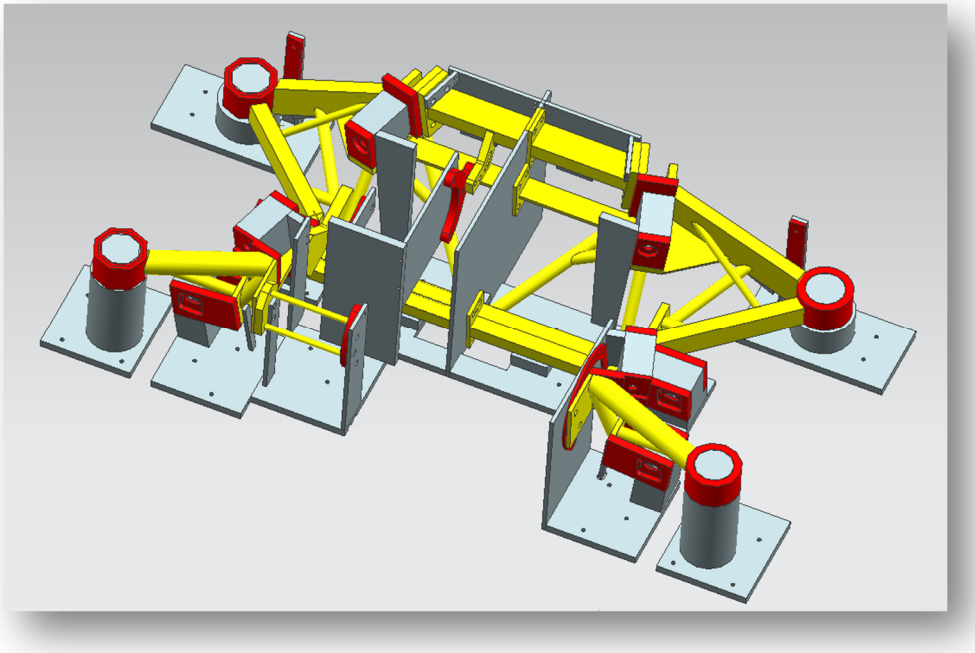


Figure 47 - Rear subframe jig (blue) with subframe (yellow) shown. Subframe critical mounting locations are highlighted in red.

From here, the less essential components in terms of positional accuracy should be supported to ensure that all parts are positioned relatively accurately. Most parts that connect the critical mounting points together do not necessarily need extreme positional accuracy, although supporting them will help during the welding process in positioning all the pieces as well as ensuring that tool clearances are not interfered with if these parts are positioned very inaccurately.

It is recommended to group multiple jig support components into the same base, so that the base can be accurately mounted onto a jig table peg board. Figure 48 shows the welding jig in CAD and in person during assembly.

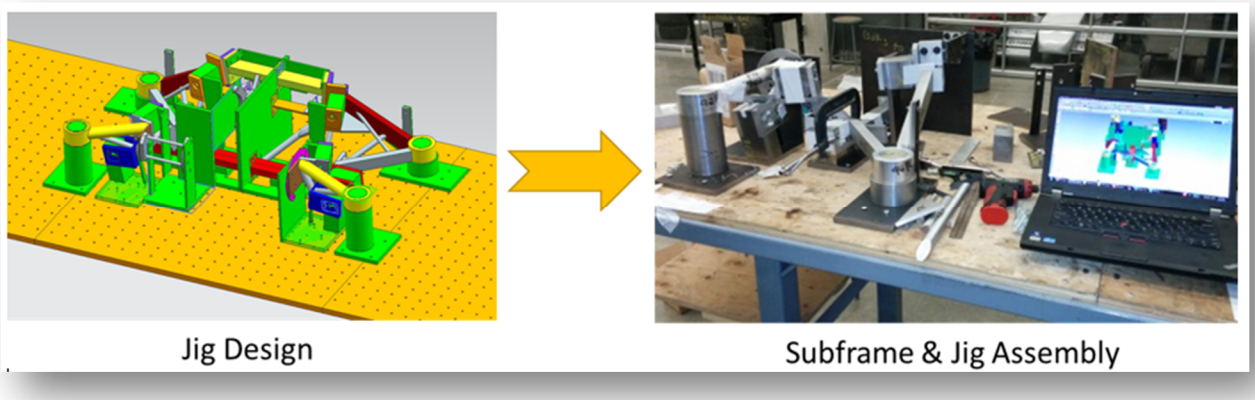


Figure 48 - Rear subframe welding jig (green in CAD) showing peg board used for locating components (Left: CAD. Right: physical jig with subframe assembled for welding)

If the structure is largely symmetrical such as in the case of the rear subframe, the jig components should be designed such that the majority of them may be disassembled from the base and flipped in order to facilitate welding of opposite sides of the subframe. This can save a significant amount of material cost and jig fabrication time.

Jig pieces should all be designed and fabricated using steel in order to ensure high geometric accuracy. From past experience, using wood as jig material sometimes causes warping due to the high heat involved during welding, especially for aluminum parts. Further, from past experience the use of a prefabricated peg board is adequate enough in the case of the subframe, and most parts of the automobile. This provides a cost effective as well as time efficient solution over CNC milling a peg board out of metal.

The use of a welding jig designed as per the aforementioned steps resulted in a very geometrically accurate subframe for UWAFT in EcoCAR 2, which was installed into the vehicle with ease. Improvements can still be made for the accuracy of non-essential parts as some tool clearance experienced interference after welding due to poor positioning. Further, it is highly suggested that in the future, the subframe jig be designed such that the entire assembly, once assembled on the jig, can be flipped upside down. This will ease the welding process significantly as the welder was unable to get to the bottom of the subframe with the EcoCAR 2 jig design, which resulted in having the assembly disassembled before the bottom can be

fully welded. With a jig that can be flipped upside down, this will reduce setup time and fabrication cost significantly.

Figure 49 and Figure 50 shows the welded and painted optimized rear subframe during assembly and in vehicle.

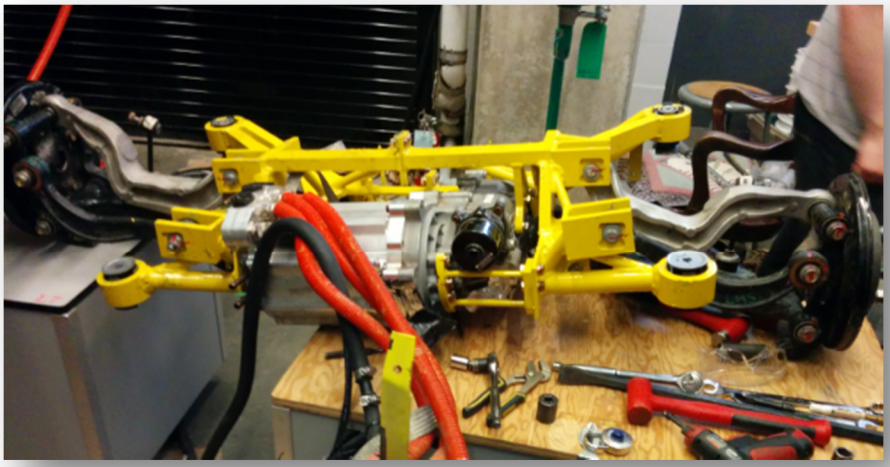


Figure 49 - New optimized rear subframe (yellow) with suspension and powertrain components installed



Figure 50 - New optimized rear subframe installed in vehicle (yellow)

Chapter 7
Suspension

One major drawback with the hybridization of a vehicle includes the significant mass increase over its conventional internal combustion engine powered counterpart, on top of the added costs. In order to compensate for the increased mass, the suspension system of the vehicle must be modified, specifically the spring and damping rates.

The design of spring rates and damping rates follows a standard analytical procedure; however the system can be tuned very differently yielding very different results based on the objective of the designer, such as comfort versus performance. This section will outline the analytical procedure in the design of spring and damping rates for an automobile.

7.1 Spring and Damping Rates Design Process

Figure 51 shows the design process for determining spring and damping rates for an automobile, used with permission from Kaz Technologies, the shock and technical experts for GM Racing.

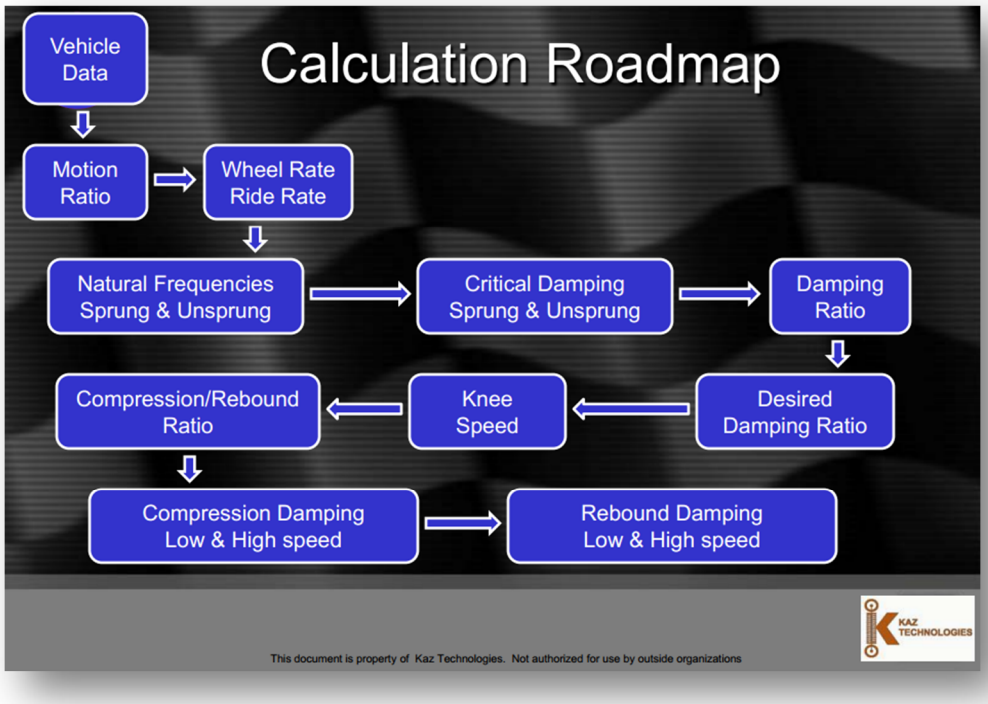


Figure 51 - Calculation roadmap for tuning spring and damping rates [18]

7.2 Vehicle Data

The first set of data required for tuning the suspension system includes the geometric locations of all the suspension hard points. This may be obtained from CAD if available or measured on the physical vehicle. At a minimum, the geometric locations related to the motion ratio of the front and rear suspension must be obtained, in order to determine the motion ratio for the spring and damper for both the front and rear suspension systems.

Further, the total vehicle mass, front vehicle mass, rear vehicle mass, front unsprung mass, rear unsprung mass, front sprung mass, and rear sprung mass must be determined for calculations. These values should reflect the weight of the driver and a half tank of gas, as well as all other fluids.

Sprung mass is generally referred to as the components which are on top of the springs such as chassis, engine, etc., whereas unsprung mass refers to the components that are not supported by springs such as wheels, brakes, etc. There are certain components which are mounted in such a way that they can be sprung and unsprung by the aforementioned definitions, such as half shafts, suspension arms, suspension links, springs, and dampers. These components are unique and half their masses should be added to the unsprung category, while the other half added to the sprung category.

If stock spring and damping rates are available, this will facilitate validation of vehicle dynamics model through comparison of the stock vehicle simulation and physical vehicle testing.

7.3 Motion Ratio

The motion ratio refers to the ratio of either the damper or spring travel relative to wheel travel, depending on whether it is referring to the spring motion ratio or the damper motion ratio. This term is often confused with and used synonymously with the term “installation ratio”, which is the inverse of the motion ratio. Generally, the motion ratio should be less than 1 while the installation ratio is greater than 1, as the spring and dampers are mounted inside of the wheel closer to the pivot point of the lower control arm. Equation 1 and Equation 2 show the definition of the spring and damper motion ratio.

Equation 1 - Spring Motion Ratio [18]

$$Spring\ Motion\ Ratio = \frac{Spring\ Displacement}{Wheel\ Displacement}$$

Equation 2 - Damper Motion Ratio [18]

$$Damper\ Motion\ Ratio = \frac{Damper\ Displacement}{Wheel\ Displacement}$$

From here on, the spring and damping rates will be specified as to whether they refer to such rates at the wheel or at the spring/damper. Wheel rates facilitate calculations as well as quarter car models, while the rates at the actual damper and spring are the rates that will be used to manufacture the spring and dampers. They are related through the motion ratio using similar triangles as shown in Figure 52, and Equation 3 and Equation 4 shows the spring and damping rate relations from spring/damper to wheel based on motion ratio.

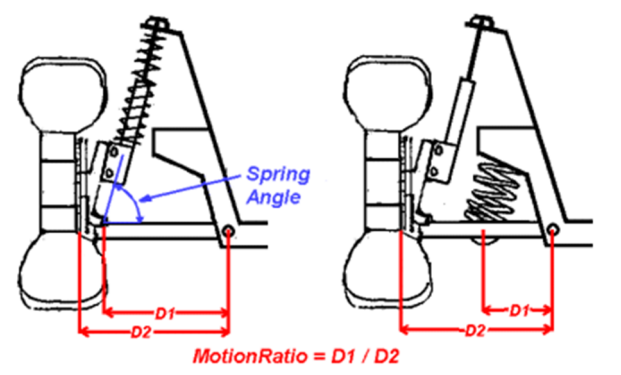


Figure 52 - Spring motion ratio [19]

Equation 3 - Wheel Rate to Spring Rate Relation [18]

$$Spring\ Rate\ (@\ wheel) = Wheel\ Rate = Spring\ Rate\ (@\ spring) * Spring\ Motion\ Ratio^2$$

Equation 4 - Damping Rate (@ wheel) to Damping Rate (@ damper) Relation [18]

$$Damping\ Rate\ (@\ wheel) = Damping\ Rate\ (@\ damper) * Damper\ Motion\ Ratio^2$$

7.4 Ride Frequencies

The ride frequency is one of many parameters which must be determined based on the designer's objective. Such decision is based on several factors such as [18]:

- Dynamic ride frequency
- Dynamic pitch frequency

- Dynamic roll rate
- Spring rates
- Sway bar rates
- Driver preferences

From literature, ride frequencies are in the range of 1 – 1.5 Hz for passenger vehicles [20], while performance and race cars can have ride frequencies above 1.5 Hz and sometimes in excess of 2 Hz [20]. In the case of UWAFT's EcoCAR 2 vehicle, a baseline ride frequency of 1.6 Hz for the front was used. This is based on the decision that comfort of vehicle may be sacrificed in order to achieve higher performance, providing the team with a competitive edge based on the scoring distribution of the EcoCAR 2 competition.

The rear ride frequency was decided to be 10% higher than that of the front. It is important to note that having the exact ride frequency for both front and rear will result in significant pitching of the vehicle which is uncomfortable for the passengers. This behavior is the result of the fact when the vehicle approaches a bump, the front wheels will always encounter the disturbance first, as illustrated in Figure 53.

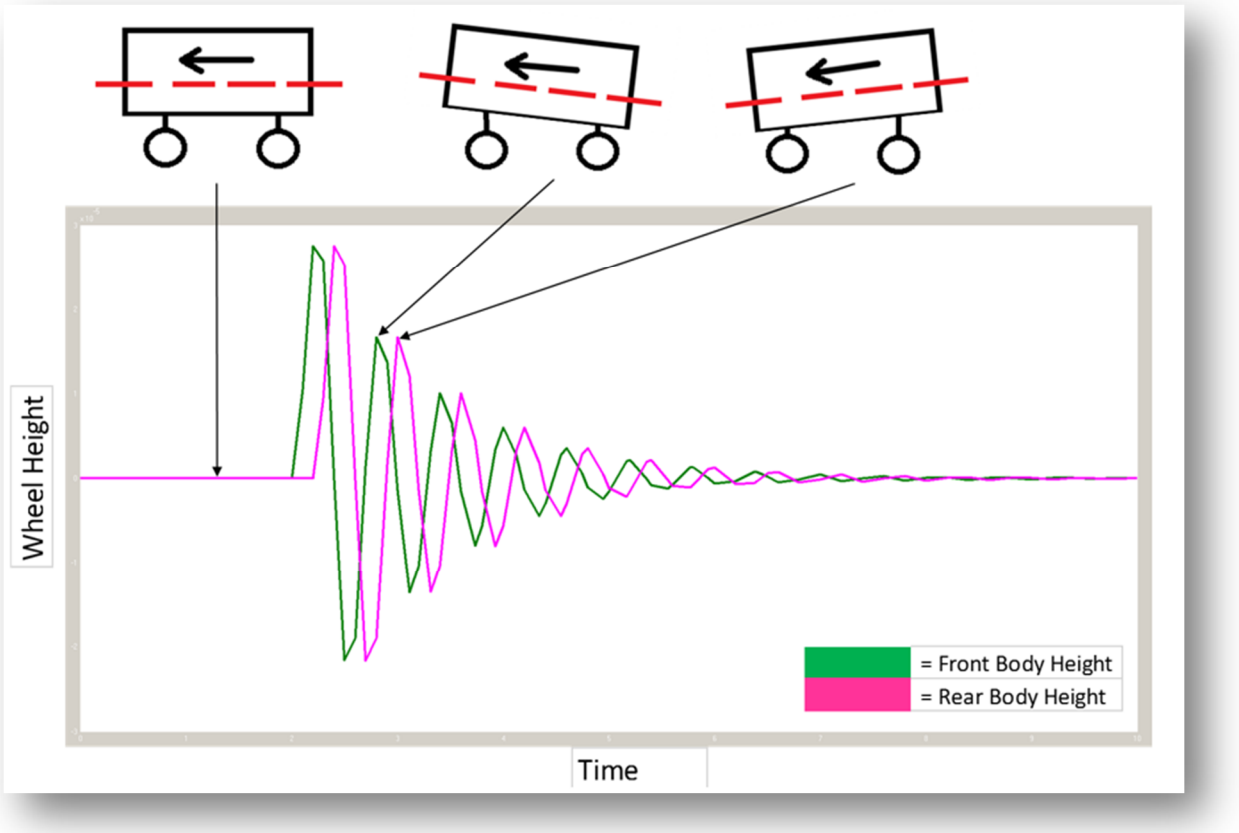


Figure 53 - Undesired vehicle pitch motion from having the same ride frequency in the front and rear

7.5 Ride Rate

It is important to note that tires also act as a spring in the system, and as such the tire stiffness should be accounted for. Such information can be obtained through testing or from the tire manufacturer. A baseline value of 200 N/mm for passenger vehicle tires was used as an assumption in UWAFT's EcoCAR 2 design. Figure 54 shows a quarter car model for the front and rear using Adams.

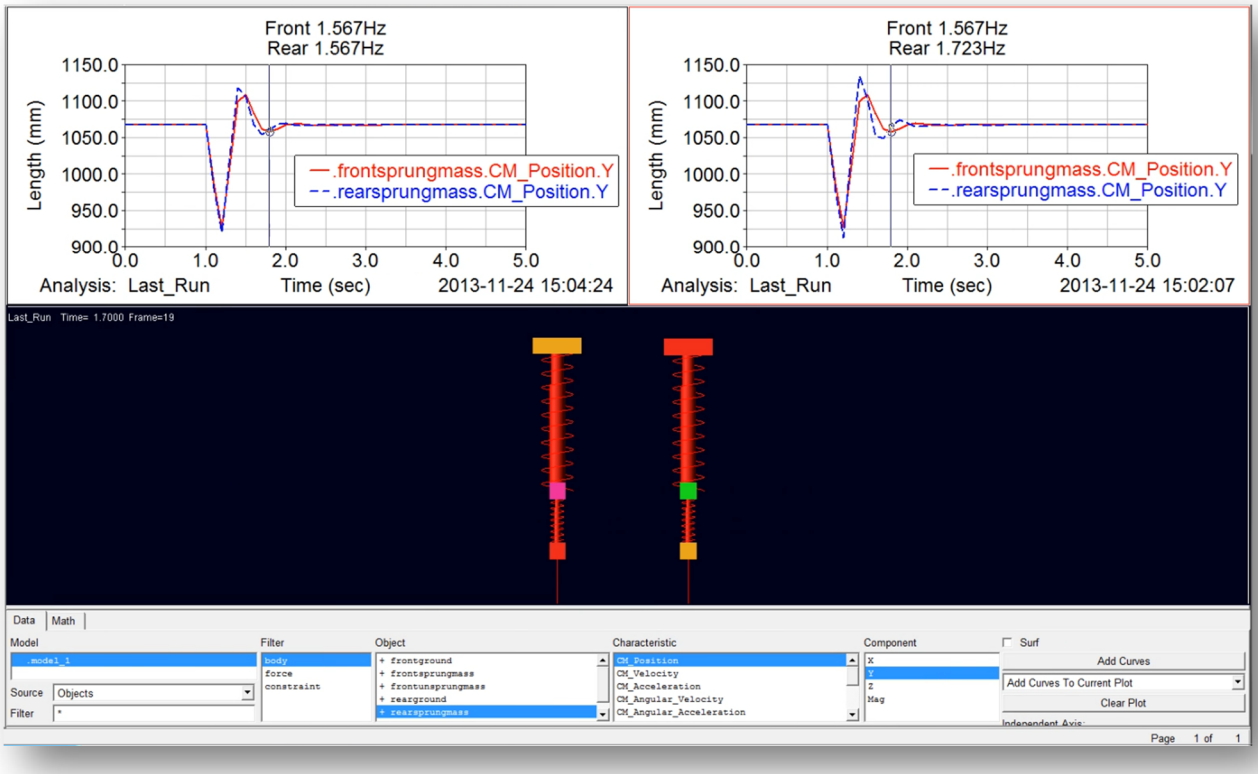


Figure 54 - Quarter car model simulation using Adams

The ride rate is the effective stiffness of the suspension and tire in a series configuration. The ride rate can be determined for the front and rear using Equation 5.

Equation 5 - Ride Rate [18]

$$RR = 0.5 * (2 * \pi * f)^2 * M_{sprung}$$

RR = ride rate (N/m)

f = ride frequency (Hz)

M_{sprung} = sprung mass (kg)

7.6 Spring Rate

The wheel rate, which is stiffness at the wheel, can be determined using the ride rate, taking into account the tire stiffness, using Equation 6.

Equation 6 - Wheel Rate [18]

$$K_w = \frac{1}{\frac{1}{RR} - \frac{1}{K_t}}$$

K_w = wheel rate (N/m)

K_t = tire rate (N/m)

RR = ride rate (N/m)

The spring rate can now be determined using the wheel rate through the following relation in Equation 7.

Equation 7 - Spring Rate [18]

$$K_s = \frac{K_w}{MR^2}$$

K_w = wheel rate (N/m)

K_s = spring rate (N/m)

MR = motion ratio

Note this equation is essentially the same as Equation 3.

7.7 Critical Damping

Critical damping refers of level of damping which lets the unsprung mass return to its rest position in the shortest amount of time, without overshoot. Under damping refers to a damping level which allows for overshoot and oscillation in the unsprung mass before returning to rest, while over damping refers to a damping level which allows for no overshoot but the sprung mass does not return to its rest position in the least amount of time. These responses are illustrated in Figure 55.

The critical damping value can be obtained with Equation 8.

Equation 8 - Critical Damping [18]

$$C_{cr} = 2 * \sqrt{K_s * M_s}$$

C_{cr} = critical damping (Ns/m)

K_s = spring rate (N/m)

M_s = sprung mass (kg)

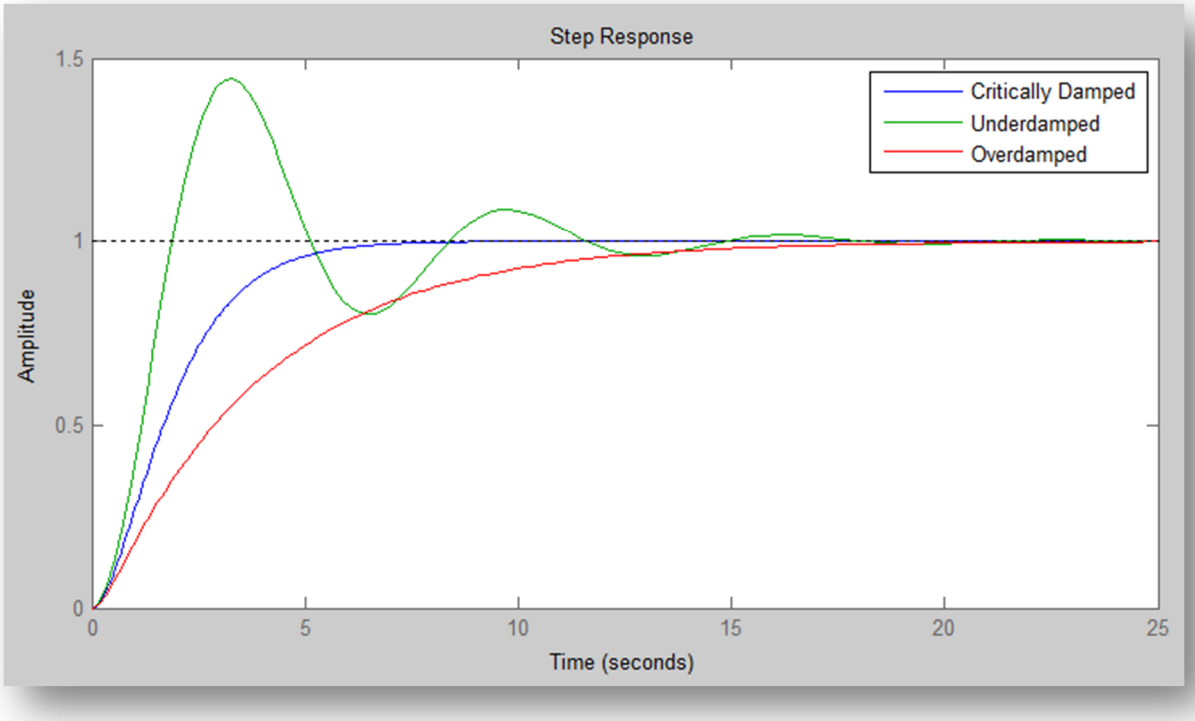


Figure 55 - Critically damped, underdamped, and overdamped responses

7.8 Damping Ratio

Dampers on the vehicle react proportionally to the speed of its compression and rebound, and as such may be thought of as "dynamic springs" [21]. Dampers serve the purpose of damping the sprung and unsprung mass, as well as control the rate of weight transfer of the vehicle during transients. It is important to note that as damper reaction force reacts proportionally to speed, dampers control the rate of weight transfer, but does not affect the actual amount of weight transfer. Other suspension components such as springs and anti-roll bars are used to control the actual amount of weight transfer, as their reaction forces react to displacement rather than speed.

The damping ratio is the ratio of damping coefficient to critical damping, defined in Equation 9.

Equation 9 - Damping Ratio [18]

$$\xi = \frac{C}{C_{cr}}$$

ζ = damping ratio

C = damping coefficient (Ns/m)

C_{cr} = critical damping (Ns/m)

Most passenger cars have damping ratios around 0.2, while performance and race vehicles often have damping ratios from 0.5 to as high as 1.0. For EcoCAR 2, a baseline damping ratio of 0.65 was chosen based on the fact that the competition scoring favored performance over comfort. Due to time constraints, a stock damper from a heavier vehicle of the same architecture (Buick Lacrosse) was chosen, tested for its damping ratios at various frequencies, and was deemed "adequate" for the increased mass and adjusted spring rates of the competition Malibu. The Buick Lacrosse semi-active dampers were selected also due to their capability to vary damping on-the-go, providing further performance and comfort. However, due to time constraints the semi-active suspension control system was dropped.

7.9 Next Steps

As previously mentioned, time constraint was a major factor in the suspension tuning on the EcoCAR 2 competition vehicle, and hence a lot of important steps and analysis were neglected. The spring and damping rates calculation sheet is shown in Appendix A – Design Methodology Instructional Materials. This section is reserved for next steps that are suggested should time allow, which will provide a much more refined design for the spring and dampers in a hybrid conversion.

Firstly, it should be stated that dampers are very effective as a component which increases the comfort and performance of a vehicle significantly. However, dampers are only one component within the vehicle's suspension system, and depend on the tuning of all other suspension components in order to maximize its own effect on the overall vehicle ride and handling. Such variables include suspension geometry, motion ratios, anti-roll bars, and more. However, as the goal of the EcoCAR series of competition is minimizing fuel consumption and well-the-wheel emissions while maintaining performance and safety of the vehicle, as supposed to maximizing ride and handling performance of the vehicle, these other suspension variables are not discussed in this thesis.

It is important to note that although the selected damping ratio yields a single damping coefficient, dampers react differently to various compression and rebound velocities, and hence the damping coefficient changes with respect to speed. Furthermore, it is commonly a misconception that the relation between reaction force

and speed for a damper is a linear relationship, as this much simplified model is used in the classroom and textbooks to get basic concepts across. In actual fact, each damper will have at least 4 different damping coefficients, as illustrated in Figure 56:

1. High speed compression
2. Low speed compression
3. High speed rebound
4. Low speed rebound

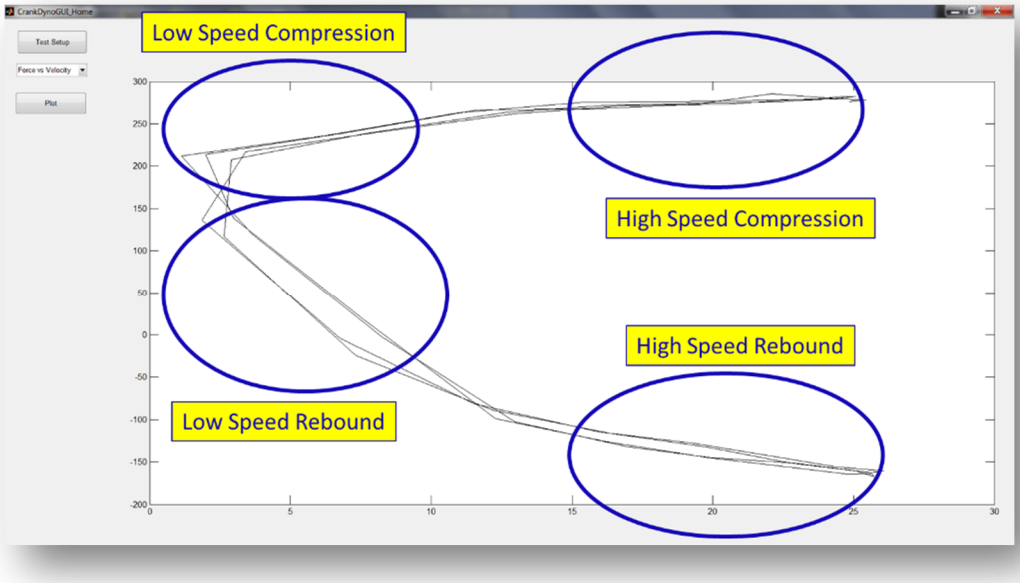


Figure 56 - Damper FV curve regions [21]

The damping curve may be further broken down to a "medium speed" section. For the purpose of this discussion, the simplification to 4 discrete damping coefficients for each damper will be used. These 4 damping coefficients work together to control the rate of weight transfer and ultimately the ride and handling of the vehicle during transient maneuvers. The use of adjustable dampers, either through physical knobs or electrically for semi-active dampers, will allow for the most tailored design to the vehicle, with semi-active dampers providing the best ride and handling through adjustment during the transients.

The tuning of the dampers can be broken down to 4 discrete phases [21]:

1. Low frequency heave and pitch balance
2. Wheel control over bumps

3. Handling
4. Testing rebound and compression adjustments

As there is a significant amount of testing required, as well as the likeliness that the components may not be ready, the benefit of using of a vehicle dynamics model in this case will prove to be very valuable. Using suspension hard points from the vehicle, a full vehicle model can be built in vehicle dynamics simulation packages such as the MSC Adams suite, and pre-defined or customized maneuvers may be applied to the vehicle model.

As this thesis is intended to be a general outline of the design process of all the critical mechanical components of the vehicle, it will not focus on the in-depth analysis of tuning the spring and damping rates, which can be a complicated thesis topic on its own. As such, further information regarding the design of spring and dampers, including an outline of the 4 steps of damper tuning, are provided from the following links [18] [21]:

http://www.kaztechnologies.com/wp-content/uploads/2014/03/FSAE-Damping-Calculations-Seminar.pdf

http://www.kaztechnologies.com/wp-content/uploads/2014/03/A-Guide-To-Your-Dampers-Chapter-from-FSAE-Book-by-Jim-Kasprzak.pdf

Chapter 8
Generator Torque Coupling

8.1 Torque Coupling Design Process

In the conversion of a vehicle into a Series Hybrid architecture, a mechanical torque coupling device is required to mechanically connect the engine with the electric generator. This is equivalent to the gearbox which couples the engine to the wheels in a conventional vehicle.

The torque coupling acts as a speed multiplier from the engine side to the generator side, as conventional internal combustion engines for passenger vehicles tend to have much lower speed limits than that of electric generators. A speed multiplier also implies a torque reduction based on basic gearing relations.

After the speed ratios are determined, the actual mechanism must be designed. Torque coupling systems of this sort are often based on gear or belt-drives. Both mechanisms have pros and cons and will be discussed in the following sections.

Lastly, noise, vibration, and harshness (NVH) should be considered in such torque coupling systems as there is a significant amount of power and vibration going through the system in a Series Hybrid vehicle. The careful design of the torque coupling system with consideration of NVH will significantly improve the perceived quality of the vehicle design as well as the lifetime of various components.

8.2 Speed and Torque Ratio

In the EcoCAR 2 vehicle, an E85 capable 2.4L GM LE9 engine was selected together with a 105 kW TM4 AC induction electric motor. The engine has a redline of 6000 rpm, while the generator has a speed limit of 11500 rpm. This naturally suggests that a speed multiplier of 2 from engine to generator will put the speed limits of the two devices close to each other.

However, another very important factor must be considered when choosing the torque coupling speed ratios. A speed multiplier of two also implies a torque reduction factor of two, based on basic gearing relations defined in Equation 10.

Equation 10 - Gear Ratio Relations

$$R = \frac{N_A}{N_B} = \frac{r_A}{r_B} = \frac{\omega_B}{\omega_A}$$

N_A = # of teeth on gear A

N_B = # of teeth on gear B

r_A = radius of gear A

r_B = radius of gear B

ω_A = rotational speed of gear A

ω_B = rotational speed of gear B

Engines and motors have varying efficiencies at different speeds and torque usually presented in the form of an efficiency map, which can be obtained either from the manufacturer or tested on a dynamometer. Figure 57 and Figure 58 show efficiency maps for the TM4 Motive B 105 kW automotive electric motor and General Motors LE9 2.4L 4 cylinder internal combustion engine, respectively.

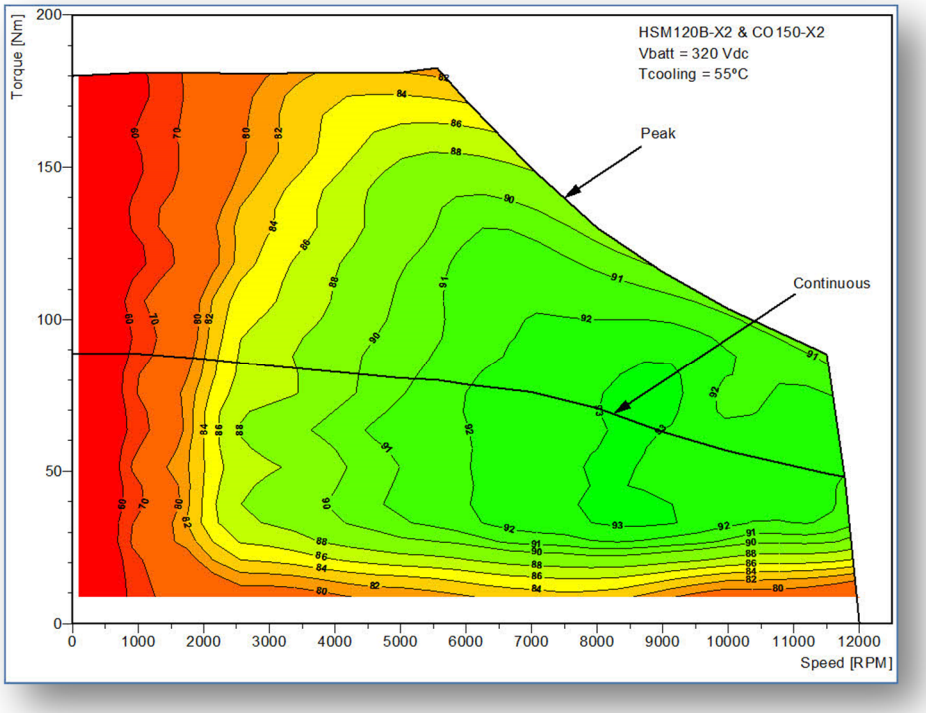


Figure 57 - TM4 Motive B 105 kW electric motor efficiency map [22]

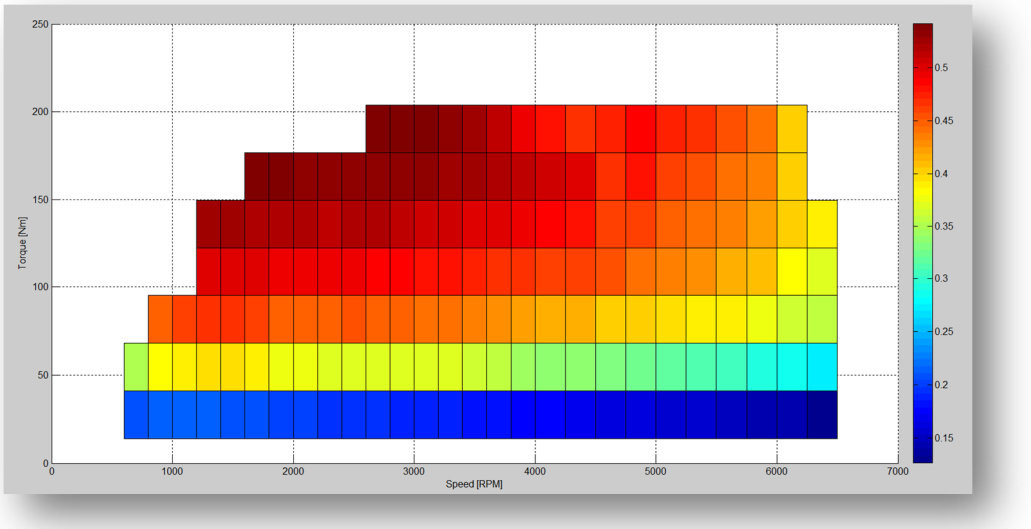


Figure 58 - GM LE9 Flex-Fuel engine estimated efficiency map

The selected motor and engine in this case happen to have their maximum efficiencies at approximately 6000 rpm on the generator side and 3000 rpm on the engine side. This further supports the use of a torque coupling speed multiplier of 2 from engine to generator.

8.3 Mechanical Design of Torque Coupling

In the EcoCAR 2 vehicle, the TM4 electric motor used as a generator has an exposed bearing on the output shaft shown in Figure 59 and Figure 60, as it was designed to be coupled inside a gearbox. Typically the exposed bearing is lubricated by oil splash inside the gearbox, hence this created the requirement that proper lubrication must be applied to the bearing and seal, as it is no longer used as intended.



Figure 59 - TM4 generator showing exposed bearing at the output shaft



Figure 60 - TM4 Generator showing exposed bearing inside torque coupling system housing

8.3.1 Motor Bearing and Seal Lubrication

The simplest method of lubrication is using an oil bath, ensuring proper oil level within the bearing area. This can be designed using references from mechanical engineering design guides or literature from bearing manufacturers such as SKF.

However, since the motor may be used at high speeds, TM4 does not recommend using small oil baths for bearing and seal lubrication as overheating can become an issue very quickly. To combat overheating, it was recommended that the bearing be lubricated by providing fresh oil feed in a jet or mist form, using an

external sump and oil pump. However such a system is more complex and was not tested by TM4, hence they do not take any responsibility in such attempts.

TM4 stated that GKN, manufacturer of gearbox that the TM4 motor is designed for, recommends 75W-80 gear oil, although TM4 has had better results and prefer using 80W-90 gear oil.

The Waterloo team has opted to use a different synthetic lubricating oil – Tribolube L6 by Aerospace Lubricants Inc. – which is a "low viscosity, oxidatively stable, corrosion resistant, wide temperature range synthetic lubricating oil" [23]. Waterloo has had success using this in the past with similar motor applications, and the very low viscosity allowed the oil to be pumped effortlessly by a generic diesel fuel pump. A lot of issues with the pump clogging and stalling occurred when the pump was being used with the recommended gear oils, which caused the switch to Tribolube.

It should be noted that if the pump clogs due to using oil of too high viscosity, thorough cleaning of the pump as well as the entire system including hoses, oil sump, bearing, etc. must be done with degreaser. Typically this can be done by first spraying down the oil pump inlet and outlet with degreaser, then running the pump to pump fresh degreaser into the system for long periods of time with the drain disconnected from the pump and disposed of.

8.3.2 Torque Transfer Mechanism

Torque can be transferred from the engine to the generator and vice versa through different mechanical systems, such as chain-drive, gear-drive, or belt-drive systems. Ideally a chain-drive system would be preferred in the case of the UWAFT vehicle as the torque coupling is operating in an oily environment. Belts should not be soaked in oil as normal belts will expand when contacting oil. However, Waterloo was unable to source an off-the-shelf chain for this relatively high speed and torque application in the very limited time constraint, with the exception of one chain designed for racing motorcycles. That specific chain had a very limited lifetime and was deemed inadequate for use in this hybrid system, so a belt-drive system was considered.

8.3.2.1 Belt-Drive System

To combat the oily environment, the Poly Chain GT Carbon Belts from Gates was chosen as this series of belts is designed to be used in oily environments due to its polyurethane construction, which did not react and expand when contacting oil. However, these belts are not designed to be soaked in an oil bath and the manufacturer was unsure of the consequences of doing so. With the time constraint in Year 2 of the EcoCAR 2 competition, such a belt was used, paired with off-the-shelf cast iron Gates sprockets in a 2:1 diameter ratio on the engine and generator. Figure 61 shows the belt-drive system being designed in the

Gates Design IQ software available free of charge, while Figure 62 shows the torque coupling system installation in CAD. Further design and tensioning details from Design IQ are shown in Appendix A – Design Methodology Instructional Materials.

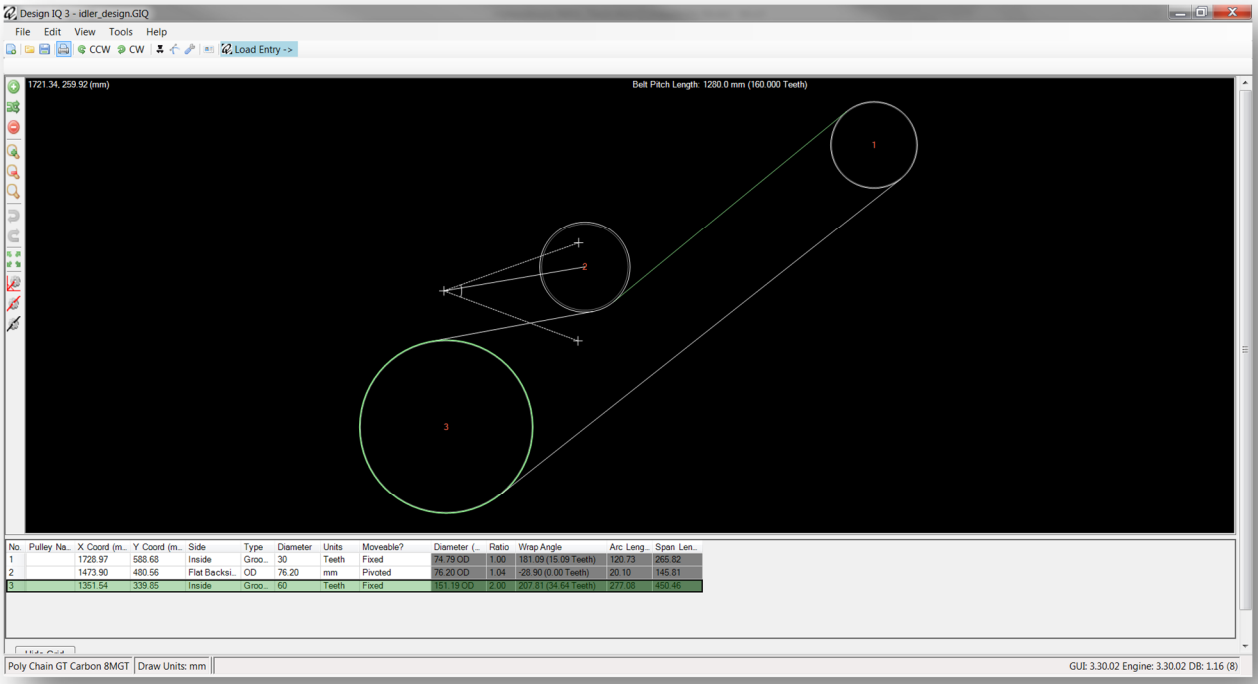


Figure 61 - Belt-drive system designed in the Gates Design IQ software

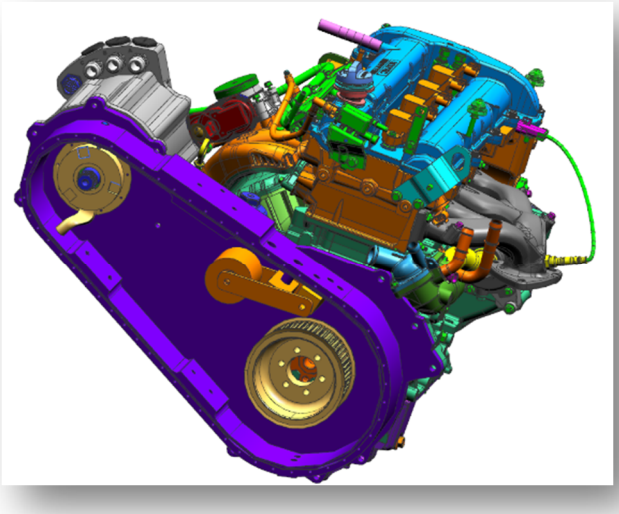


Figure 62 - CAD of torque coupling belt-drive system

8.3.2.2 Sprockets

Gates offer off-the-shelf sprockets for the Poly Chain GT Carbon Belts based on belt width, designed for use with a tapered bushing. However due to the rim speed that these sprockets will be operating at, caused by high rotational speed and relatively large radius sprocket, it was suggested by Gates application engineers that the cast iron off-the-shelf parts would not provide adequate strength. Hence custom sprockets based on the off-the-shelf parts using different material were designed by UWAFT and custom made by Gates. Figure 63 and Figure 64 shows the custom sprockets fabricated by Gates.

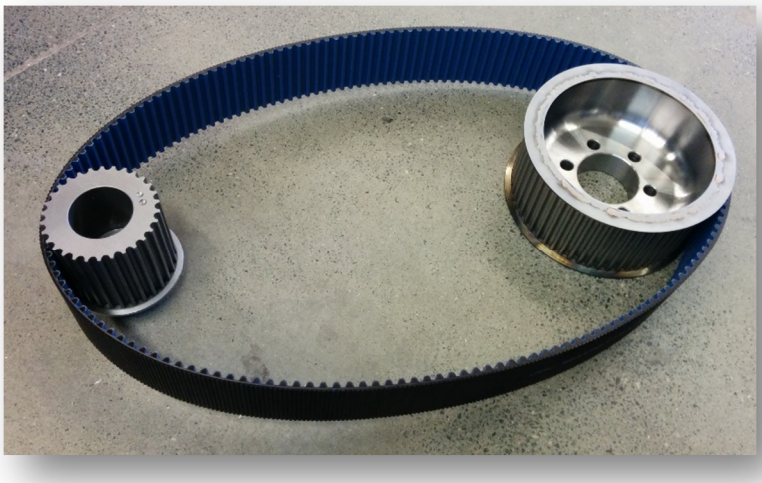


Figure 63 - Custom engine and generator Gates sprockets with the Gates Poly Chain GT Carbon Belt

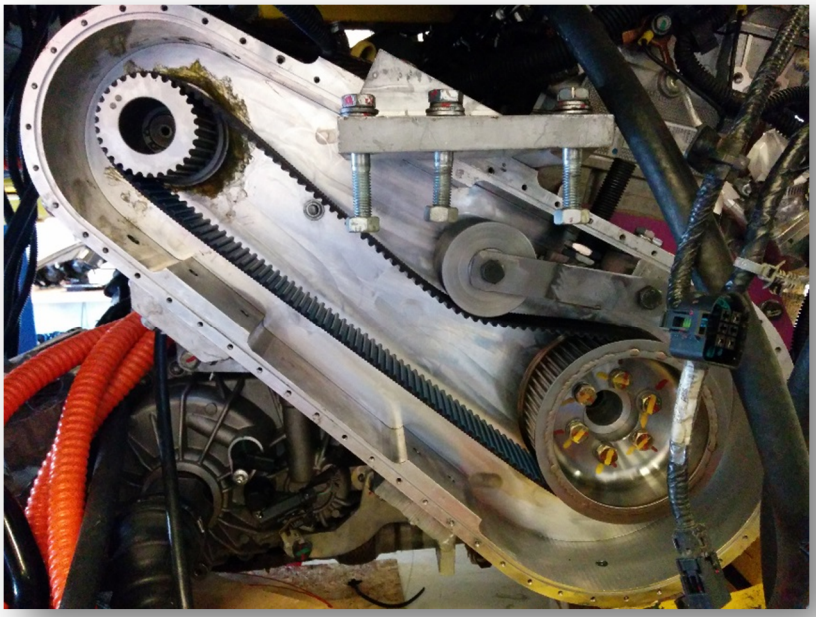


Figure 64 - Custom Gates sprockets and Gates Poly Chain GT Carbon Belt being test fitted in vehicle (oil dish not installed on generator)

The custom generator sprocket utilizes a splined design on the generator side which sits on the splines on the motor output shaft, while eliminating the outside belt flange to facilitate easier assembly of belt onto sprocket. There is an outside flange on the engine sprocket which will keep the belt from falling out. Further, there is an extruded hub on the inside of the sprocket with a specified high smoothness for the shaft seal of the generator oil dish to sit on, as shown in Figure 65 and Figure 66. A snap ring on the motor output shaft keeps the generator sprocket in place, although using a snap ring implies there will be a tiny bit of play for the sprocket along the shaft, which should be eliminated in a future improved design.



Figure 65 - Generator sprocket showing hub with specified smooth surface for the oil dish shaft seal and no outer belt flange

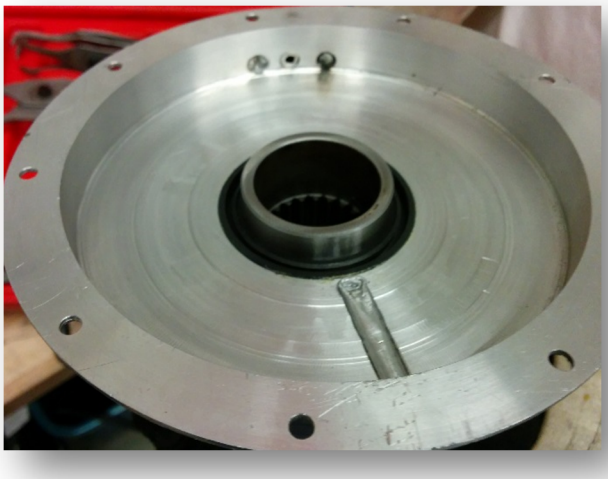


Figure 66 - Inside of oil dish showing shaft seal sitting on the generator sprocket hub

The custom engine sprocket is similar to the off-the-shelf part with the exception that it no longer uses a tapered bushing to mount to the engine output shaft, but instead uses a bolted design. Six long bolts hold the sprocket to where the engine flywheel used to sit, through an in-house machined aluminum spacer in between to align the engine sprocket with the generator sprocket. This eliminated previous issues with the sprocket coming loose if the tapered bushing was not tightened enough using set screws, or the key sliding out and/or breaking during continuous high-torque operation. A large fillet was also added on the inside of

the sprocket to increase strength and eliminate stress concentration. The engine sprocket is shown in Figure 67.



Figure 67 - Custom engine sprocket installed in vehicle showing bolt-on design and large fillet

8.3.2.3 Belt Tensioner

An additional idler/tensioner pulley was required in the system, as the belt must be chosen such that it is slightly longer providing a small amount of slack so that it can be installed over the sprockets. However, Waterloo was unable to find an off-the-shelf tensioner which was able to fit in the belt-drive enclosure which had already been designed and fabricated prematurely. Hence a custom tensioner had to be designed and fabricated.

The author designed a simple tensioner which utilized a threaded rod and multiple nuts to tension the belt and lock the tensioner in position, as shown in Figure 68.

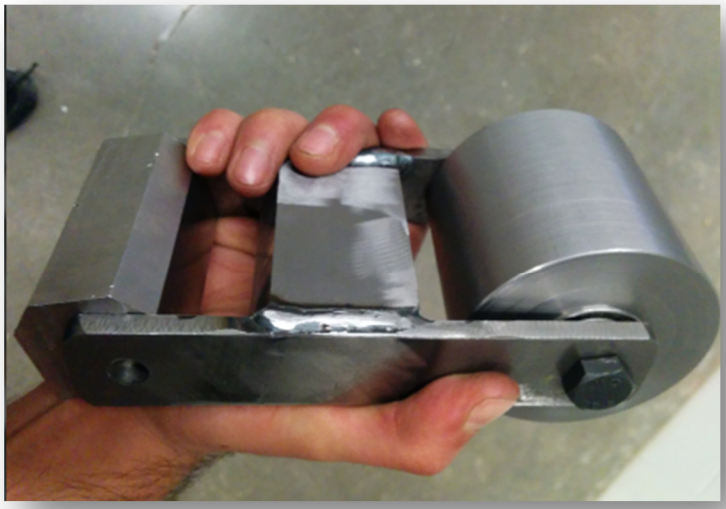


Figure 68 - In-house designed and fabricated belt tensioner

With the threaded rod going through the belt-drive system enclosure, two nuts on top tightens and locks into each other so that turning the top nut will rotate the entire threaded rod. This allows the assembly to act like a hex cap bolt so that the rod can be turned by a socket or wrench, while also allowing the adjustability of where the nuts sit so that the tension can be adjusted throughout the life of the belt. The installed tensioner is shown in Figure 69.

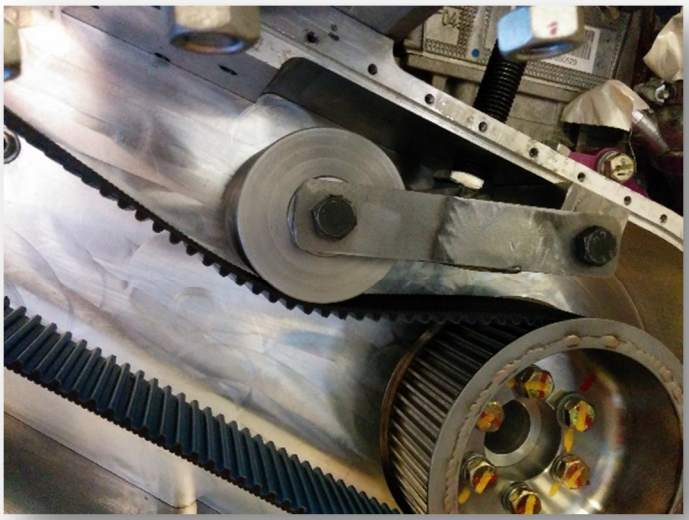
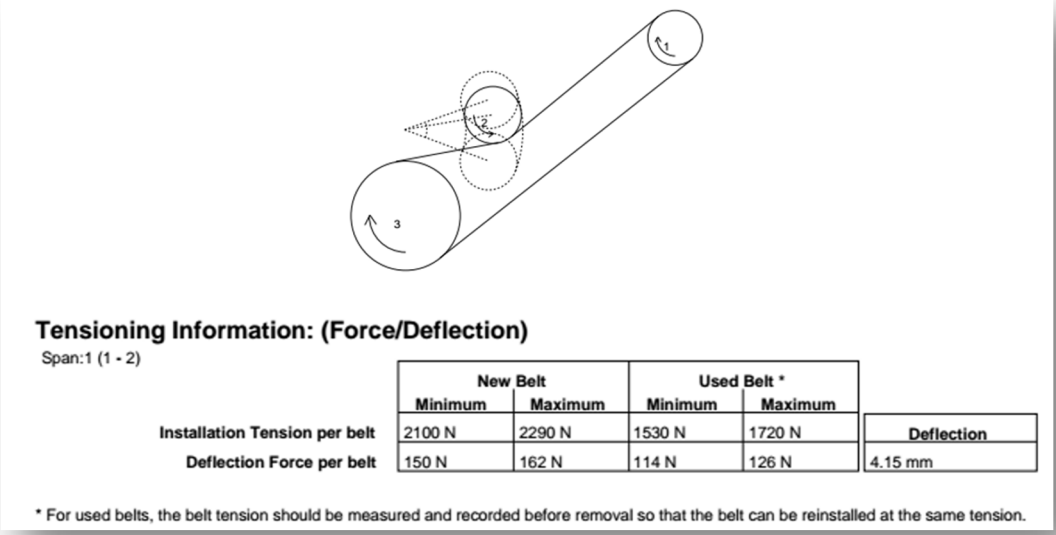


Figure 69 - Tensioner installed showing threaded rod and nuts for tension adjustment going through the belt-drive housing

On the inside of the enclosure, the threaded rod has three nuts. The bottom two nuts tightens and locks into each other just like the ones outside the enclosure to prevent rotating separately from the rod, and serves to make the physical contact from the rod to the tensioner push assembly. This protects the threads on the rod from being damaged from the contact with the push assembly. Lastly, the top nut inside the enclosure is designed to be tightened after the correct tension is set, to lock the threaded rod in place and therefore locking the amount of tension on the belt.

The amount of tension the belt requires can be computed using Gates' free design software, Design IQ. With the locations of the sprockets and tensioner in place, Design IQ can compute the required tension on each portion of the belt, on a new belt as well as a used belt, as shown in Figure 70.



Tensioning Information: (Force/Deflection)

Span:1 (1 - 2)

	New Belt		Used Belt *		
	Minimum	Maximum	Minimum	Maximum	
Installation Tension per belt	2100 N	2290 N	1530 N	1720 N	Deflection
Deflection Force per belt	150 N	162 N	114 N	126 N	4.15 mm

* For used belts, the belt tension should be measured and recorded before removal so that the belt can be reinstalled at the same tension.

Figure 70 - Belt tensioning data as taken from Gates Design IQ software report

The tension of the belt can be adjusted then measured using various belt tension gauges such as a force-deflection gauges, which measures the deflection based on the force applied normal to the belt's surface, or a sonic tension meter which measures the natural frequency and in turn calculates the tension of the belt at that specific section. Gates produces both types of tension gauges, however both have their disadvantages. The force-deflection gauge cost ranges from $80-200 and requires a very high force and accurate force application in terms of amplitude, direction, etc. to be applied on the belt surface; with the space constraints this was not possible in the vehicle. The sonic tension meter costs upwards of $800 and the expenses cannot be justified for UWAFT as it will only be used when installing the belt.

An alternate technique to adjust and measure the belt tension was devised following the principals of the sonic meter. With the belt tensioned to a tight feel similar to the serpentine belt in a conventional vehicle, multiple smartphone apps were used to measure the natural frequency of each belt portion when flicked. The use of multiple apps confirmed the relatively close readings of the natural frequencies. This method of measuring the belt tension proved to be adequate for this application.

8.3.3 Custom Sprockets

With the conclusion of EcoCAR 2 Year 2, and the start of the third and final year, more time was available to redesign the belt-drive system for improved reliability. Further, with the failure of the initial design during the third year due to fatigue, as the initial design was not designed to the full capabilities of the hybrid system, this created an opportunity to redesign the belt-drive system components.

In order to redesign the system such that the full capability of the hybrid system can be sustained, although keeping in mind these conditions such as redlining of the engine will never be reached in the designed hybrid controls system, the sprockets and idler pulley had to be increased significantly in both width and diameter. This created multiple issues: the existing enclosure cannot accommodate the increased width, and the increased diameter causes the rim speed of the sprockets to exceed material strength.

Custom sprockets must be made using mild steel instead of the cast iron off-the-shelf parts to accommodate the relatively high rim speeds of the sprockets. As the parts are made as one-offs, features of the sprockets can be changed slightly and as such this was an opportunity to improve the mounting of the engine sprocket.

The engine sprocket adapter with the relatively weak keyway was removed, and the new engine sprocket was designed to be bolted right onto the engine crankshaft with an aluminum spacer in between, in the manner that the original flywheel was designed to be bolted onto the crankshaft. This ensured that the mounting method was strong enough to sustain the full power and torque of the engine, while reducing mass significantly as the initial engine sprocket adapter was designed using steel. The new aluminum spacer is 426 grams versus the original steel adapter at 1340 grams, implying a 68% weight reduction.

Further, the newly designed generator sprocket does not have a flange on the outside, in order to facilitate easier installation of the belt onto the sprocket. The flanges on the engine sprocket keep the belt from misaligning or falling off the sprockets. The generator sprocket continues to use a spline connection to the generator output shaft, and the spline specifications were obtained from TM4.

Although FEM analysis shows that aluminum could have been used for the fabrication of these sprockets, which would have reduced mass significantly as well as machining costs, it was not considered as the

limited time constraint and funding did not allow for accidents or errors. Mild steel was used as an added safety factor. Large radius fillets were used wherever possible to eliminate stress concentrations.

8.3.4 Generator Bearing Oil Enclosure

During the redesign of the belt-drive system in Year 3 of EcoCAR 2, one addition to the system was an oil enclosure "dish" which sealed the lubricating oil for the bearing from getting on the belt, as shown in Figure 71. This ensured that belt integrity would not be affected by constantly being soaked in oil. The oil enclosure will be referred to as the dish from here on to avoid confusion between the belt-drive system enclosure and the oil enclosure inside.

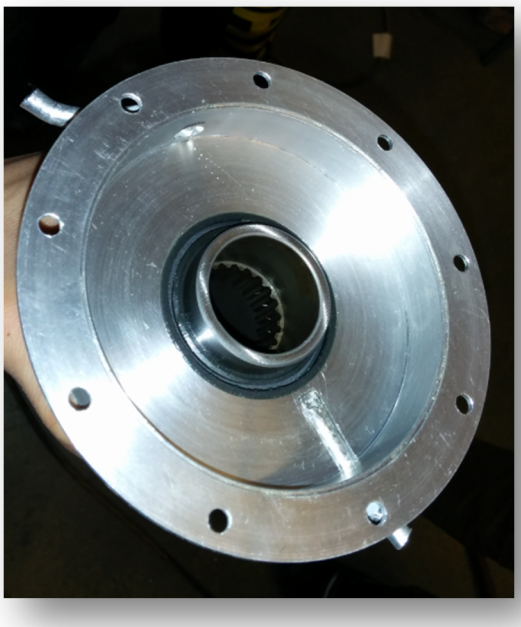


Figure 71 - Oil dish showing inlet directing oil stream into bearing (bottom of picture) and outlet (top of picture)

The dish seals the oil against the back of the belt-drive enclosure by using an oil seal cut-out with the shape of the dish's flange, as shown in Figure 72. The dish is bolted onto the enclosure evenly around its flange using small bolts.

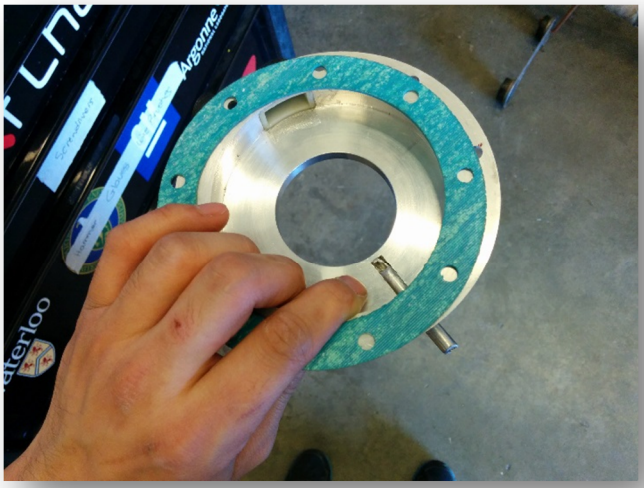


Figure 72 - Oil dish showing cut-out oil seal (blue) that is sandwiched between the dish and the belt-drive housing

Since the generator output shaft spins with a maximum rated speed of approximately 11,500 rpm, a special shaft seal was required on the center of the dish which allows for such high shaft rim speeds. It was decided that assembly and sealing would be easier on the sprocket hub, which spins with the shaft, given the space constraints. Hence when designing the improved generator sprocket in Year 3, the hub on the sprocket has a specified smoothness to ensure that there is a good seal and that friction caused by the spinning sprocket does damage the seal. The smoothness required depends on the seal and this information can be requested by the seal manufacturer. In this case, smoothness required was of ISO standard, R_a = 0.2-0.5 micrometers, R_z = 1.2-3 micrometers. Refer to Appendix B – Drawings for the sprocket drawing with specified smooth surface finish to accommodate the high speed shaft seal.

A shaft seal with such a high rated rotational speed was not found from off-the-shelf catalogs, hence a special custom-made seal was required, shown in Figure 73. Generally the seals rated for such high speeds must be made of carbon Teflon or similar material.



Figure 73 - Shaft seal custom ordered for high rotational speed

Since the generator bearing requires a flowing source of lubricating oil, the dish has an inlet and outlet which allows oil to be pumped in from the top and drained from the bottom. A hole was drilled down through the top of the dish with a small aluminum tube going through the dish such that the tube outside of the dish provides a surface for a hose to be inserted over and clamped onto. The end of the tube inside the dish is bent and cut at an angle such that oil going through the tube is aimed and sprayed at the bearing instead of straight down.

A similar tube without the bend is used as an outlet in order for a hose to be inserted over and clamped onto as a drain. The hose goes to an oil reservoir built from aluminum. Refer to Figure 71 for a photograph of the original oil inlet and outlet tubes, with the inlet tube bent such that the inlet oil stream is directed at the generator bearing.

One problem encountered during the testing of the dish was that because the seal was not designed to withhold pressure, having an outlet with the same diameter of the inlet sometimes caused the oil to not drain fast enough, as the inlet is pressurized by the pump. This caused a buildup of oil inside the dish, eventually popping the seal out of place and rendering the dish useless as oil flowed out of the system into the belt enclosure. The initial dish with identical diameter inlet and outlet hoses is shown in Figure 74. An improvement was required such that the outlet is now several times larger than the inlet, ensuring that there is no chance of fluid and pressure building up inside the dish. Due to the space constraints and the positions of existing outlet holes in the belt-drive enclosure, an adapter with a unique shape was required such that the drain can be much larger than the inlet, while a large ¾ inch hose can go over the adapter. Such adapter was 3D printed out of ABS material as shown in Figure 75, although polycarbonate is preferred due to its resistance to higher temperatures.

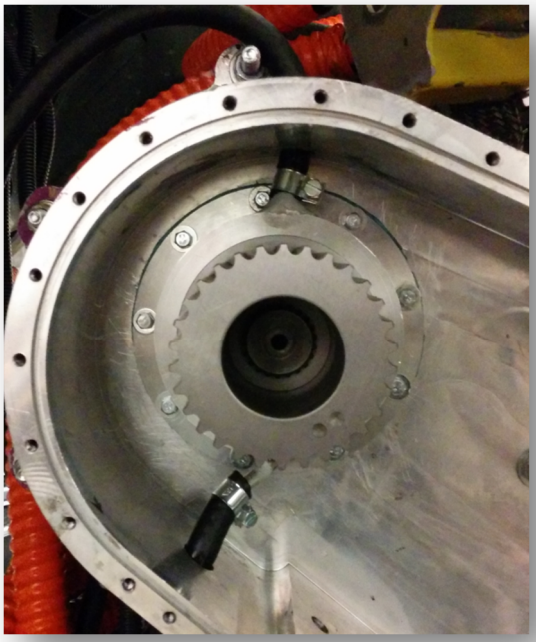


Figure 74 - Old oil dish with small drain outlet installed in belt-drive housing, causing oil to become pressurized within the dish

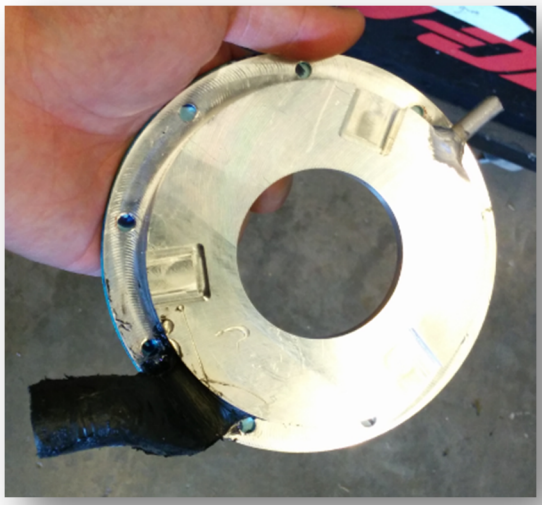


Figure 75 - Redesigned oil dish with larger oil drain outlet made of 3D printed ABS plastic (black piece), and 3 notches for clearance when using puller to uninstall sprocket from motor shaft

Additional sealant needs to be applied to the back of the oil dish as well as around the 3D printed drain adapter which is bonded to the dish with epoxy. Keep in mind that the sealant must be able to withstand the temperature, oily environment, as well as cure such that it does not come off easily. This proved to be one

of the problems as using a sealant that could not handle such high temperatures caused the sealant to get onto the belt and idler pulley, and eventually seizing the bearings on the idler and causing catastrophic failure.

As an added protection against leaks from the oil dish, the drain from the bottom of the belt-drive system enclosure that was previously the main drain when oil was free to fill the enclosure is kept. This drain also goes to the oil reservoir such that any small leaks or failure of the oil dish seal will be contained, and more importantly feeding back into the lubrication system such that the pump and generator bearing will not be starved.

8.3.5 Expanded Enclosure

Due to the increased width of the redesigned sprockets, the belt-drive system enclosure needed to be modified. A new enclosure was too costly and required removal of all the powertrain components from the engine bay and disassembly in order to replace the enclosure. As such, a modification of the existing enclosure was made such that the sprockets would fit. A particularly challenging part of the modification included the extremely tight space constraint, as there were only millimeters of clearance between the outside of the enclosure to the component next to it, which was the inverter for the front traction motor, as shown in Figure 76.

The front traction motor could not be relocated due to lack of space in the engine bay. Further, the front traction inverter must be removed in order to service the belt-drive system components such as belt, sprockets, etc., and the only way of installing the inverter required the inverter to be angled into the inside of the enclosure in order to be slid out from the wheel well. This implies that the lid must be closed after the inverter is installed.

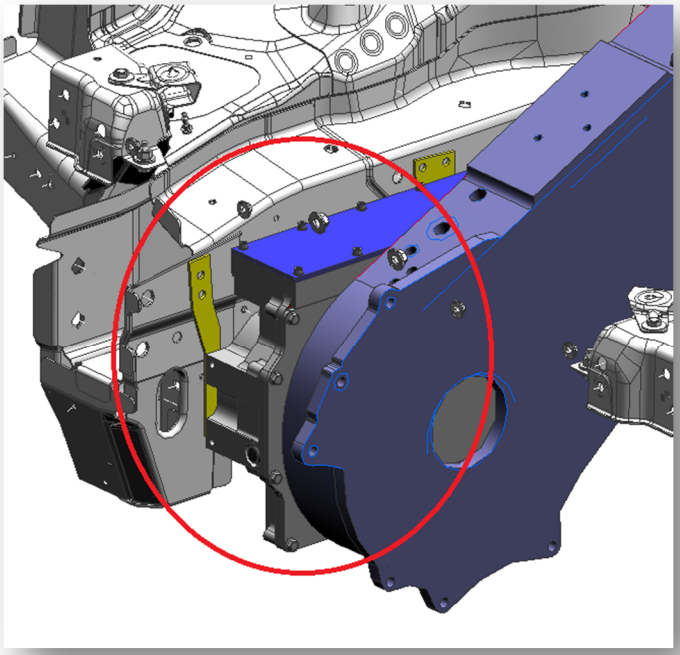


Figure 76 - CAD view of front traction inverter installed between frame rail and torque-coupling housing

With such tight space constraints, a unique design solution was required for the belt-drive enclosure lid. The lid was designed to be a 2-piece assembly, since a one piece U-shaped cross-section lid could not be physically installed with the inverter in place. The final design is shown in Figure 77.

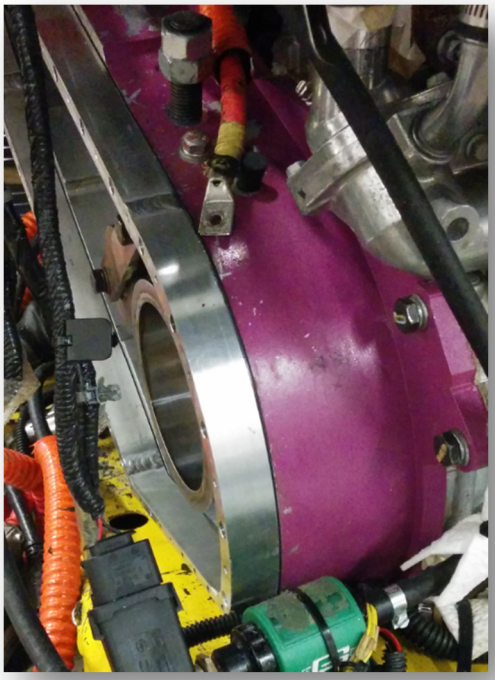


Figure 77 - Belt-drive housing spacer (silver) installed on belt-drive housing to allow for installation of motor inverter, which needs to intrude into belt-drive housing (purple) during installation

The lid was to be assembled using a spacer with the same shape as the belt-drive system enclosure such that it can extend past the sprockets' and idler's width. The spacer had holes that were drilled along the edges which were at identical locations to the original enclosure. However, only every other hole was drilled as a through-hole to bolt the spacer onto the enclosure and with a counter-bore such that the head of the bolt does not extend past the surface of the spacer. The other half of the holes were drilled only partially through the spacer as tapped holes and were meant for the other flat part of the lid to be bolted onto the spacer, as shown in Figure 78.

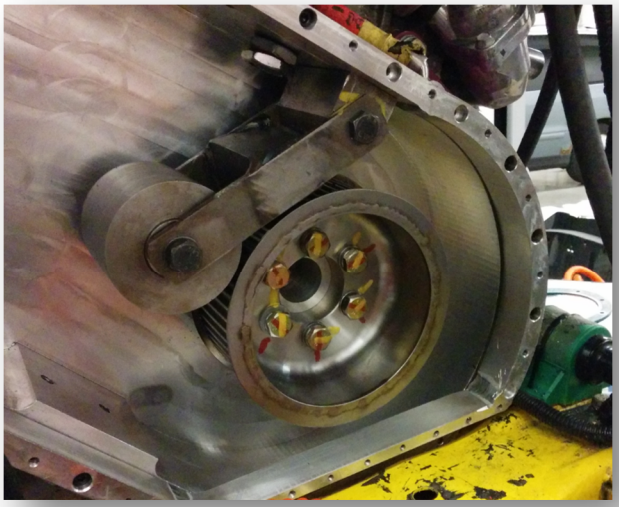


Figure 78 - Belt-drive housing spacer showing counter-bore through holes (with black alley-key bolts installed) for mounting spacer to housing, and tapped blind holes for installing flat cover on top

Lastly a very thin aluminum lid was bolted onto the spacer to close off the enclosure, shielding foreign material from entering the belt-drive system. A rubber seal was cut out and bolted between both the spacer and enclosure gap, as well as the flat-lid and spacer gap, as shown in Figure 79. This provided a water-tight seal such that water from the outside environment cannot enter the belt-drive system, causing corrosion to the idler and sprockets which were made of mild steel.



Figure 79 - Belt-drive housing spacer with rubber seal glued on. Rubber seal goes on both sides of the spacer (between housing and spacer gap, and flat lid and spacer gap)

8.3.6 NVH

One overlooked design aspect of the belt-drive system was the noise, vibration, and harshness (NVH). When the new system designed in Year 3 was run without the lid on, there was a very significant amount of vibration and a very loud constant frequency noise from the constant engine speed and load due to the Series Hybrid architecture.

As a last minute fix, soft adhesive sound dampening pads were glued onto the flat-lid which was bolted onto the belt-drive system enclosure, as shown in Figure 80. This temporary fix was surprisingly effective and brought the noise down to a relatively acceptable level – just slightly higher than an average conventional internal combustion engine powered vehicle, although most of the vibrations remained.

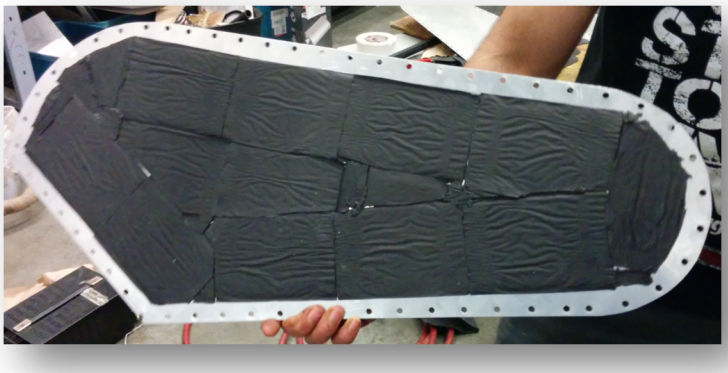


Figure 80 - Flat lid installed on top of belt-drive housing spacer after inverter is installed in vehicle. Black adhesive mats were glued on to reduce noise and vibration.

The NVH performance is one area that should be improved upon in the future in order to design a vehicle with increased overall consumer acceptability.

8.3.7 Failures

Although the redesigned belt-drive system from Year 3 worked well for a brief couple of weeks, the system started to fail during the final Year 3 EcoCAR 2 competition. During the competition the noise from the system started increasing, and eventually torque was no longer transferred from the engine to the generator due to belt failure.

Upon disassembly of the system when the car returned to Waterloo, it can be seen that the belt was sheared completely, and the bolt from the idler pulley used as the axis of rotation for the pulley was completely ground off as supposed to being sheared off. There was also black “goo” that was spread all over the inside

of the belt-drive system enclosure, and the bearings on the idler pulley were both seized. The failed torque coupling parts are shown in Figure 81 to Figure 85.



Figure 81 - Sheared torque-coupling belt removed from vehicle



Figure 82 - Broken tensioner assembly showing snapped bolt



Figure 83 - Broken tensioner assembly disassembled



Figure 84 - Snapped tensioner bolt. Further examination shows it was rounded through friction from rubbing and ultimately broken off.



Figure 85 - Idler pulley from tensioner assembly showing seized bearing from black "goo", causing the bearing inner race to rotate relative to bolt causing high friction and ultimately snapping the bolt acting as a rod

After inspection, it was decided that the black “goo” had gotten onto the idler pulley bearings, causing the bearings to seize and ultimately the idler pulley was unable to rotate. This in turn caused the bearing inner races to rotate against the bolt, which ground the bolt down and eventually snapped the bolt. This was evident from the round ground-up shape of the bolt. The idler pulley was no longer fully supported by the bolt as the bolt had snapped, however the idler stayed on the bolt as the belt-drive system enclosure did not allow enough space for the idler pulley to fall off completely. The idler sitting at an angle caused the belt to fall partly off the surface of the seized idler. Eventually the rubbing between the belt and idler pulley caused the belt to shear.

It is unknown whether the black “goo” is the sealant used on the oil dish on the generator bearing, which did not cure completely and was flung around, or the adhesive from the sound dampening pads put onto the inside of the enclosure lid. Another possibility is that both of these were the cause of the black “goo” that spread across the enclosure and seized the idler bearings, and heat from the system can also be a factor which caused the “goo” to separate from the dish and/or the lid.

8.3.8 Lessons Learned

The most significant lesson learned from the design, assembly, and failures of the torque coupling system was that this is a very major and critical component to the hybrid vehicle architecture, hence more time should be allocated to the design and testing of such system. This was the first time the team has attempted such a design, and as such countless obstacles were encountered, causing catastrophic failure of the system several times.

It should also be noted that the system must be designed beyond the full capability of the powertrain components. The original belt-drive system was designed to what the expected operating point was with no safety factor, which was below the maximum capability of the engine and generator. This in turn caused catastrophic failure of the torque coupling system from factors such as fatigue, unexpected load spikes, and temperature.

Attention must also be paid to the kind of sealant and adhesives used inside the belt-drive system enclosure, as any loose or uncured material may get on moving parts, causing it to be spread across all the components and ultimately seizing moving parts such as the idler pulley bearings, causing catastrophic failure. All material used must also be resistant to the oily environment and high temperatures of the engine bay.

8.3.9 Future Improvements

Future improvements suggested include the noise, harshness, and vibration (NVH) of the torque-coupling system. Such system that transfer relatively high torque and speeds of major powertrain components creates

significant amount of vibration and noise, which must be suppressed through careful design of mounting locations and appropriate damping. Such NVH issues contribute to the overall consumer acceptability of the final vehicle.

Further, many aspects of the idler pulley in the belt-drive system can be improved. Such improvements include using a steel shaft that is turned down accurately by a lathe to the specific diameter required by the inner races of the idler pulley bearings, as supposed to using a bolt of approximate diameter. This reduces the amount of play on the bearings, and creates more of a "press-fit" on the bearing inner race, preventing the bearing inner race surface from rotating relative to the shaft. An extreme amount of rotation on the inner race surface relative to the shaft caused by seizing was the cause of grinding and ultimately snapping of the shaft.

With a custom shaft that is turned down, the profile of the shaft can also be customized such that a spacer is not required to be inside the pulley between the two opposite bearings. This allows a much more accurate fitment and prevents the bearings from being cocked, where the inner race is pushed in or out from the outer race, causing damage and seizure of the bearings.

The belt-drive system, specifically the tensioner assembly has been redesigned since the author has graduated from the University and the team, as part of learning from the failures of EcoCAR 2. The improvements mentioned above has been addressed in the redesign. However, as the author did not take part in these improvements, the details of the improvements cannot be addressed in this thesis. Such details can be obtained from the current team members of the University of Waterloo Alternative Fuels Team.

Chapter 9
Other Mechanical Components

This chapter outlines the mechanical design processes for other critical components of the hybridization and electrification of a conventional internal combustion engine powered vehicle. The components outlined in this chapter do not include as much details as the previous sections, not because these are less important or less critical components, but rather because less time was spent by UWAFT in EcoCAR 2 on the design process of these components than those preceding this section.

The components outlined in this chapter includes:

- High voltage battery
- Front powertrain component mounting
- High voltage distribution/fuse box
- High voltage air conditioner (AC) compressor mounting
- Powertrain component cooling loops
- Electrical routing
- Exhaust
- Heated catalytic converter

9.1 High Voltage Battery

The high voltage battery is a very critical part of the electrification of a vehicle, and serves as an energy storage system for the electrical energy obtained either from charging from the grid, regenerative braking, or a generator powered by a second source of energy, which was a gasoline engine in this case.

One main concern with the high voltage battery is the relatively high electrical potential, but more importantly the very high amounts of current that can be drawn instantaneously from the battery pack. Waterloo's EcoCAR 2 vehicle is powered by a 19.8 kWh A123 lithium-ion battery pack that operates at 345V nominally. Safety is a major concern in the event of a collision with the vehicle. The battery must be able to disconnect itself from the rest of the vehicle, fused properly at several appropriate locations throughout the vehicle, as well as not compromise the structure or designed crush-zones of the vehicle.

The A123 battery pack used is composed of 7 battery modules at approximately 50V each, and each at about the same physical size as an average 12V lead-acid battery found in conventional vehicles. The modules are connected in series in order to provide approximately 345V overall.

There are also several additional components to the battery pack, including:

Fused Manual Service Disconnect (MSD) – which disconnects the battery pack circuit in half hence disconnecting the overall circuit and providing no voltage to the rest of the vehicle. Disconnecting the battery pack in half also means that the highest electrical potential is now either 150V (3-module side) or 200V (4-module side), further reducing the risk and severity of accidents when servicing the live battery pack.

Pre-charge circuit – as the voltage of the overall battery pack is relatively high at 345V, the battery cannot be instantaneously connected to the rest of the vehicle as that will result in the possibility of welding the switch shut, referred to as arcing. This is when the voltage spikes up as the switch is about to close and there is only a small air gap in between the contactors. A pre-charge circuit turns on to slowly bring the voltage of the rest of the vehicle up to the voltage of the battery pack through a large resistor, before the contactor is closed to directly connect the high voltage battery to the vehicle. The pre-charge circuit must then turn off in order to avoid having the large resistor gradually overheating and ultimately burning out.

Battery Management System (BMS) – the main computer or "brain" of the battery pack, which monitors all vital information from the battery modules through sensors, such as voltage, temperature, current, etc., and communicates with external components, such as the plug-in charger, vehicle supervisory controller, etc., in order to safely control the battery pack during functions such as charging, discharging, closing and opening of contactors, balancing of cells, and more.

Measurement and Balance Board (MBB) – located at each one of the modules, this is used to measure and report vital data, such as voltage, from the battery module to the Battery Management System (BMS).

Current Shunt Module (CSM) – this is used to measure the overall current going in and out of the battery pack.

Figure 86 shows the aforementioned battery pack components mounted to the front of the battery pack, as seen from the passenger compartment when the rear seats are folded down.



Figure 86 - Front of high voltage battery pack showing compartment housing battery-related electronic components as seen from passenger compartment behind rear seats

9.1.1 Mechanical Mounting

Waterloo's battery pack design was a single large battery pack located in the trunk floor of the vehicle. The trunk was cut out in order for the battery pack to extrude below the floor, leaving more trunk space in the vehicle for the passengers. Although the pack is a single enclosure as supposed to having two enclosures with modules separated throughout the car, there is still an upper and lower part of the battery pack. The lower part extruding through the trunk floor contains 4 battery modules mounted vertically, while the upper part contains 3 battery modules mounted horizontally, as shown in Figure 87.



Figure 87 - High voltage battery pack installed in vehicle with cover off, showing top pack (3 horizontal modules) and bottom pack (4 vertical modules)

The upper and lower pack contains a main steel tube structure which is welded together as upper and lower packs, as seen in Figure 88 to Figure 90. The upper and lower pack structures are then bolted together when inside the vehicle.

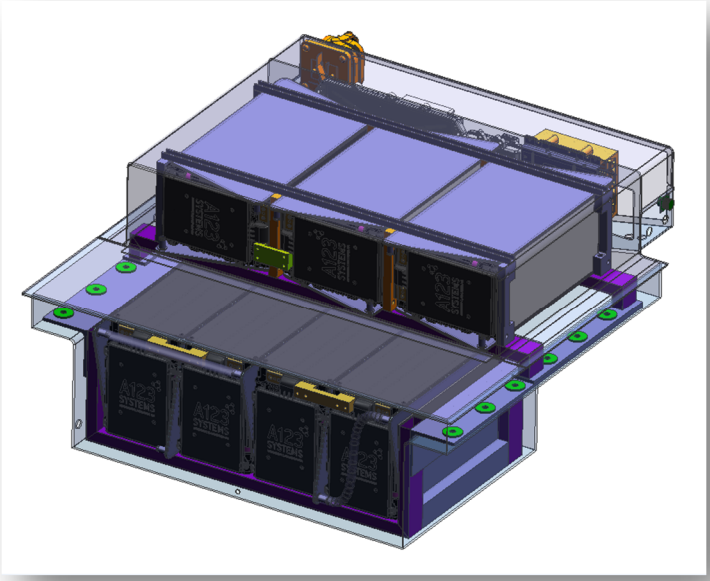


Figure 88 - High voltage battery pack showing tubular structure and modules in CAD

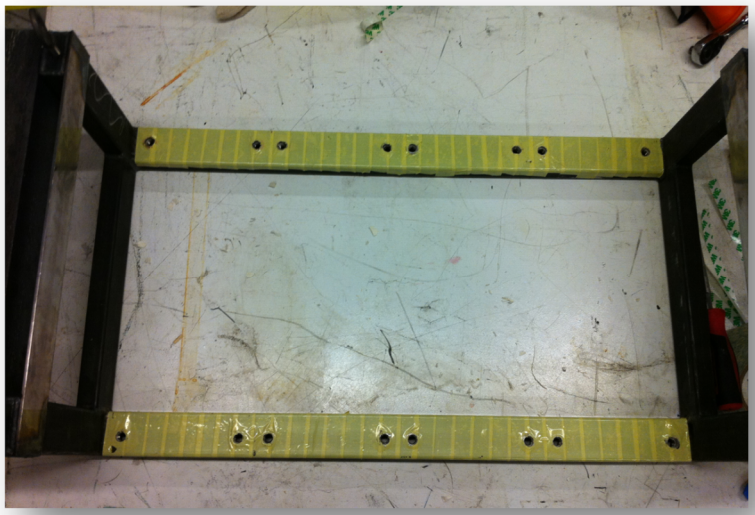


Figure 89 - Bottom structure for high voltage battery pack welded together with threaded inserts installed



Figure 90 - Top structure for high voltage battery pack welded together with threaded inserts installed

The lower pack structure bolts directly onto the vehicle frame rails. However, as the trunk floor contains ridges and ribs, an intermediate spacer milled to the contours of the trunk floor while providing a flat surface for battery pack mounting was used. The spacer is welded onto the trunk floor and tapped, as shown in Figure 91. The lower pack is then bolted onto this spacer.

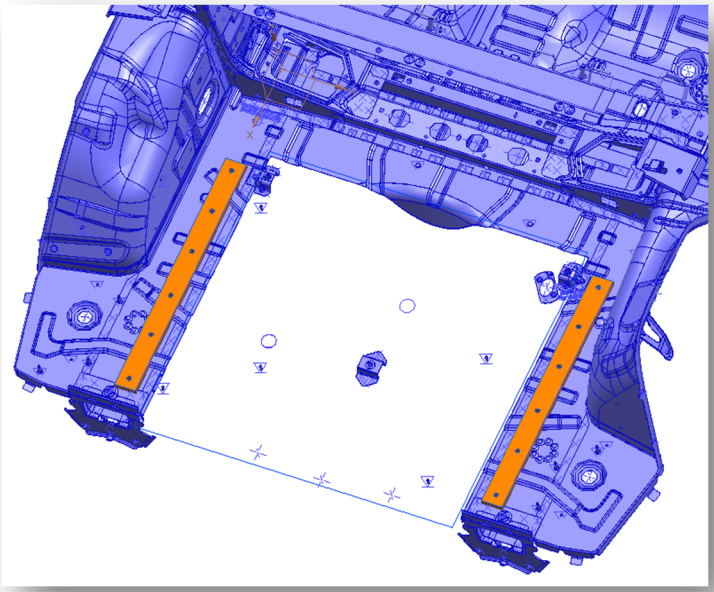


Figure 91 - Steel rails welded to trunk floor provide flat mounting surface for battery structure

The lower pack modules are bolted vertically onto the lower pack frame, with four long bolts at each corner of the modules, as shown in Figure 92. The hollow tube frame is drilled at these locations and threaded inserts were installed such that the bolts can thread up to them. This proved to be a very poor design as it is extremely hard to keep the threaded inserts perfectly centered during installation, and hence tolerance was an issue where the bolts and threaded inserts do not line up very well. Further, it is very easy to start spinning the threaded inserts, in which case they become useless and must be removed. Lastly, the threaded inserts are not designed to take a large amount of force, hence one concern is that the heavy mass of the modules can pull the threaded inserts out of the tube structure under high force movements. This can happen if the thread inserts are not installed properly, such as insert holes being drilled slightly too large. This did not cause any issues during the testing of the vehicle, but should be avoided.



Figure 92 - Bottom battery pack assembled

The top pack modules are installed sideways onto the top pack frame as shown in Figure 93. Threaded rods are pushed through the module bolt holes, with a spacer between each module which is bolted onto the frame itself, as well as spacers at the end of the modules.

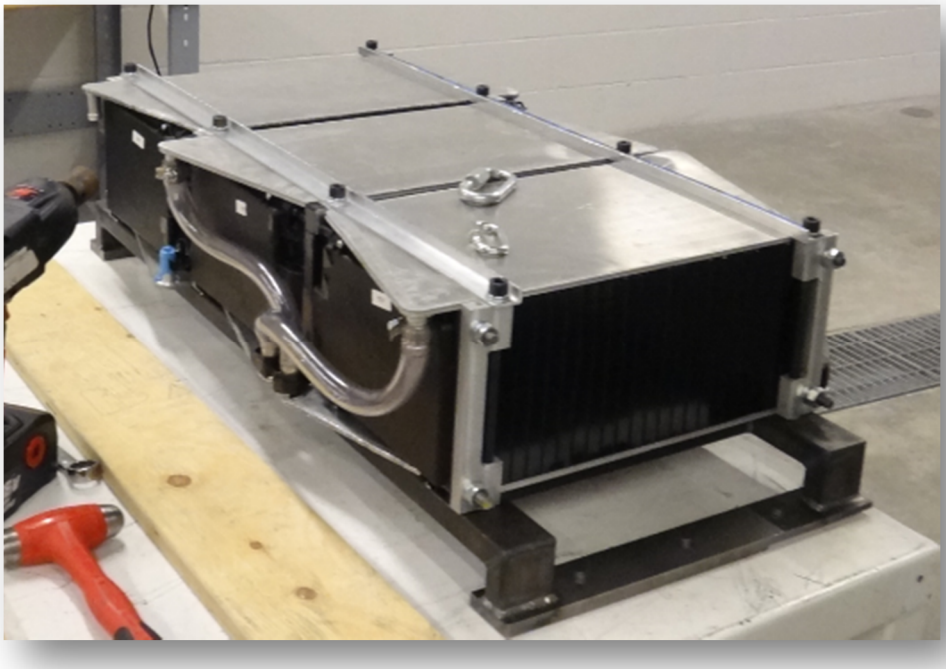


Figure 93 - High voltage battery pack showing aluminum cold plates (silver) installed on both sides of each modules allowing coolant to cool each individual module, and C-shaped spacers on the outside and between each module for mounting

9.1.2 Cooling of Battery Pack

In a typical HEV, preheating and cooling of the battery pack are very important in order to ensure that the pack operates at the optimal temperature range. A battery pack operating in very cold conditions causes the electric driving range of the vehicle to decrease significantly, while operating the pack at too high or too low of temperatures causes accelerated degradation to the battery.

For the purpose of the EcoCAR 2 competition, heating was not required as the competition did not take place in cold environments. However, cooling was a concern from the various driving cycles that the vehicle was required to complete.

Initially the pack was designed to be water-cooled, with cold plates sandwiched on both sides of every module, and coolant pumped through it constantly to draw heat away from the pack. Refer to Figure 93 for a photograph of the original cold plates.

This proved to be an extremely poor design as the high number of hose connections introduced an extremely high risk in coolant leaks. The cooling system was tested several times outside of the vehicle which resulted in leakages several times. This is an extremely dangerous scenario as the leaked coolant can cause shorting of the battery and ultimately cause catastrophic accidents. The cooling system was installed in the vehicle but was never filled with coolant or run due to the high risks, and it was found that cooling of the battery pack was not an issue for the purpose of the competition due to the relatively high thermal mass of the battery pack. This means that it will take a large amount of energy and time in order for the battery pack to finally heat up to the point it needs to be cooled. Ultimately the cold plates were taken out of the vehicle and replaced with aluminum plates to maintain support for the modules.

Computational fluid dynamics analysis (CFD) was completed on the battery pack to roughly calculate the amount of heat given off, in order to verify that the battery pack will not require cooling for the purpose of the competition. However more detailed analysis should be completed when this task is undertaken in the future.

9.1.3 Battery Pack Enclosure

The battery pack requires an enclosure such that the dangerous high voltage elements are isolated from accidental contact. An enclosure made of a special carbon fiber material was designed and fabricated to enclose the battery pack, where the material was not conductive. However, for added safety, additional high voltage isolating material was adhered onto the inner shell of the enclosure to ensure isolation.

Parts of the enclosure were made of plexi-glass such that the inner components of the battery pack can be viewed from the outside, while providing isolation. This includes a portion of the bottom pack, as well as the electronic modules placed at the front, revealed when the back seats are folded down for battery pack servicing. This is shown in Figure 94 and Figure 95.

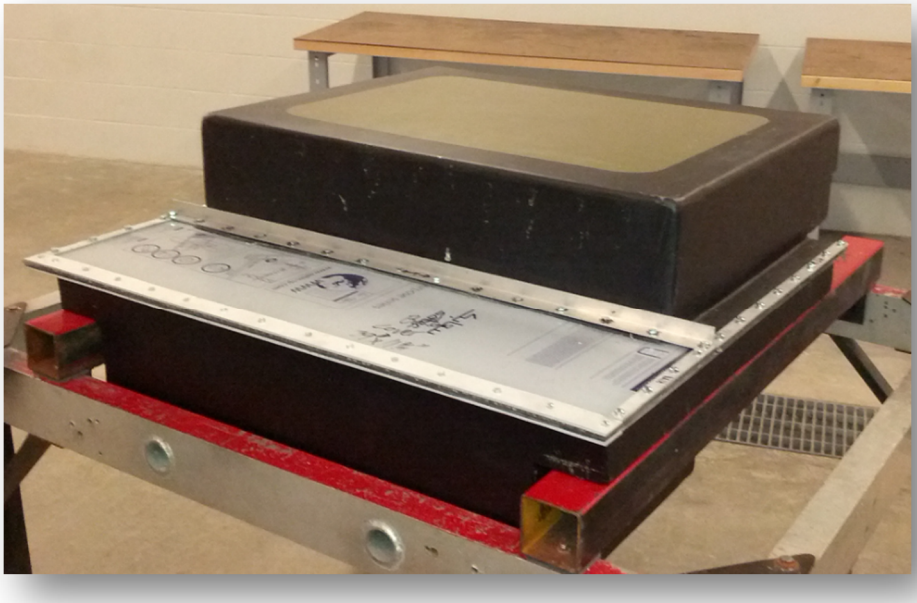


Figure 94 - High voltage battery pack carbon fiber enclosure showing clear plexi-glass cover on the bottom pack from the rear (opaque protection film has not been removed)

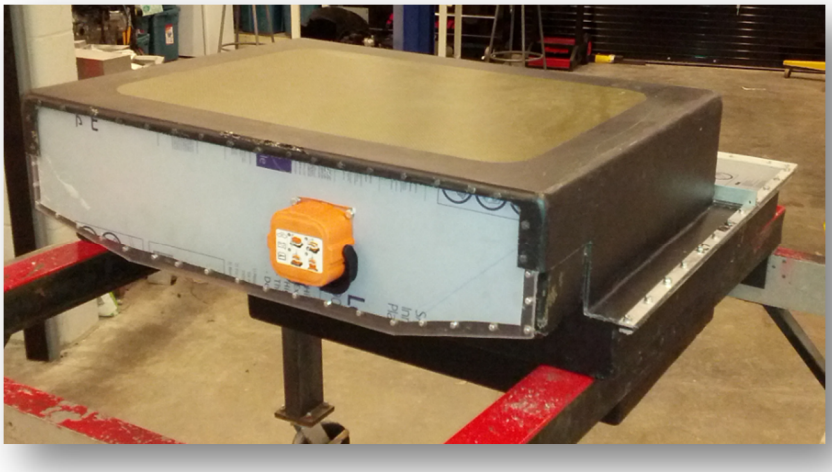


Figure 95 - High voltage battery pack carbon fiber enclosure showing clear plexi-glass cover on the top pack from the front (opaque protection film has not been removed)

The electronic components such as the BMS and MSD are placed in the front of the battery pack, in its own separate compartment from the battery modules as shown in Figure 96.

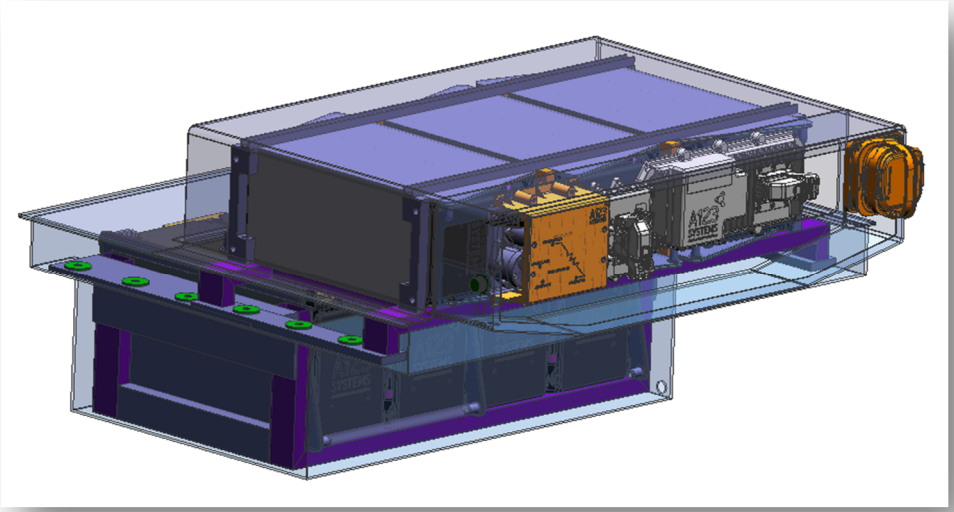


Figure 96 - High voltage battery pack CAD showing electronic components mounted in a separate compartment in the front of the pack

Pressure relief valves were installed at the bottom of the enclosure as a safety precaution in case of any pressure build up inside the enclosure from reactions in the battery modules. However, during Year 2 of the EcoCAR 2 competition, A123 requested that a hole be drilled at the bottom of the high voltage battery pack enclosure to act as a drain in case of a coolant leak in the battery cooling loop, hence the pressure relief valves became obsolete and were removed. A drain hole at the bottom of the enclosure was drilled and a shield was installed on it to prevent water from going into the battery pack from the outside, as shown in Figure 97.



Figure 97 - Bottom of high voltage battery pack enclosure showing shield covering a drain hole in case of a coolant leak inside the battery pack

9.2 Front Powertrain Component Mounting

A challenging aspect to converting a conventional vehicle to a Series Hybrid architecture is the packaging of a high amount of components that are required, particularly for an all-wheel-drive architecture with separate motors powering the front and rear axles. This creates challenges in packaging of the powertrain components in the relatively small engine bay of the Malibu, shown in Figure 98.

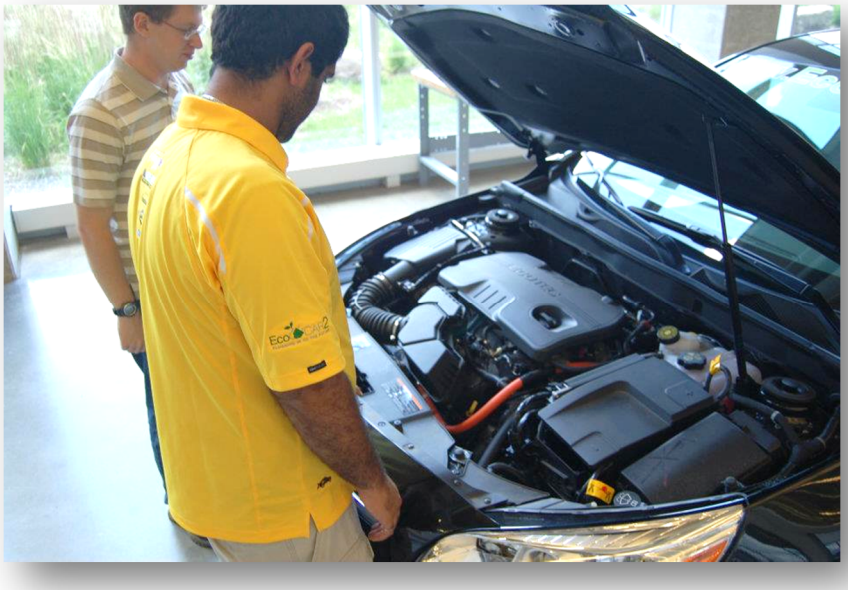


Figure 98 - Engine bay of stock 2013 Chevrolet Malibu

It was decided in Year 2 that the powertrain components in the front engine bay, including the 2.4L engine, generator, front traction motor, fixed gear reduction gearbox, and belt-drive system, is to be hard mounted into one assembly, as shown in Figure 99. This combined assembly is then vibration mounted to the chassis of the vehicle, through reusing 3 of the original engine/transmission mounts, and one altered vibration mount in the front of the vehicle. The side mounts act as the load bearing mounts to hold the assembly up, while the front and rear mounts act as torque mounts to limit the rotation of the assembly during torque output or input from the traction motor, as shown in Figure 100.

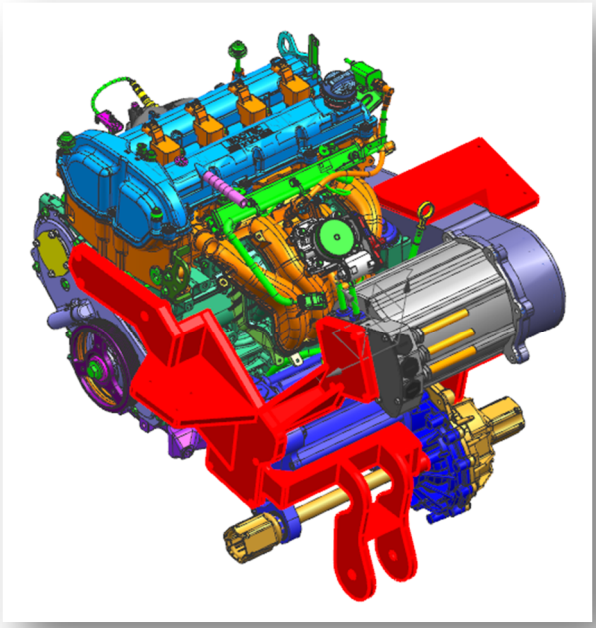


Figure 99 - Front powertrain assembly (mounting structure shown in red)

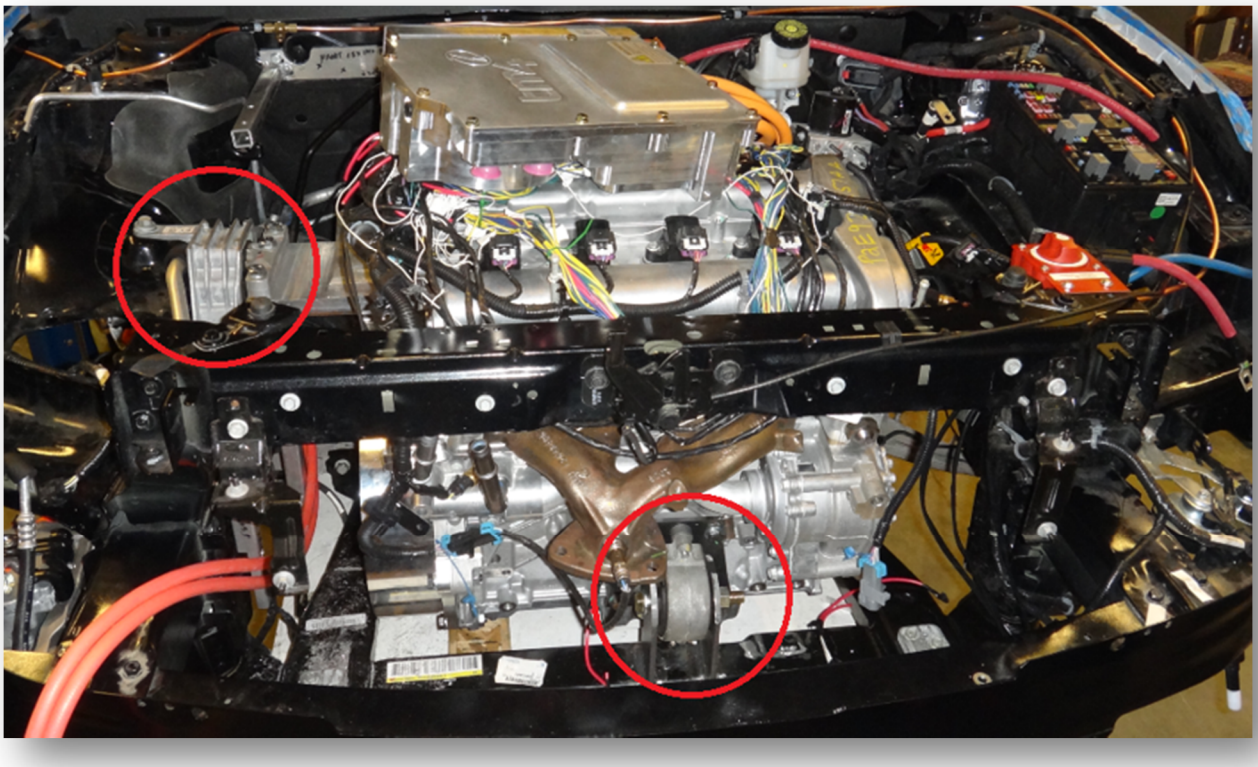


Figure 100 - Engine bay showing 2 of 4 isolation mounts on the front powertrain component

Although this is not an ideal design, it serves the basic requirement of packaging all the critical powertrain components into the vehicle while still providing some level of noise and vibration dampening.

It was later realized that the mass of the assembly held by the stock engine mounts had increased very significantly, and the neutral center and axes of rotation had shifted significantly while the torque output of the motor is significantly higher than that of the original stock engine. This caused the entire assembly to jerk violently and the mounts to bottom out during high torque scenarios such as tapping of the gas pedal at low speeds. This shook the entire vehicle and the effect not only reduced passenger comfort, but also introduced the risk of damaging powertrain components as contact was made while the assembly jerked.

This was discovered very late in the Year 3 competition year, and as such a last minute fix was applied. The engine mounts were removed from the vehicle and urethane casting compound was poured into the gaps and allowed to set. This created a solid mount of very high stiffness, varying from 80A shore to 85D shore between mounts, reducing the movements of the powertrain assembly during high torque scenarios, at the expense of increased vibrations. This was a trade-off that was deemed acceptable as it reduces the chance of component damage from contact and the jerking sensation of the vehicle when the massive assembly bottoms out the mounts. Figure 101 to Figure 105 show the modification of the stock engine mounts with urethane compound.

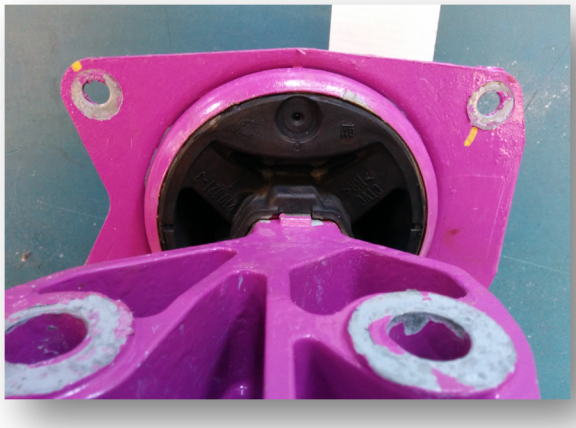


Figure 101 - Stock powertrain rubber isolation mount showing hollow sections



Figure 102 - Liquid urethane mixtures - once the two liquid mixes the urethane mixtures hardens within minutes



Figure 103 - Taping up the bottom of the isolation mounts so urethane mixtures do not drip through



Figure 104 - Pouring of urethane mixture into the hollow parts of the isolation mounts

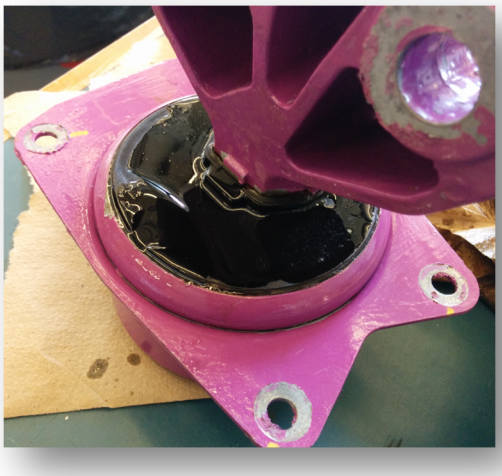


Figure 105 - Urethane mixture hardening, creating a much stiffer powertrain isolation mount for reduced movement

Suggestions for future work include better NVH analysis of the powertrain system, in order to avoid issues such as excessive movements of the powertrain assembly, bottoming out of mounts, component contact, and more.

Further, warping of the front aluminum engine mounting structure which were welded together was a significant issue during assembly as several mounting holes were up to centimeters off from the design

locations. This caused a lot of issues during assembly of the powertrain assembly, as well as some component damages. In the future when designing and fabricating aluminum mounts which must be welded, a welding jig should be used in order to increase the accuracy of the product using a technique similar to that employed for assembling and welding of the aluminum rear subframe. Figure 106 shows the aluminum engine mounting structure.



Figure 106 - Welded aluminum front powertrain mounting structure with relatively low geometric accuracy due to not using a welding jig to fix critical points

9.3 High Voltage Distribution/Fuse Box

The high voltage distribution/fuse box is required to branch off the main high voltage bus from the high voltage battery into the different high voltage components within the vehicle, as shown in Figure 107. This is required as the splicing and soldering that is typically seen on low voltage electrical systems cannot be done on the high voltage systems due to safety reasons. Further these distribution boxes act as fuse boxes as each branch contains an appropriately sized fuse based on the components that are powered off that branch.

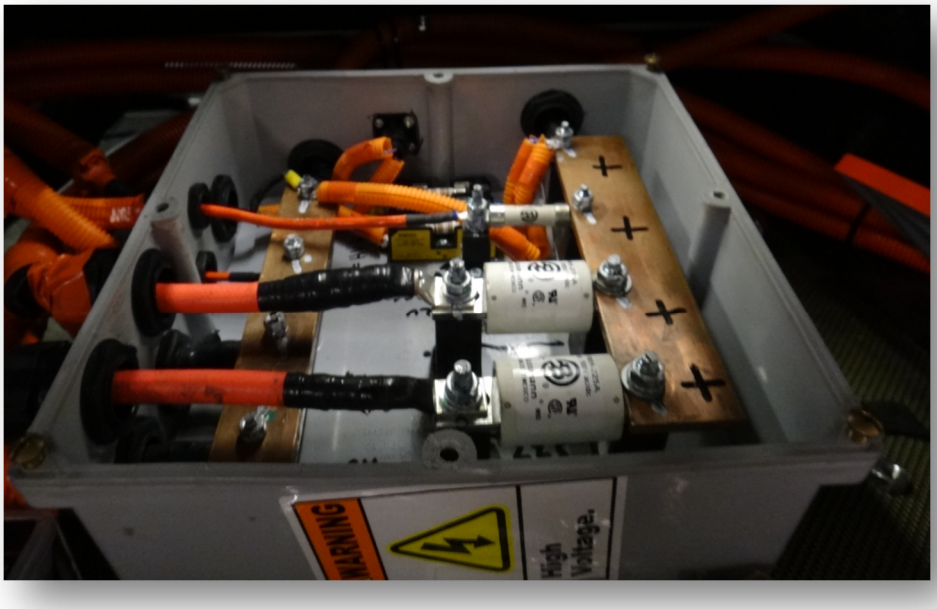


Figure 107 - Rear high voltage distribution/fuse box showing positive and negative copper bus bars, high voltage fuses, and various connections to individual high voltage components

There may be more than one distribution box in the vehicle. In the case of UWAFT's EcoCAR 2 vehicle, the high voltage bus coming from the high voltage battery first branches off in the rear high voltage distribution box with one branch supplying power to the front of the vehicle. That branch is then further distributed in the front high voltage distribution box, supplying branches to the high voltage components in the front of the vehicle. Refer to Appendix C – Electrical Schematics for the high voltage schematics of the vehicle.

When designing the distribution box, several key factors must be considered, including bus bar size, minimum air gap, finger-proof design, and enclosure material and environmental rating.

The bus bars used to distribute the high voltage bus into branches must be sized appropriately to prevent overheating and melting from high power passing through. Minimum bus bar size for the EcoCAR 2 competition are mandated as shown in Table 8.

Table 8 - High voltage bus bar minimum cross-sectional area as mandated by EcoCAR 2 rules [24]

Current Rating (A)	Cross Section (mm^2)
225	70.3
400	242.0
600	322.6
800	483.9

The only exception to using bus bars of the above specified cross-sectional area or greater is when the bus bars are purchased off-the-shelf and rated for the appropriate current level by the manufacturer.

Air gap between opposite polarity of any exposed live high voltage components, as well as between an exposed live high voltage component to any conductive material are mandated to prevent accidental contact, as shown in Table 9. In this context, "exposed" high voltage components are any components that may be live and are not completely protected, such as the bus bars inside a high voltage distribution box. This does not mean the components are exposed in the sense that a foreign object such as a finger can contact it, as in the case of the high voltage distribution box all exposed live components are sealed within the box.

Table 9 - Minimum spacing between exposed live high voltage components to opposite polarity and to any conductive material as mandated by EcoCAR 2 rules [24]

Potential, Volts RMS (peak)	Minimum Spacing (mm)		
	Between Any Two Uninsulated Live Parts of Opposite Polarity		Between Any Uninsulated Live Part and Any Conductive Material
	Through Air	Over Surface	Shortest Distance
0 to 50 (0 to 70.7)	1.6	1.6	1.6
>50 to 150 (70.7 to 212.1)	3.2	6.4	6.4
>150 to 300 (212.1 to 424.2)	6.4	9.5	12.7
>300 to 400	9.5	12.7	12.7

As per EcoCAR 2 rules to maintain a high level of safety in the vehicles designed, there may be no exposed high voltage within the vehicles allowing contact with foreign objects. Further, all high voltage connectors and enclosures must be protected and finger-proof, such that an insulated rod that is ¼ inch in diameter and 4 inches long must not be able to contact any live high voltage components. The high voltage systems must

be drop-proof such that they are protected from contact with any loose items that are dropped such as a wrench [24].

With the interior components designed, an enclosure size can be picked accordingly with special attention to air gap and clearances such that electrical lugs can be installed on standoffs, as shown in Figure 108.

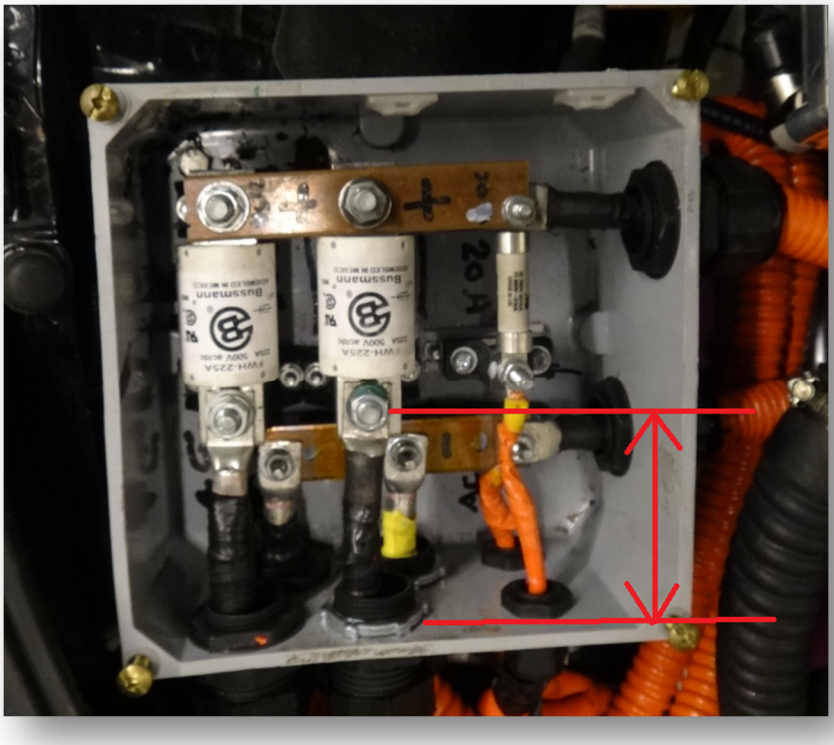


Figure 108 - Front high voltage distribution/fuse box showing minimum distance from standoff to enclosure wall to allow for installation of the lugs

The box must have appropriate environmental ratings, including temperature, waterproofing, chemical compatibility, etc. [24]. For this, an off-the-shelf fiberglass enclosure rated NEMA 4X was chosen with the dimensions needed for the interior components. Figure 109 shows the NEMA rated box and Figure 110 shows the box installed in the vehicle.



Figure 109 - NEMA 4X certified enclosure for high voltage distribution/fuse box with lid painted orange to indicate high voltage from McMaster-Carr

Link to above box: http://www.mcmaster.com/#74995k63/=vdf9sy



Figure 110 - Front engine bay of UWAFT EcoCAR 2 competition vehicle showing front high voltage distribution box installed (left side in orange)

9.4 High Voltage AC Compressor Mounting

As UWAFT's EcoCAR 2 vehicle is a Series architecture, the engine is not always on while the car is operating. For this reason, a typical AC compressor which is driven by the engine cannot be used to power the AC system. Instead, an electric AC compressor that runs off the high-voltage bus is used. This component was taken from the Chevrolet Volt which also requires an electric AC compressor as the Volt's engine is not always on either.

As per the EcoCAR 2 rules, all high voltage components and routing must be within the frame rails of the vehicle. However, due to the packaging challenges of the additional components of a Series Hybrid architecture, there was no space within the frame rails in the engine bay for the AC compressor. Permission was granted by the EcoCAR organizers for placing the AC compressor outside the frame rails just behind the front right fog light, after a proposal was submitted by UWAFT with the design and analysis of a steel bracket shielding the high voltage AC compressor from light to moderate impact. High impact would have set off the inertial switch in the vehicle, cutting off the high voltage battery from the high voltage bus and effectively shutting down all high voltage components, including the AC compressor.

The space behind the fog light was very tight, and as such CAD positioning of the AC compressor's orientation, as well as CAD design of the AC compressor mounts proved to be a very valuable resource. The AC compressor was mounted successfully along with the steel bracket shield inside the front right fender with millimeters of clearance at several locations as shown in Figure 111 and Figure 112, which would have been significantly harder to do without the use of CAD.



Figure 111 - Mounting of high voltage AC compressor

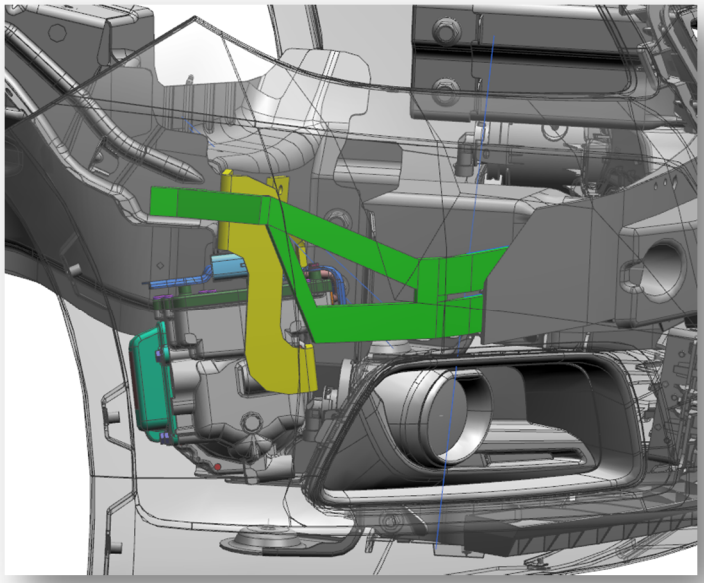


Figure 112 - Design of AC compressor mounting in CAD, showing very tight tolerance due to lack of space

9.5 Powertrain Component Cooling Loops

One of the often overlooked aspects of a hybrid vehicle conversion is the cooling of powertrain components. The task of cooling seems misleadingly simple, however this can have a huge effect on the vehicle's performance when major components such as the motors and batteries start overheating. UWAFT's EcoCAR 2 vehicle had a very poorly designed cooling loop in Year 2 of the competition, which resulted a disabled vehicle from traction motors overheating, causing a disqualification in the autocross event. The overheating issues were caused by a very long and high loss cooling path with lots of elevation changes and loops, causing the system to be extremely difficult to bleed even with a professional coolant suction pump. Air bubbles that were trapped in the low spots of the loop eventually made it to the pump after some time, causing the pump to no long be capable of pumping fluid. In situations like these, the pumps will often overheat from pumping dry and cause irreversible damage to the impellers. Luckily the pump used in the UWAFT vehicle had been able to withstand this particular incident, otherwise without the pump the vehicle would have been inoperable for the remainder of the competition.

Basic thermal calculations should be performed on the design of the cooling loop in order to size the pumps and radiators properly. Computational fluid dynamics (CFD) may also be used as an advanced simulation of the cooling loop designs. These methods can be found in most thermodynamics engineering textbooks, and will not be covered in this thesis.

Careful efforts were taken to redesign the cooling loops used in the UWAFT vehicle during Year 3 of the competition. The cooling system consisted of four separate loops:

1. Rear traction motor and inverter
2. Front generator, traction motor, and 2 inverters
3. Internal combustion engine
4. High voltage battery

The rear traction motor loop had its radiator located in the right rear wheel well behind the wheel. The front motor loop was split into two loops, one for the traction motor and inverter, and the other for the generator and inverter. Each of these had a separate radiator in the front radiator stack behind the grill. The engine loop also had its own radiator in the front radiator stack. The high voltage battery cooling loop was dropped as it was deemed unnecessary. The air conditioning system had its own separate loop which is not listed here. Refer to Appendix D – Cooling Loops for cooling loop schematics.

As with all simulations, they must be tested in a real world scenario to validate simulation results. As such these cooling loops were tested with the components running in real world conditions in order to validate that they were capable of keeping the powertrain components within allowable operating temperatures.

9.6 Electrical Routing

Modern vehicles have increasingly complicated electrical systems, which requires a network of electrical routing to enable communications between electrical systems. EVs and HEVs consist of additional low voltage electrical routing as well as introduces high voltage electrical routing for the electrical powertrain. With the introduction of high voltage electrical routing within the vehicle, special care must be taken into account in order to maintain safety both during the everyday operation of the vehicle as well as during a catastrophic collision of the vehicle.

9.6.1 Low Voltage Routing

During the process of electrifying or hybridizing a vehicle, additional Electronic Control Units (ECU) must be added for the control of the added components. For example, the Battery Control Module (BCM) controls the high voltage battery, the motor controllers controls the motor and generators, and a supervisory controller controls the interaction of all the vehicle subsystems of the overall vehicle. These added components almost certainly have to interact with the existing vehicle's computers, sensors, and actuators. The added components can do so through being hardwired to the existing components or the information can be relayed through the supervisory controller.

Common best practices for electrical routing should be used, such as wire gauges, wiring insulation type, conduit protection, fusing, twisting of Controller Area Network (CAN) wires to reduce noise, etc. Furthermore, in any prototyping environment, special care must be taken in the quality of manual labor work such as crimping, stripping, soldering, etc. It is from the author's experience that careless labor will almost certainly result in days or weeks of diagnostic work when connections start failing after several months either permanently or intermittently, especially when built in a student environment.

Proper schematics should always be designed prior to the implementation of the wiring, as this allows much easier diagnostic and planning, as well as more efficient use of material through proper wire lengths.

Lastly, it is to the author's experience that wiring and routing is often done free-hand on the vehicle even after proper schematics have been created. Although this will save hours or even days of design work initially, it will almost certainly result in lost days whenever major components are taken in and out of the vehicle. For example, during EcoCAR 2 the UWAFT team has removed the front subframe along with all the powertrain components in the engine bay several times. Each time this is done, all wiring to the front powertrain components had to be disconnected, and reconnected when the front components are reinstalled. However, as there was no design into where the wiring is routed, it often takes about 1-2 days to properly reconnect all the wiring harnesses as well as properly route the wires taking into account of moving parts and clearance issues. Occasionally the lack of a designed placement of the wire routing also resulted in wires not being properly secured during reinstallation and being damaged by moving parts. It is strongly advised to design all electrical routing in CAD prior to implementation in order to save time during assembly and lower the risk of damages to the wiring.

9.6.2 High Voltage Routing

All best practices with low voltage wiring applies to high voltage wiring as well, with certain exceptions such as not soldering high voltage cables together due to safety. Proper schematics should also be created prior to implementation of the high voltage routing.

Special attention must be paid to high voltage routing, as the increased electrical potential is a safety risk. Note that unlike the low voltage circuits which shares a common ground through the chassis of the vehicle, the high voltage circuits have a separate negative bus which is not shared with the low voltage circuit or the chassis. This acts as an additional safety precaution as it would require cutting through both the positive and negative polarity high voltage cables in order to create a short circuit or arc, as the high electrical potential is between the positive and negative polarity high voltage cables only and not with the chassis. Since both polarity cables are protected separately by each individual cable's shielding and insulation, as

well as a protective conduit around each cable, the chances of splicing into all the protection of both cables and then shorting them together is highly minimized. Further in UWAFT's vehicle, ground fault protection is used in which the chassis of the vehicle is always monitored and if a leakage from either the positive high voltage or negative high voltage to chassis ground is detected, measured in electrical resistance, the Battery Management System (BMS) will notify the supervisor controller, which in turn indicates a ground fault warning so the driver can safely pull over and exit the vehicle.

All high voltage routing must be outside of the passenger compartment, although there are some located in the trunk of the UWAFT vehicle as the battery is located in the trunk, and further they must be located within the structural frame rails for safety against a collision. The high voltage cables should be routed as far away from low voltage wiring where possible, and if they must cross path, do so at a perpendicular angle such that electromagnetic interference (EMI) is minimized. This is especially important for CAN communication wires which are widely used in modern vehicles, and as such CAN wires should be routed as far away from high voltage cables as possible. Further, orange conduit which are flame proof and crush proof should be used around each individual high voltage cable for added safety and to prevent splicing through the insulation, while the orange color immediately lets emergency response teams know that the cable is high voltage in the case of an accident.

The high voltage system uses a High Voltage Interlock (HVIL) system for added safety, in that a low voltage circuit going through various predetermined devices powers the relay in the high voltage contactors located at the high voltage battery. Current in this low voltage HVIL controlling circuit must be present in order for the high voltage contactors to be closed, supplying high voltage from the battery to the rest of the vehicle. If any one component in the low voltage HVIL controlling circuit opens, such as when the inertial sensor senses a high-G collision and opens the HVIL circuit, the high voltage contactors would open and hence disconnecting the high voltage battery from the rest of the vehicle. Components on the HVIL circuit varies, but typically includes the inertial sensor, gas pump, engine, mechanical E-stop push buttons, etc.

There are certain locations where the high voltage bus will have to branch out to several paths serving different high voltage components, and these are done in the high voltage distribution boxes. In these weather sealed and protected boxes, exposed high voltage components exist such as exposed lug nuts, copper bus bars, standoffs, and high voltage fuses. Precautions regarding the designing of these components such as spacing are outlined in Section 9.3.

Lastly, designing the high voltage electrical routing prior to implementation just as in the case of the low voltage wiring is highly recommended to ease assembly and maintenance.

9.7 Exhaust

As the UWAFT vehicle is a Series Hybrid, a small engine is located in the engine bay in order to drive an electrical generator during charge sustaining mode. In this operating mode, the battery's state of charge (SOC) is maintained at a relatively constant level by matching the electricity generated by the generator with the electrical load of the vehicle. Due to relocation of the engine, specifically the 180 degrees rotation of the engine such that the exhaust headers are facing the front of the vehicle, custom exhaust routing had to be designed and fabricated to route exhaust gas from the headers to the back of the vehicle. Due to time constraints and a lack of experience in exhaust fabrication, the vehicle was taken to an exhaust shop and the fabrication work was outsourced, taking into account EcoCAR 2 regulations on exhaust outlet location, diameter, ground clearance, clearance from gas tank and high voltage components, etc. A design in CAD was lacking in the case of UWAFT's EcoCAR 2 vehicle, and the technician simply routed the exhaust around new powertrain components and structure which were mostly in the vehicle already. However, the more care should be put into the exhaust routing in terms of designing in CAD before implementation to avoid guess work.

It was also an EcoCAR 2 requirement for the exhaust system to be completely leak free at up to 3 psig pressure. Note that even stock exhaust systems installed in the factory or by professionals most likely will have small leaks, and they often occur at the flanges or welds. One way to test for leaks is to pressurize the exhaust system using a plug with a regulated air hose inlet as shown in Figure 113, and spraying soap water onto the exhaust system. Small bubbles indicate leaks.

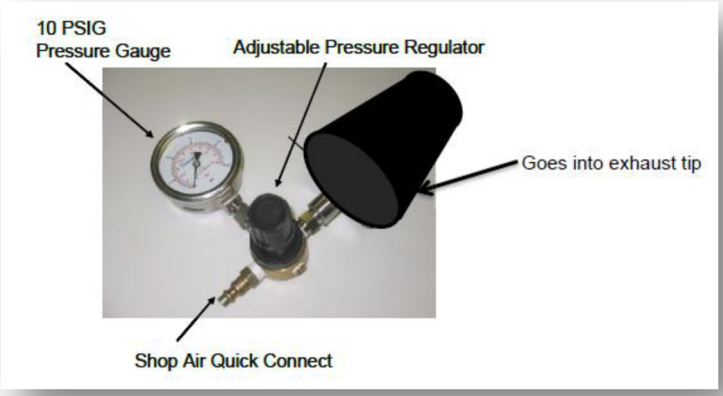


Figure 113 - Exhaust leak check fixture [24]

Although exhaust leaks are a well-known fact for EcoCAR competitors and organizers, the amount of work that goes into repairing leaks during EcoCAR competitions are often grossly underestimated, wasting 1-2

days out of the short competition week on just leak repairs alone. It is highly recommended for the exhaust system to be thoroughly tested and all gaskets replaced every time they are taken apart in order to reduce time spent at EcoCAR competitions repairing leaks! There are various exhaust sealants that can be purchased over-the-counter which will seal exhaust systems, while some work better than others. The author recommends the exhaust sealant by Walker which was used with good results during the EcoCAR 2 Year 2 final competition.

9.8 Heated Catalytic Converter

The catalytic converter in the exhaust system of an automobile powered by an internal combustion engine serves to reduce emissions. It does so in two stages: reduction stage, and oxidation stage. During the reduction stage, platinum and rhodium are used to reduce NOx emissions by separating the oxygen and nitrogen. In the oxidation stage, platinum and palladium catalyst reduce unburned hydrocarbon and carbon monoxide by combining carbon monoxide with oxygen, producing carbon dioxide [25].

Catalytic converters have a high operating temperature typically around 300 degrees Celsius, and does little to reduce harmful emissions before reaching its operating temperature [26]. For this reason, manufacturers often design the catalytic converter to be positioned close to the engine in order to heat up faster.

In order to further reduce harmful emissions, preheating of the catalytic converter was considered for UWAFT's EcoCAR 2 vehicle. By preheating the catalytic converter, it reaches operating temperature much more quickly and starts reducing emissions much earlier when the engine first turns on. Further, as UWAFT's vehicle is a Series architecture which operates in charge sustaining mode, additional benefits of preheating can be obtained for the intermittent start/stop operation of the engine.

In a Series Hybrid architecture, the engine does not always run. The engine in the UWAFT vehicle was designed to only operate when the battery SOC reaches a threshold near the 20% range, when the vehicle enters charge sustaining mode within UWAFT's control strategy. In this operation mode, the engine starts up to charge the high voltage bus, and shuts down when reaching the upper threshold of approximately 25% SOC. The battery SOC continues to fluctuate between the upper and lower threshold with the engine turning on and off intermittently until the vehicle is plugged back into the wall. This implies that the estimated times when the engine will start up can be calculated based on battery SOC and instantaneous energy use, and the catalytic converter can be preheated ahead of time based on these estimates.

Heated catalytic converters can be purchased from suppliers which take in different voltages. It would be ideal to power the converter off the high voltage bus as it saves the conversion losses when the high voltage

is converted to 12V through the DC-DC converter. However in UWAFT's case, the catalytic converter was powered off 120VAC through a 12VDC to 120VAC converter. This setup is non-ideal as there is a conversion loss from high voltage to 12VDC, then from 12VDC to 120VAC, but this decision was limited by the time constraints and the supplier's capabilities working with that timeframe.

The catalytic converter was fabricated with flanges on the ends so that it mates to the exhaust pipe like another section. The AC lines came out of the catalytic converter and was routed into the trunk where the 12VDC – 120VAC converter and the catalytic converter control box was installed. The system was never fully tested in vehicle due to time constraints, and because the engine torque coupling systems encountered issues during the competition which ended its operation.

In the future, much more thorough analysis and testing of the baseline vehicle, hybridized vehicle, as well as the preheating of the catalytic converter in terms of emissions and energy use should be completed in order to determine whether the addition does in fact decrease emissions. Further, the decrease in emissions should offset the additional energy use and reduced electric range of the vehicle such that it is favorable score-wise for the competition. The same care for the leakage of the exhaust system as outlined in Chapter 9.7 should be exercised as any disassembly and modification to the exhaust system will almost definitely result in new leaks. Figure 114 and Figure 115 shows the heated catalytic converter.



Figure 114 - Heated catalytic converter

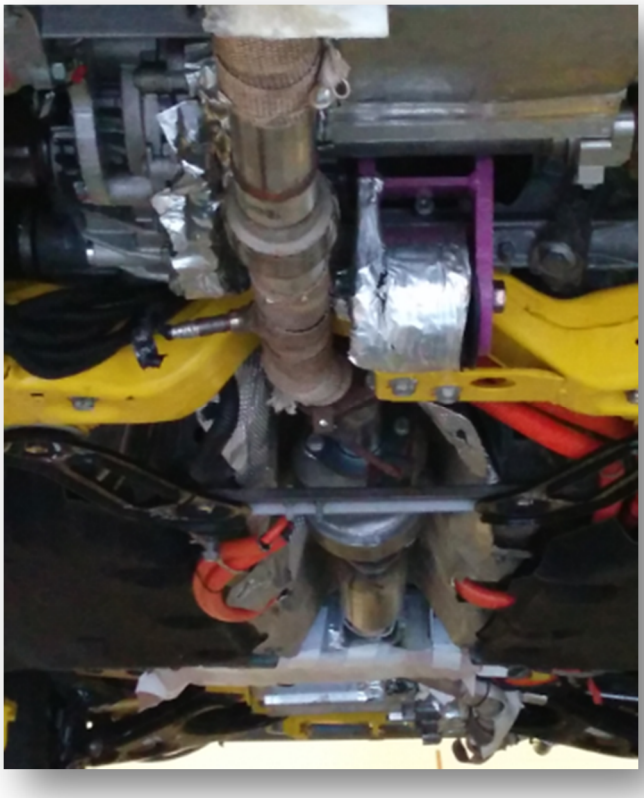


Figure 115 - Heated catalytic converter installed in vehicle

Chapter 10
Conclusion

This thesis describes the mechanical branch of a Hybrid Electric Vehicle (HEV) conversion, including the design, optimization, analysis, fabrication, and integration of the mechanical components of such conversion. It specifically outlines the mechanical designs, improvements, and lessons learned from the conversion of a 2013 Chevrolet Malibu to an All-Wheel-Drive Series Plug-in Hybrid Electric Vehicle by the University of Waterloo Alternative Fuels Team (UWAFT). The vehicle uses two separate 105 kW TM4 AC induction motors for the front and rear axles providing traction, powered by a 19.8 kWh A123 energy storage system. The high voltage battery can be charged through either a level 1 or level 2 charger, or using the hybrid system on-board which consists of a 2.4L GM LE9 Flex-Fuel engine capable of running on E10 to E85 gasoline/ethanol mixture, powering a third 105kW TM4 motor acting as a generator.

The thesis also describes a design process in which the team has developed over the course of many vehicle design competitions. The process expands on the engineering design process learned in the classroom as well as builds on the years of experience and learned lessons from countless component failures, which is a very unique experience that team members participating on engineering student teams obtain first hand.

Following the presentation of the mechanical design process, design projects specific to the UWAFT EcoCAR 2 vehicle which are relevant to most other hybrid conversions are presented and discussed. Mistakes made from early design iterations and lessons learned are discussed to help readers avoid falling into the same pitfalls.

The custom half shaft designs in UWAFT's EcoCAR 2 vehicle followed the previously used design process of simply measuring the approximate required length and turning down the shaft profile on a lathe from round stock. Splines were rolled onto the ends which mated to the constant velocity (CV) joints that matches the vehicle's hub and gearbox differential output, however they were not perfect as they were not designed to the original spline specifications. They also had a much different spline run-off, which allowed the half shaft CV joint tripods to slide past the splined area into the middle of the shaft occasionally. Several quick temporary fixes were attempted, including cutting a snap ring slot into the splines to stop the tripod which ultimately caused failure in the shaft, as it introduced a high stress concentration. In the end, a proper design and fabrication procedure as suggested by major driveline supplier GKN was employed for the final set of half shafts on the vehicle, using proper spline specifications, fabrication tolerances, and induction hardening process.

The rear subframe was optimized using Altair's Hyperworks in conjunction with Optistruct. With much experimentation and guidance from the very helpful staff at Altair, UWAFT was able to design a much optimized geometry, reducing the subframe mass by approximately 60% from the initial design to approximately 39 lbs. A proper jig was also designed to facilitate welding of the subframe components, to ensure much more accurate geometric tolerances as part of the lessons learned from the initial design built and used in Year 2 of the EcoCAR 2 competition.

The suspension system had been designed in Year 3 as part of the optimization phase, which focused mainly on tuning the spring stiffness and damper coefficients to achieve a target ride frequency as well as ride height. As the competition scoring allocation favored vehicle performance more than ride and comfort, ride frequencies and damping ratios were tuned for performance on the UWAFT vehicle. The springs were custom made by RMW Industries who also helped with spring calculations to get the vehicle to the target ride height. Dampers were taken from a Buick LaCrosse which had semi-active control capability.

The generator torque coupling in UWAFT's vehicle was a major component of the vehicle, which was not allocated adequate time and attention for design and fabrication. This ultimately resulted in a failure of this critical system during the final competition, rendering the vehicle an Electric Vehicle (EV) instead of a Series Hybrid, as the torque coupling system is a critical path from the internal combustion engine to the rest of the system. Multiple designs which were not up to the full power and speed requirements of the engine/generator combination resulted in several iterations of redesign as well as catastrophic failures of the torque coupling system. The final system was designed beyond the power and speed requirements, however it is suspected that the sealant used to seal the generator bearing housing was unable to take the heat and ended up melting off and getting on the bearings of the tensioner pulley. This resulted in the bearings and the tensioner seizing, and finally the shearing of the belt which was sliding on the seized tensioner. A redesigned tensioner as well as other sealant were chosen to seal the system, however this was not worked on by the author and hence out of the scope of this thesis.

Lastly, other mechanical projects were discussed such as the high voltage battery pack, front powertrain component mounting, high voltage distribution/fuse box, high voltage air conditioner (AC) compressor mounting, powertrain component cooling loops, electrical routing, exhaust, and heated catalytic converter. The design of these mechanical projects were relatively smaller compared to the previously discussed topics or was not the focus of the author's work, and hence were only discussed in brief with a limited scope.

Student teams provide an invaluable experience which compliments the engineering concepts learned in class. Many employers give students with extra-circular experience priority when considering new hires.

The experience from going through the entire design process as used in the automotive industry, as well as the lessons learned from failures first hand provide students with a unique jump start to working in the industry. In addition to the technical skills that students can learn from team participation, there are vast amounts of soft skills learned from these experiences as well. The success of such student team projects are dependent on the teamwork and cooperation of a number of students. These students also need to be able to take the initiative to learn various technical skills required for the project, which are often not taught in the classroom. Students have a chance to practice their communication and presentation skills through interacting with suppliers and presenting to judges and sponsors. The success of the project is dependent on the students' abilities to plan and lead. Such examples are only a glimpse of the soft skills that are learned through participation on student project teams, and reveal why students that choose to invest their time into such teams are highly sought after by employers upon graduation.

The main objective of this thesis is to outline the design processes and lessons learned from the author's experience working on UWAFT, such that future students may use this as a starting point in their quest to completing their own mechanical design projects.

Chapter 11
Recommendations

1. **Allocate resources based on how critical the component is**

   The amount of resources allocated to different projects did not always align with the level of importance of those projects. A good example is the generator torque coupling design which was an afterthought following the design of the torque coupling enclosure. This resulted in increased complexity in the design due to the space constraints that were imposed by the enclosure, and ultimately the failure of the system during the final competition rendering the vehicle an EV instead of a Series Hybrid.

2. **Ensure adequate testing for critical components**

   The generator torque coupling system was not tested thoroughly and resulted in multiple failures throughout Year 3 of the EcoCAR 2 competition. Had the system been thoroughly tested earlier in the year, lots of money could have been saved from rushed custom order parts. Further the final failure during the final competition may have been fixed if it was in fact the sealant not being able to take the heat and causing the tensioner to seize. This could have been repaired within a week using spare belts and a different heat tolerant sealant.

3. **Maximize having the vehicle driving on the road**

   It is advised from experience to maximize the amount of time the car spends driving on the road. Even when there are not any specific test plans or specific components to test, having increased drive time allows for the weak components to break and issues to surface. This is ideal as a minor breakdown may only take days or even hours to fix on campus, but may cause a disqualification at the competition if they break during or just prior to a competition event. An example is the half shaft which sheared the night before the vehicle was to be shipped for an emissions event in Ohio. The half shaft had been on the car for about 6 months prior to the failure, but the vehicle was rarely driven and the issue did not surface until right before the event.

4. **Be realistic with design projects**

   A lot of resources, especially 4th year students working with the team through courses, were placed on projects that were far above and beyond the basic necessity of the vehicle. Such examples

included semi-active suspension, active headlights, and more. While these are great to have on the vehicle and may certainly improve the consumer acceptability greatly or may even have a great effect on scoring, these should be the last projects to be tackled. More resources should be allocated on critical parts that are essential to vehicle operation, such as basic spring and damper tuning, component mounts, torque coupling systems, etc.

5. **Put in extra effort in Year 1 (design year) and aim to design the vehicle to its final specification instead of just using place holders**

   A very significant amount of the time spent in Year 2 and Year 3 of the competition was on component redesigning, and a lot of times these were the first design iteration of the components on the vehicle. This resulted in very little to no test time on a lot of the designs, as well as increased costs due to rush orders and higher risk of component failures. This can be mitigated through an increased effort in earlier years to design vehicle components to their final specifications, instead of thinking that these components will "eventually come together" or that it will be an easy task later. Further, a lot of time could have been saved in the later years if more effort was spent to ensure all mechanical items going into the vehicle are designed and packaged in CAD. Items such as electrical routing, coolant routing, and coolant loops should be designed in the early years such that all routing have a specific place to go. In EcoCAR 2 during the final years, hours at a time were spent cleaning up the engine bay of electrical and coolant routing every time the front subframe and front powertrain components were disassembled from and reassembled to the vehicle. This is because wires did not have a specific designed position to be routed and hence they were manually done differently every time. This further caused wires and coolant hoses to be damaged occasionally when clean up was not done well following a subframe reassembly where items were touching moving parts. Lastly, wires and coolant hoses were mostly longer than they needed to be as routing changed every time, and none of the routing were optimized, increasing costs as well as vehicle mass.

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Appendix A – Design Methodology Instructional Materials

Suspension Design Worksheet

Y3 UWAFT Malibu				
	Front mass		Rear Mass	
	lbs	kg	lbs	kg
100% unsprung				
wheel & tire	46	20.87	46	20.87
Brake Disc	19	8.62	12	5.44
Brake caliper	15	6.80	11	4.99
knuckle	7	3.18	13	5.90
hub/bearing	11	4.99	11	4.99
C-shape knuckle link	N/A	N/A	3	1.36
50% unsprung				
strut	N/A	N/A	5	2.27
spring	N/A	N/A	6	2.72
strut & spring	19	8.62	N/A	N/A
Control Arm	8	3.63	18	8.16
Stabilizer link	1	0.45	1	0.45
Tie Rod	2.56	1.16	N/A	N/A
Toe Link	N/A	N/A	6	2.72
Camber link	N/A	N/A	7	3.18
half shaft & outer CV left	7.93	3.60	6.89	3.13
half shaft & outer CV right	7.74	3.51	8.98	4.07

Corner Weights	lbs	kg
Stock		
Total Mass	3393	1539.04
Y2 Comp		
Front Left	1033.97	469
Front Right	967.83	439
Rear Left	1197.11	543
Rear Right	1276.48	579
Total Mass	4475.39	2030.00
Y3 Fall UWAFT Malibu		
Front Left	1045	474.00
Front Right	998	452.68
Rear Left	1193	541.14
Rear Right	1249	566.54
Total Mass	4485	2034.36
Y3 OHIO UWAFT Malibu		
Front Left	1161.79	526.97905
Front Right	1018.49	461.97905
Rear Left	1156.33	524.5
Rear Right	1273.17	577.5
Total Mass	4609.78	2090.96

Y3 UWAFT Malibu			
		Front	Rear
Unsprung Mass (kg)	216.51	106.32	110.19
Total Mass (kg)	2034.36	926.69	1107.67
Spung Mass (kg)	1817.85	820.37	997.48
Unspr/Spr Ratio	0.12	0.13	0.11
	spring	damper	
installation ratio front	1	1	
installation ratio back	0.513	0.731	

Quarter Car Model			
	front	rear	
unsprung mass kg	53.15985	55.09669	
sprung mass kg	410.1844	498.7391	
freq Hz	1.57	1.72	
C critical kgHz	8092.61	10779.83	
damping ratio	0.65	0.65	
Cwheel Ns/m	5260.197	7006.887	
Cwheel Ns/mm	5.260197	7.006887	
RR	39915.19	58249.22	
Kwheel N/m	49867.55	82185.39	
K wheel N/mm	49.86755	82.18539	
Cdamper Ns/mm	5.260197	13.11265	
Kspring N/mm	49.86755	312.2913	

Y3 OHIO UWAFT Malibu			
		Front	Rear
Unsprung Mass (kg)	216.51	106.32	110.19
Total Mass (kg)	2090.96	988.96	1102.00
Spung Mass (kg)	1874.45	882.64	991.81
Unspr/Spr Ratio	0.12	0.12	0.11
Spring Angle @ 5 inches gnd clearance		1.098593115	1.4424731
damper angle @ 5 inches gnd clearance		1.098593115	1.36078086
	spring	damper	
installation ratio front	1	1	
installation ratio back	0.63	0.927	

Quarter Car Model			
	front	rear	rear
unsprung mass kg	53.15984842	55.09668626	55.0966863
sprung mass kg	441.3192016	495.9033137	495.903314
freq Hz	1.57	1.4	1.72
C critical kgHz	8706.875615	8724.386761	10718.5323
damping ratio	0.65	0.65	0.65
Cwheel Ns/m	5659.46915	5670.851395	6967.046
Cwheel Ns/mm	5.65946915	5.670851395	6.967046
RR	42944.92665	38371.8571	57918.0112
Kwheel N/m	54687.72926	47481.65314	81527.5909
K wheel N/mm	54.68772926	47.48165314	81.5275909
Cdamper Ns/mm	5.65946915	6.599162131	8.10754205
Kspring N/mm	54.68772926	119.6312752	205.410912

Design IQ Software – Belt Drive System Design

Figure 116 and Figure 117 shows the belt-drive system design in Gates Design IQ software.

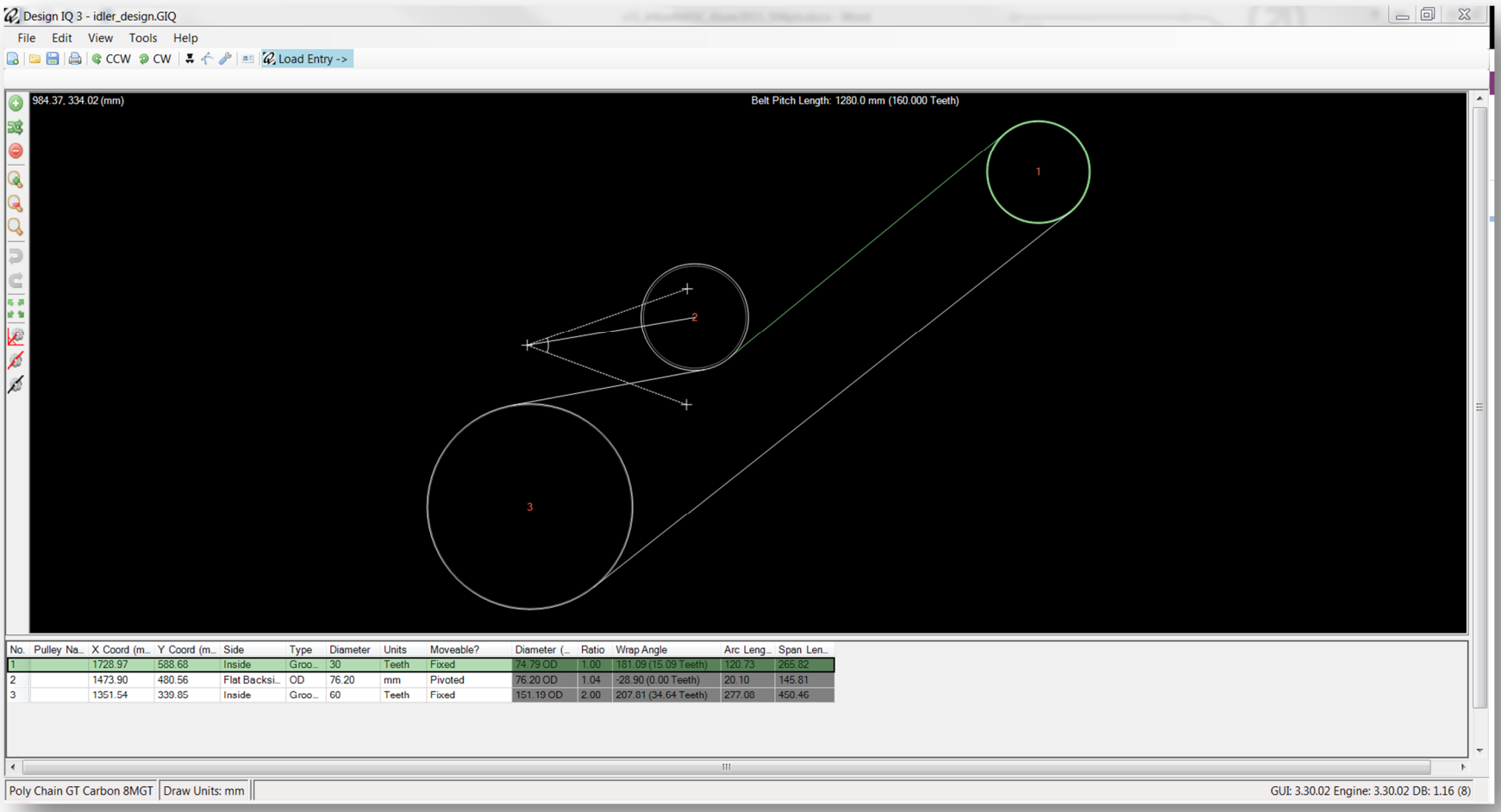


Figure 116 - Design IQ - Belt drive system sprocket and tensioner setup

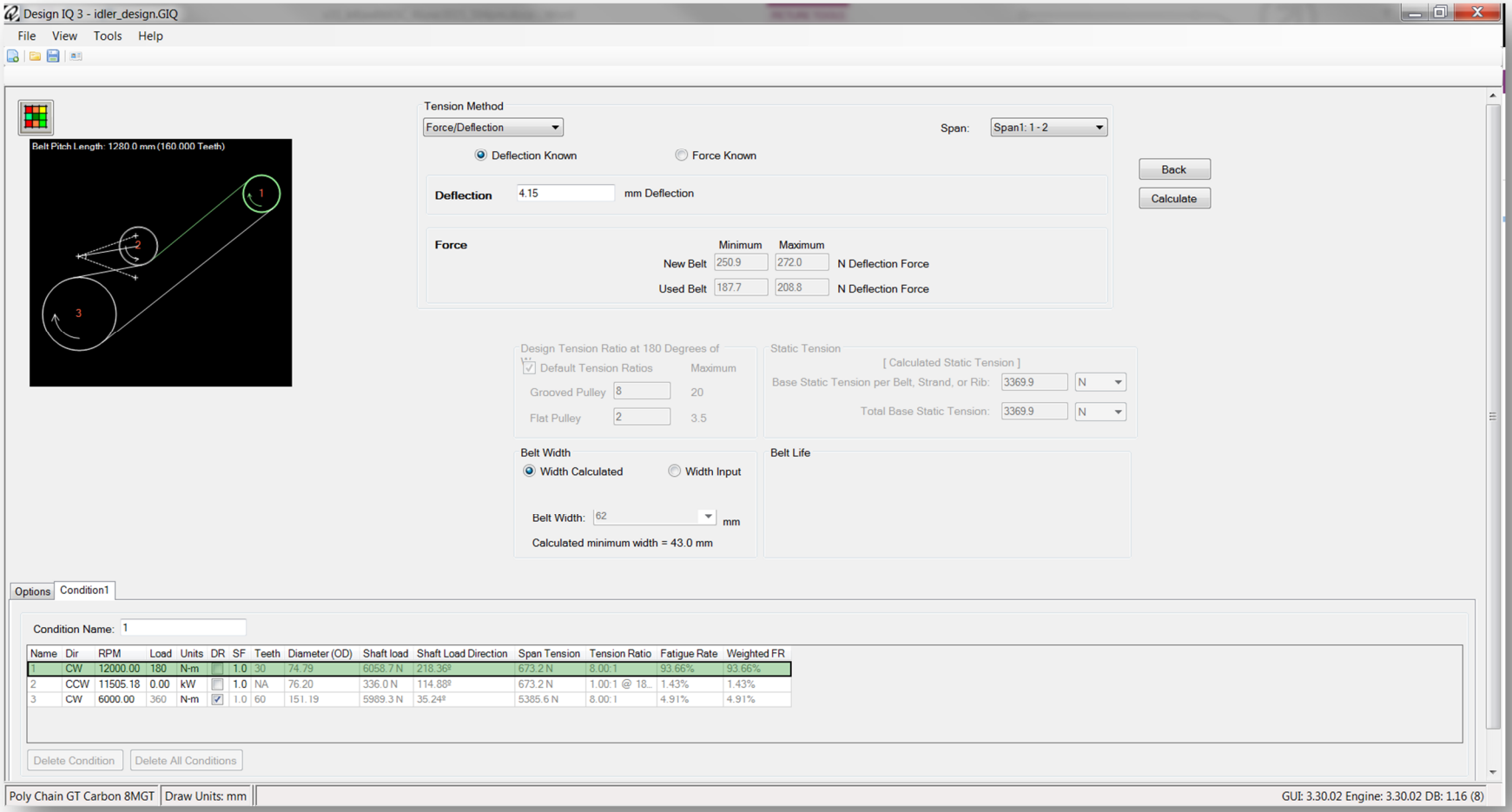


Figure 117 - Design IQ - Belt drive system load condition setup

Appendix B – Drawings

Half Shaft Drawing

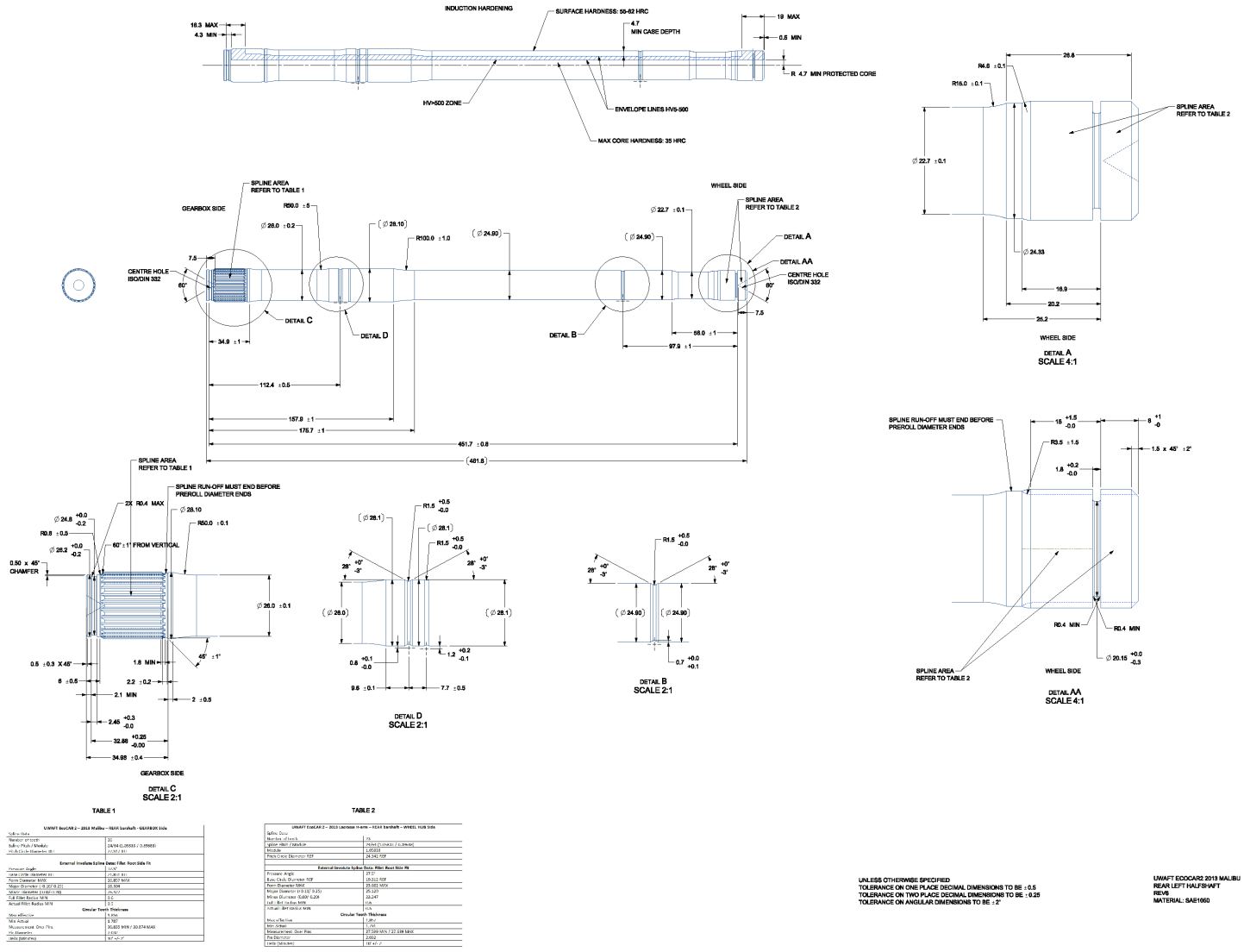


TABLE 1

UWAFT EcoCAR 2 – 2018 Malibu – REAR Sunshaft – GEARBOX Side	
Spline Data	
Number of teeth	20
Spline Pitch / Module	24/64 (1.0583) / 0.99031
Pitch Circle Diameter (D)	21.167 / 21
External Involute Spline Data: Fillet Root Side Fit	
Pressure Angle	30.00°
Base Circle Diameter (E)	17.4911 / 17.4911
Form Diameter MAX	20.857 MAX
Major Diameter (-0.257/-0.321)	20.906
Minor Diameter (+0.00/-0.08)	19.707
Full Fillet Radius MIN	0.6
Actual Fillet Radius MIN	0.7
Circular Tooth Thickness	
Max effective	1.646
Min Actual	1.787
Measurement Over Pins	20.823 MIN / 20.874 MAX
Pin Diameter	2.032
Teeth (Minutes)	90° 45' 0"

TABLE 2

UWAFT EcoCAR 2 – 2018 Malibu – REAR Sunshaft – WHEEL HUB Side	
Spline Data	
Number of teeth	25
Spline Pitch / Module	24/64 (1.0583) / 0.99031
Module	1.05333
Pitch Circle Diameter REF	24.342 REF
External Involute Spline Data: Fillet Root Side Fit	
Pressure Angle	27.5°
Base Circle Diameter REF	19.512 REF
Form Diameter MAX	25.583 MAX
Major Diameter 0.0 (-0.257/-0.321)	25.527
Minor Diameter (0.00/-0.206)	24.247
Full Fillet Radius MIN	0.6
Actual Fillet Radius MIN	0.6
Circular Tooth Thickness	
Max effective	1.454
Min Actual	1.595
Measurement Over Pins	27.599 MIN / 27.699 MAX
Pin Diameter	2.032
Teeth (Minutes)	90° 45' 0"

UNLESS OTHERWISE SPECIFIED
TOLERANCE ON ONE PLACE DECIMAL DIMENSIONS TO BE ± 0.5
TOLERANCE ON TWO PLACE DECIMAL DIMENSIONS TO BE ± 0.25
TOLERANCE ON ANGULAR DIMENSIONS TO BE ± 2°

UWAFT ECOCAR2 2018 MALIBU
REAR LEFT HALFSHAFT
REV6
MATERIAL: SAE1060

Generator Sprocket Drawing

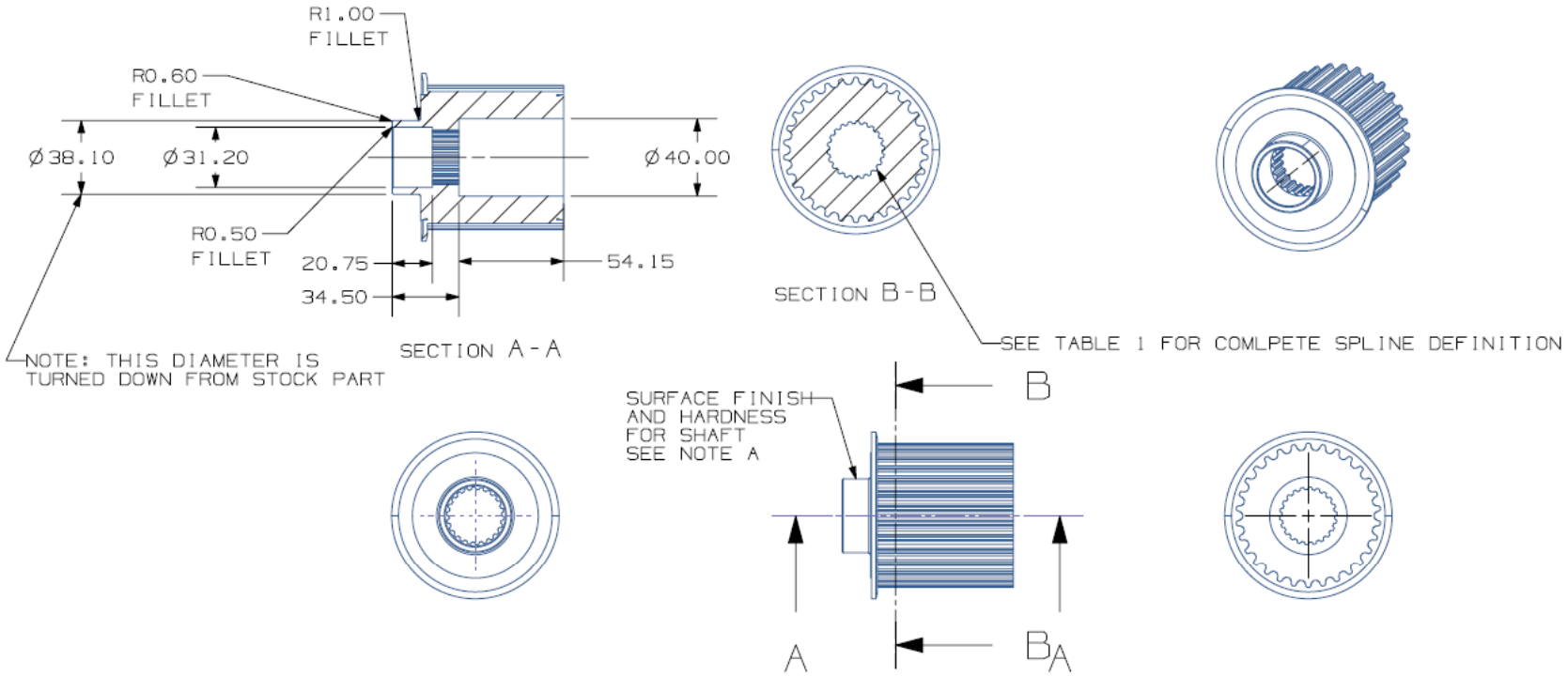


TABLE 1 (DIMENSIONS ARE IN mm)		
SHAFT DIN5480 - W30x1.25x22x8h		
NUMBER OF TEETH	z	22
MODULE	m	1.25
PRESSURE ANGLE	α	30°
TIP CIRCLE DIAMETER	d_{a1}	29.75
ROOT FORM CIRCLE DIAMETER	d_{Ff1}	27.44
ROOT CIRCLE DIAMETER	d_{f1}	27.25
MAX EFFECTIVE TOOTH THICKNESS	s_{vmax}	2.613
ACTUAL MAXIMUM REFERENCE TOOTH THICKNESS	s_{max}	2.596
ACTUAL MINIMUM TOOTH THICKNESS	s_{min}	2.568
INSPECTION		
MEASURING CIRCLE DIAMETER	D_M	2.75
MAX REF DIMENSION OVER MEASURING CIRCLES	M_{1max} Ref.	(33.079)
MIN DIMENSION OVER MEASURING CIRCLES	M_{1min}	33.04

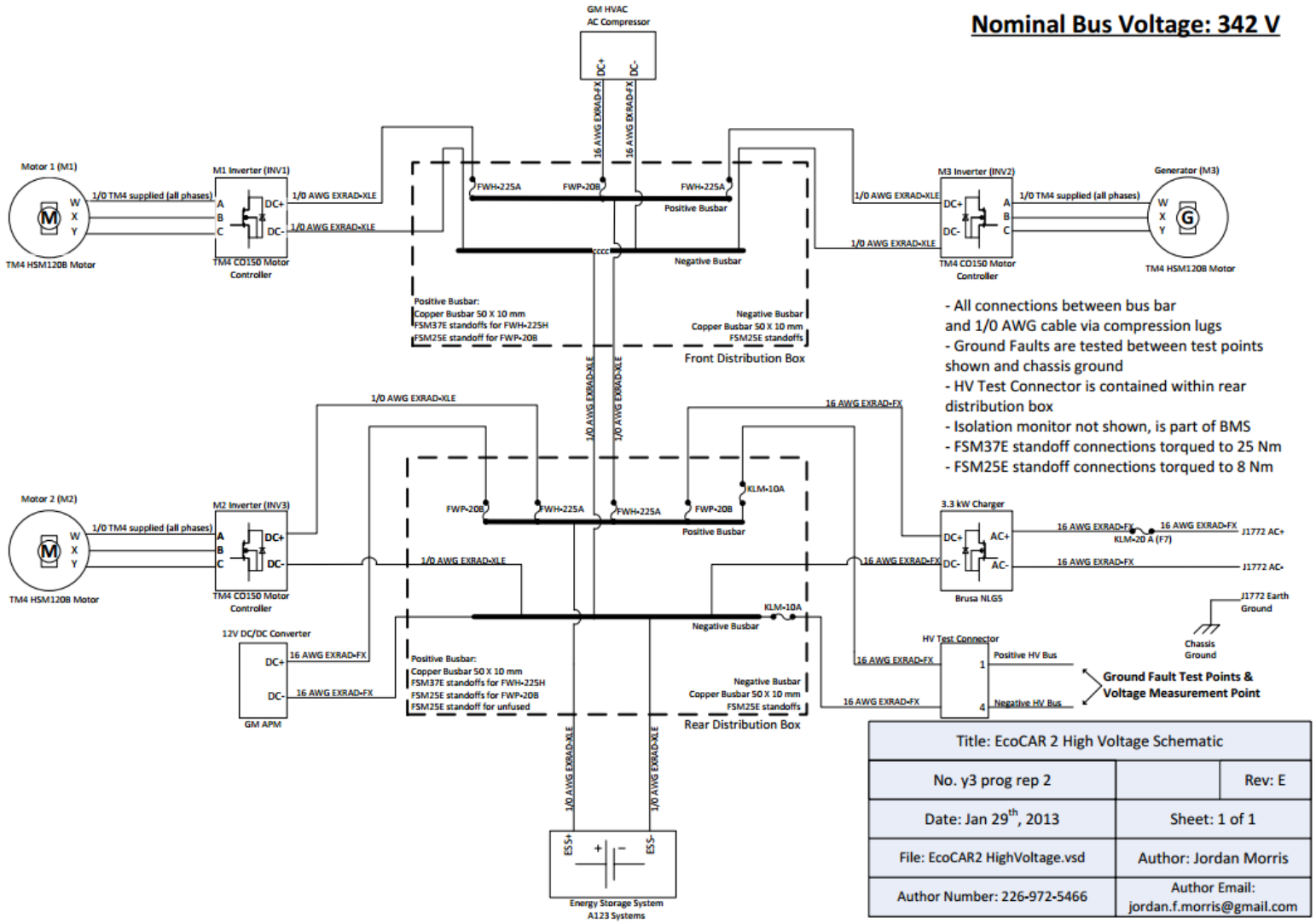
NOTE A (ONLY APPLIES TO SHAFT)

SURFACE FINISH:
ISO STD
Ra = 0.2-0.5 micrometers
Rz = 1.2-3 micrometers

HARDNESS:
58 HRC

PB8MX_30S_62
REV4

Appendix C – Electrical Schematics



Appendix D – Cooling Loops

Figure 118 illustrates the front motors cooling loop for the UWAFT EcoCAR 2 vehicle.

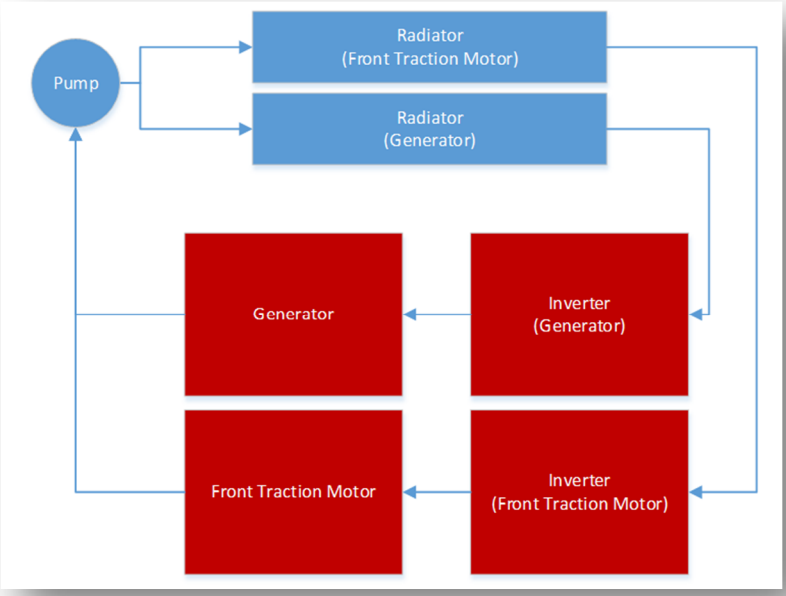


Figure 118 - Front motors cooling loop

Note that there was no reservoir used for the front motors cooling loop. Instead a "T-junction" was put into the highest point of the coolant loop which was capped normally with a plug. The plugged was removed and served as a filling point during coolant top up. Hence the entire loop was always filled with coolant and the loop itself served as a "reservoir".

Figure 119 shows the rear motor cooling loop for the UWAFT EcoCAR 2 vehicle.

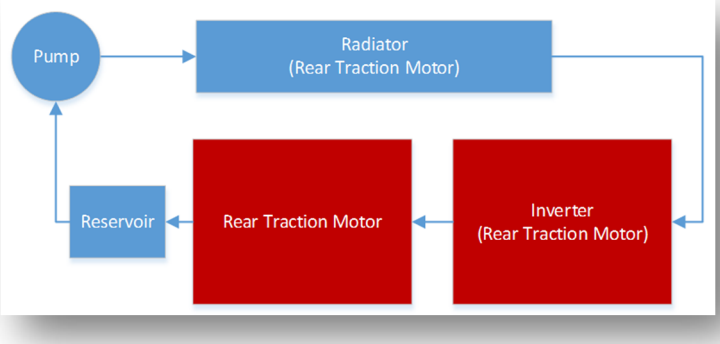


Figure 119 - Rear motor cooling loop