2018 Formula SAE Race Car Electrical System

A Major Qualifying Project
Submitted to the Faculty of
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Abstract

This report presents the research, design, and construction of all electrical systems necessary to develop a fully-functional Formula-style race car to compete in the Formula Society of Automotive Engineers (FSAE) 2018 competition held in Michigan. The project was performed in cooperation with the FSAE Mechanical Engineering Major Qualifying Project (MQP). Three main electrical categories were required, namely critical vehicle systems, e.g. engine control unit integration with engine sensors and a motor-controlled shifting system, the FSAE-required safety systems, e.g. an electronic throttle body safety device, circuit protections, and emergency cutoff systems, and the additional designs that added value to the vehicle, e.g. an electronic driver interface, digitally controlled shifting, and a custom gear indicator sensor. One of the primary objectives of this project was to design a wiring harness easily applicable to future WPI FSAE vehicles. For this reason, each electrical system was built to be modular for ease of replacement or replication. Schematics and detailed documentation were designed in order to help convey the information to people of other disciplines. Additionally, two wiring harnesses were built: a test-stand wiring harness and a custom, one-off in-vehicle wiring harness. The test-stand wiring harness will be used by future teams to use for initial critical system testing and act as a guide for final vehicle wiring, with minimal modifications anticipated.

Executive Summary

Electronics have been increasingly integrated into the automotive industry since the invention of electronic fuel injection (EFI). EFI kick started electrical development in vehicles as automotive engineers now had a highly tunable platform to achieve an increase in power and fuel economy. As sensor technology improved, so did engine reliability. Recently, sensors have been extensively placed throughout an automobile platform for convenience and safety purposes such as blind spot detection and backup cameras.

While automobiles have seen a significant leap in technology, vehicles in the power sports industry have been much slower to adapt. EFI has been around for quite some time, but its installation in sport vehicles has been common for only about ten years. As these vehicles are outfitted with new technology, engineers or technicians must adapt. In 2016 and 2018, the WPI FSAE competition vehicles both featured EFI and other sensing capabilities that a purely mechanical team did not possess sufficient expertise to design and implement. Thus, the 2018 FSAE competition vehicle was built by two teams: A Mechanical Engineering team and an Electrical & Computer Engineering team; this report documents the work of the latter.

The primary responsibility of the ECE team was to ensure the engine operated properly with all internal and external sensor inputs as well as actuator outputs. In order to complete this task, a Haltech engine control unit (ECU) was used. The ECU is an embedded device that electronically controls all internal combustion events and is the centerpiece of the EFI system. The ECU is connected to the engine with a wiring harness. The wiring harness ties the engine sensor outputs to the ECU for signal processing and sends corresponding outputs to the engine actuators to facilitate engine operation. Two wiring harnesses were built - one for use by future teams on the engine test stand, and one custom-built harness for use in the 2018 competition vehicle itself.

The main goal of the ECE team was to construct a robust, reliable, and replicable vehicle electrical system. Previous years' designs have lacked reliability and proper documentation for replicability, limiting the capability of the WPI FSAE team in competitions given that the design had to be built from scratch with no previous electrical guidelines every year. Critical to the design aspect of the wiring of the car was to make a design that was reusable, and furthermore to create a design that was modular. These two design aspects meant that the wiring designed for this year's vehicle could be removed or replicated for future vehicles. Additionally, future electrical and computer engineering MQPs could implement additional designs for the secondary and tertiary harness and replace the existing designs in order to add functionality to the car without changing the basic and critical functions of the vehicle when related to engine function and safety. Therefore, this project serves as a platform for other teams to design on. Everything is laid out for future teams to succeed in creating a basic electrical system so that more focus can go into cutting-edge sensing and data logging technology.

Initial research into automotive electrical systems required the creation of a block diagram in order to assess the system requirements that would have to be met in order create a functional vehicle. Figure 1 illustrates the initial intention of the project and what the resulting systems were based on.

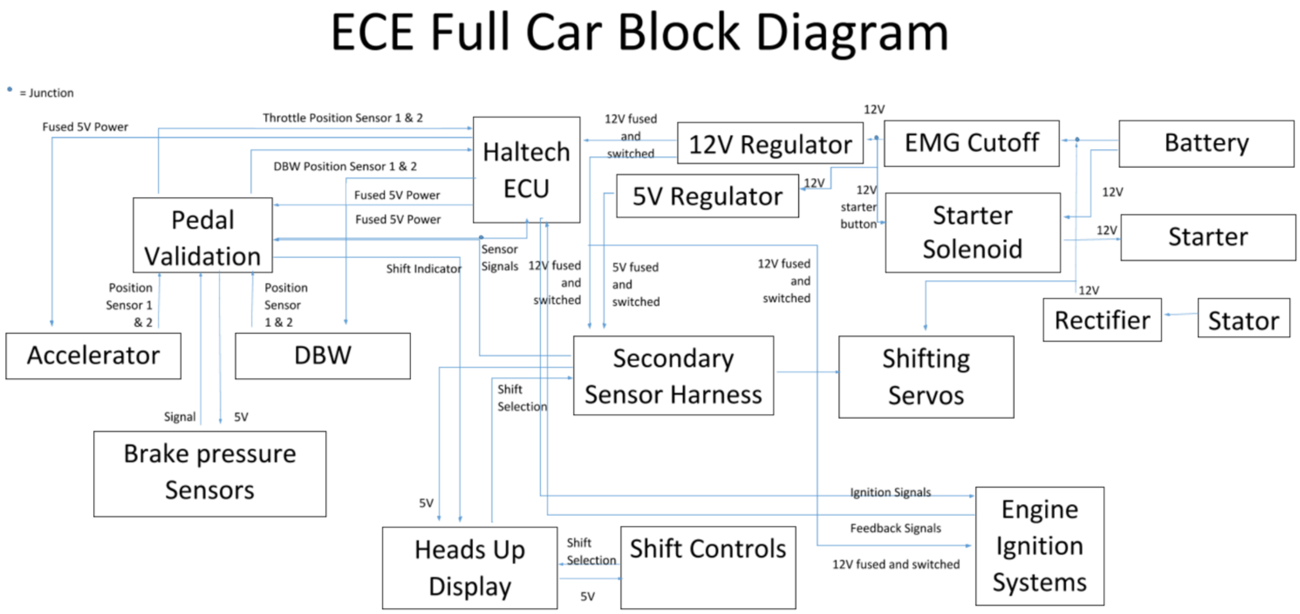

Figure 1: FSAE vehicle electrical system block diagram

From this diagram, a number of systems were implemented and integrated in order to work with each other including, drive-by-wire (DBW), power, shifting, and driver interface. Some of these were in the primary harness while the others were located in in the secondary and tertiary harnesses, which can all be isolated from one another in order to test circuitry and troubleshoot electrical issues quickly. The DBW system was especially critical and required a variety of testing procedures in order to ensure proper function and actuation of the throttle body in relation to the throttle pedal. Consequently, parts were sourced that were OEM and created by reputable manufacturers in order to ensure accuracy in our DBW system. The entire system was wired using a specific implementation wiring procedure in order to ensure that it was done correctly and according to a custom wiring map that illustrates all of the wiring connections that had to be made. Using the industry standard schematic software Cadence Design Entry, this ECU wiring map is seen in Figure 2.

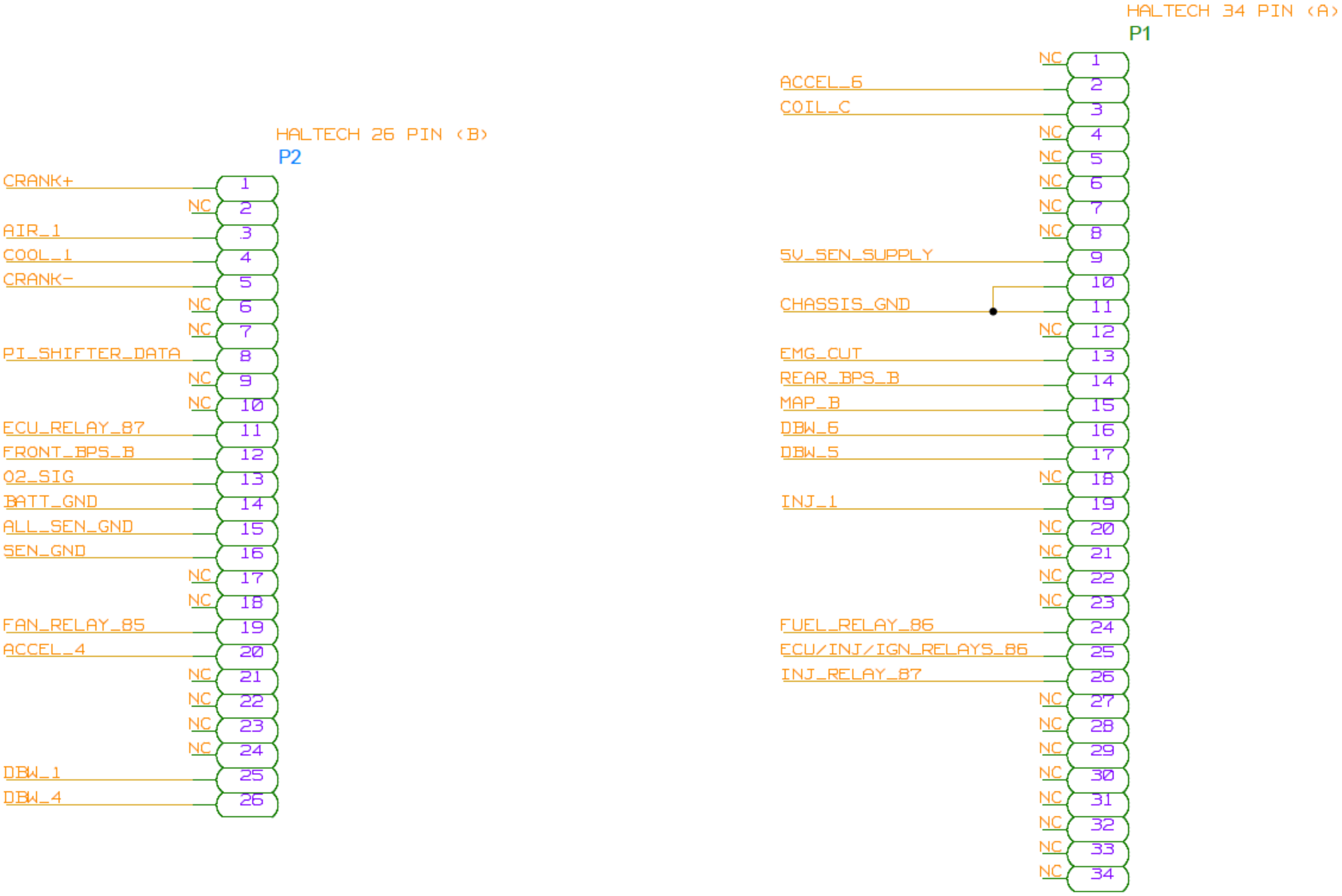

Figure 2: Haltech wiring map. Note the high number of NC's or "no connects" as the vehicle uses a single-cylinder engine and requires fewer electrical connections than vehicles with larger engines.

The system was calibrated by the Haltech Elite 1500 ECU in order to allow proper function of the actuators and sensors in the primary wiring harness system. The Haltech ECU is seen in Figure 3.

Figure 3: Haltech Elite 1500 ECU [1]

The ECU was properly calibrated with the data tables for each sensor in the wiring harness to allow for proper vehicle function. All of these functions were incorporated into the primary harness to allow for critical vehicle functions to operate without interfering with the telemetry or safety circuitry of the secondary and tertiary harnesses.

One shortcoming of the 2016 competition car was the shifting system. Our original design of the shifting system was intended to be faster, lighter, and simpler to implement than the pneumatic system used in the previous competition car. It was designed to use relays, activated by a 555-timer circuit to power a motor. The motor was connected to the gear selector of the sequential transmission attached to the engine. This design ran into a number of implementation problems, both electrically and mechanically. The transmission did not have enough back-drive torque to re-center the motor after shifting, and the 555-timer circuit did not operate reliably when connected to the rest of the system. Given the number of problems with the timer implementation, the team decided to redesign the shift system using information from testing.

The final design of the shift system needed to incorporate a number of additional features that otherwise would have been implemented elsewhere, such as the shifting indication system for the Haltech and a gear display interface for the driver. The team decided to base the new system on a Raspberry Pi instead of an Arduino, largely because it can be programmed in Python and has a greater potential for future upgrades. Testing the first version of the code revealed a number of problems, both in the control program and the wiring. After solving these problems, the prototype version of the PiShifter worked well and we started programming the second version. Version 2 of the code solved a number of remaining problems and changed sensor interfaces to improve failure handling.

All design work has been completed for an individual of another field of study to build a base electrical system on a future vehicle. This is not just limited to the wiring harness, but it also includes the required safety systems such as the Brake Plausibility Device.

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List of Acronyms

MQP -Major Qualifying Project
WPI - Worcester Polytechnic Institute
ECE - Electrical and Computer Engineering
SAE - Society of Automotive Engineers
FSAE - Formula Society of Automotive Engineers
EMS - Engine Management System
ADI - Analog Devices Inc.
TI - Texas Instruments
CCS - Code Composer Studio
TPS - Throttle position sensor
BPS - Brake pressure sensor
DTC - Diagnostic Trouble Code
APPS - Accelerator pedal position sensor
PCB - Printed circuit board
ECU - Engine control unit
ATV - All terrain vehicle
RPM - Revolutions per minute
OEM - Original equipment manufacturer
O2 - Oxygen
DC - Direct current
AC - Alternating current
ETC - Electronic throttle control (drive-by-wire)
IC - Integrated circuit
RAM - Random access memory
GPIO - General purpose input/output
RTOS - real-time operating system
ADC - Analog-to-digital converter
EMG cut - Emergency engine cut off
GPS - Global Positioning System

1. Introduction

1.1 Competition

The Society of Automotive Engineers (SAE) is an international professional organization dealing with all things automotive, including current innovations in both traditional internal combustion drivetrains, hybrid systems, and improvements of secondary electronic systems such as driver aids. The society manages a variety of standards related to automotive technology and are the regulating body in many cases. SAE runs multiple student design competitions yearly, including Baja SAE, SAE Supermileage, and Formula SAE (FSAE) [2]. A photograph of the participation in the FSAE competition is seen in Figure 4.

Figure 4: FSAE competition attendees [3]

These programs are all design challenges that strive to introduce students to the ideas behind automotive engineering design and therefore help facilitate the growth of automotive engineering as a field.

Formula SAE is a series of competitions that challenges teams to create a track car for competition. Along with this competition comes a series of rules and regulations put forth by SAE in order to ensure that all vehicles meet the standards of competition [4]. The competition is designed to deal with all aspects of the creation of a formula style race car. In addition to judging on engineering design, the competition also entails a number of other static events including tech inspection, design presentation, cost presentation, and business presentation that together requires the teams to not only be aware of the vehicle mechanically but additionally the practicality of the design and how the design of the vehicle is justified. Vehicles compete in a number of events that are designed to score the teams' vehicles on performance criteria in various scenarios. Throughout all of these dynamic and static competitions, points are awarded that will ultimately result in a ranking in comparison to the other teams competing. No dynamic events can be attended without passing technical inspection for the vehicle.

FSAE Michigan is the most popular single competition in the entire FSAE schedule throughout the year and is the event regularly attended by the WPI FSAE team. Most recently, WPI has been competing in Michigan on a two-year build cycle for each vehicle that is brought to competition. The WPI FSAE Team rebooted regular FSAE Michigan competition attendance in 2015, utilizing an older car to enter competition while creating the initial design and frame for a new platform of car for the 2016 competition year. Two MQPs worked on the 2016 car, one Mechanical Engineering and one Electrical & Computer Engineering. This gave our team the potential advantage of better electronic controls relative to most other teams, allowing for better tuning and driving capabilities.

1.2 High Level Motivation

At the beginning of the 2015-2016 academic year, a new vehicle platform underwent the first iteration of an electrical design. This design, through incredibly ambitious, left much to be desired in execution. The final design of the 2016 Formula car wiring consisted of multiple microcontrollers and a variety of one-off PCBs that rendered the design overcomplicated, poorly executed, and prone to failures as the team experienced within the first year of the car's creation. These designs were created hastily with improper waterproofing and resulted in many loose or damaged connections as seen in Figure 5.

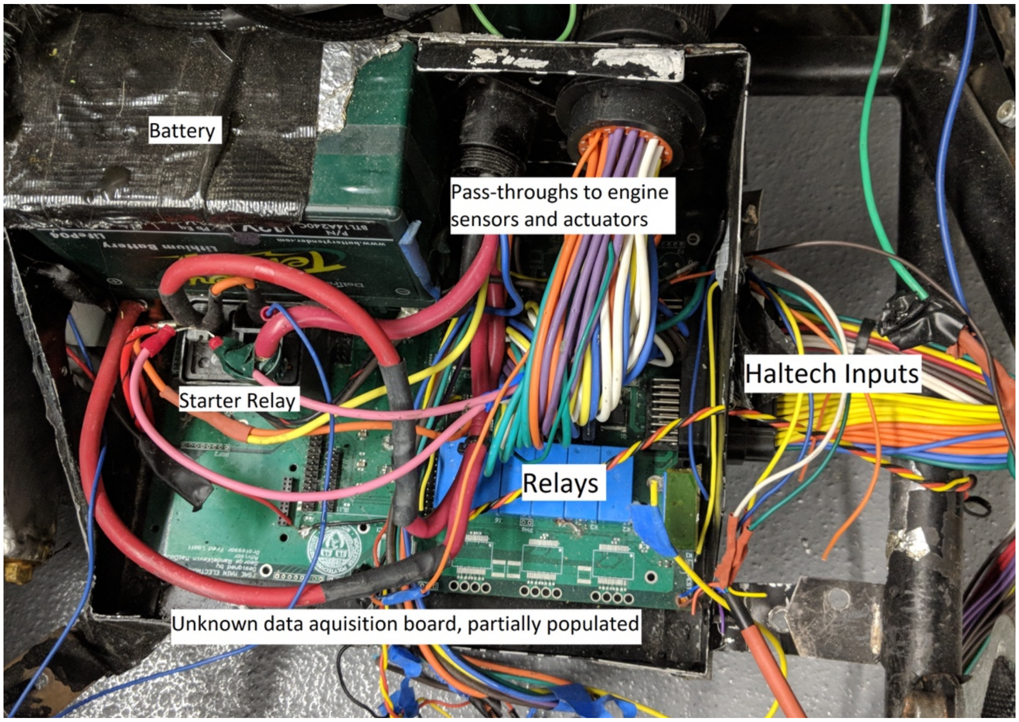


Figure 5: 2016 FSAE vehicle wiring

Connectors were not used in the harness and therefore any technical problems with the vehicle were difficult to troubleshoot. These oversights led this team to strive to create a more reliable and modular harness that could be adapted and used for years to come.

In order to be successful in competition, a solid electrical foundation needed to be designed for future years' projects to build upon rather than starting from scratch each time. Therefore, time was spent in order to design a system that prioritizes reliability above all.

1.3 Current State of the Art

Before this project began, the most recent FSAE vehicle was built in the 2015-2016 academic year when the team returned to regular competition attendance. This vehicle was used as a guide on what features to include or modify and what features to completely redesign. The 2015-2016 FSAE vehicle's electrical system was based around a Haltech Elite 1500 ECU, complete with a drive-by-wire system. It utilized all sensors and actuators for basic engine operation such as the crankshaft position sensor, fuel injector, and ignition coil. The engine used was from a Yamaha YFZ450R sport ATV, seen in Figure 6.

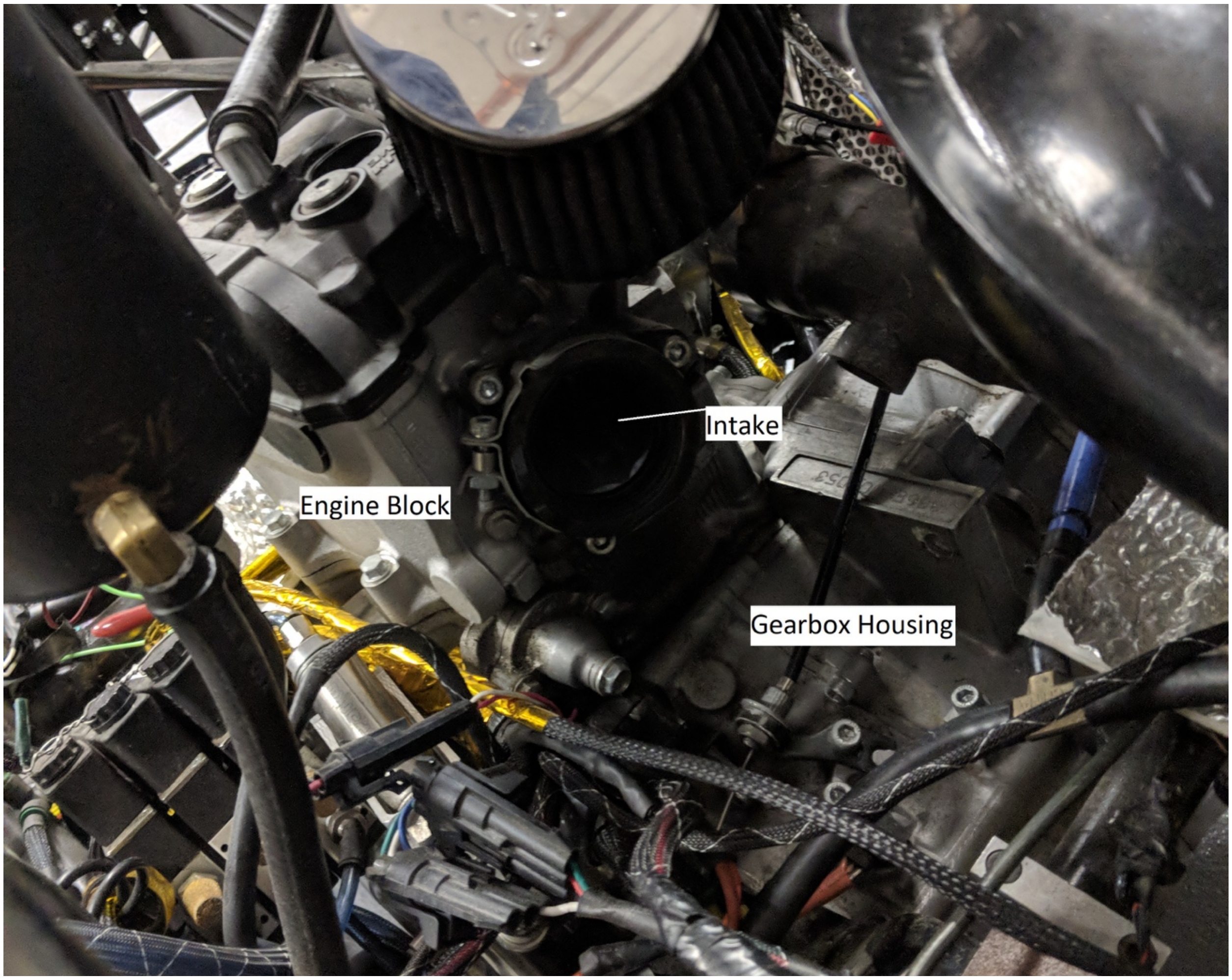


Figure 6: Yamaha YFZ450R sport ATV engine installed in the 2016 FSAE vehicle

It had an upgraded aftermarket stator kit for increased electrical output and utilized a lightweight lithium ion motorcycle battery to store this power.

Similar to a dirt bike engine, the YFZ450R ATV engine is built using sequential gearbox manual transmission with a foot shift lever [5]. The engine is mounted behind the driver, so the team developed a paddle shift system controlled by buttons on the steering wheel of the car, seen in Figure 7.

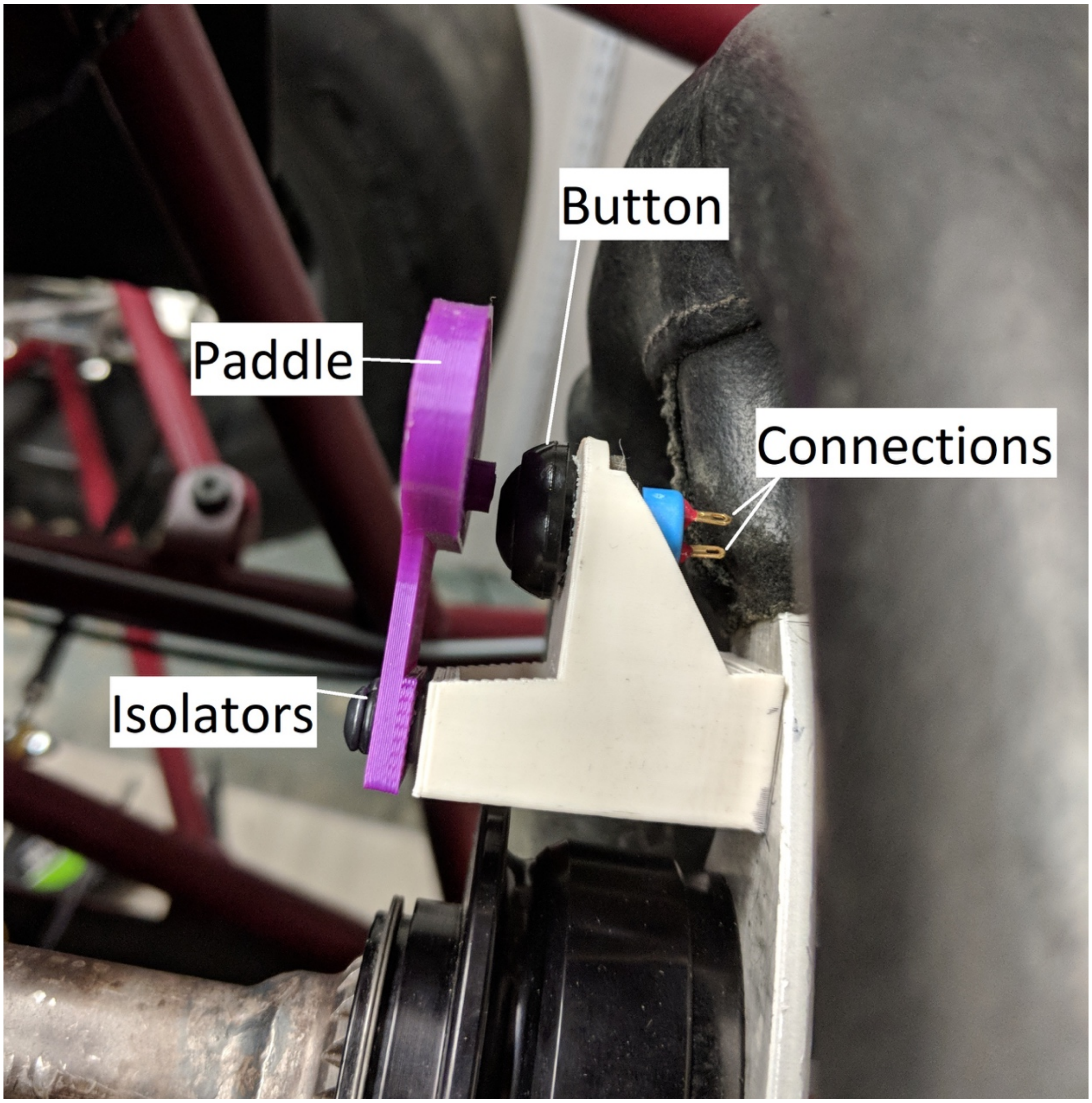


Figure 7: Paddle shift system on steering wheel

The shift lever was actuated by a pneumatic system which included an on-board air compressor and a pressurized air storage tank, seen in Figure 8.

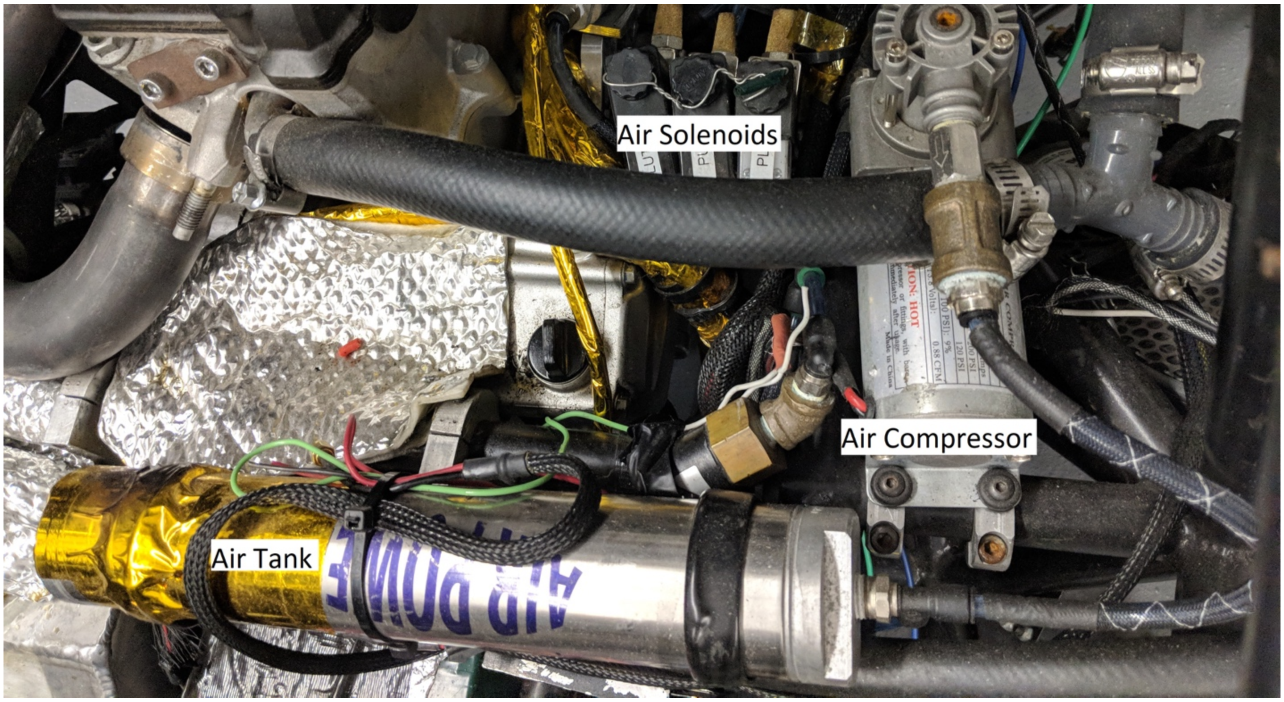


Figure 8: Pneumatic shift system

The 2015-2016 vehicle included substantial electrical sensing capabilities. The design included two microcontrollers, a TI MSP432 and a TI TM4C129. These microcontrollers processed information from multiple peripherals; a battery current sensor to track battery charging or discharging, multiple air pressure sensors to verify aerodynamic design, rotary position sensors for the suspension position and steering angle, fuel flow sensor for gas mileage information, inertial measurement unit for position and acceleration information, brake temperature sensor, and wheel speed sensor. Communication systems included a GPS receiver for position, lap time, and acceleration data, and an XTend 900MHz transceiver to relay vehicle information to a pit computer equipped with data logging software. The vehicle was equipped with a custom steering wheel with a driver interface displaying tachometer, gear, and speed information [6]. The custom steering wheel and internal PCB of the steering wheel can be seen in Figure 9 and Figure 10 respectively.

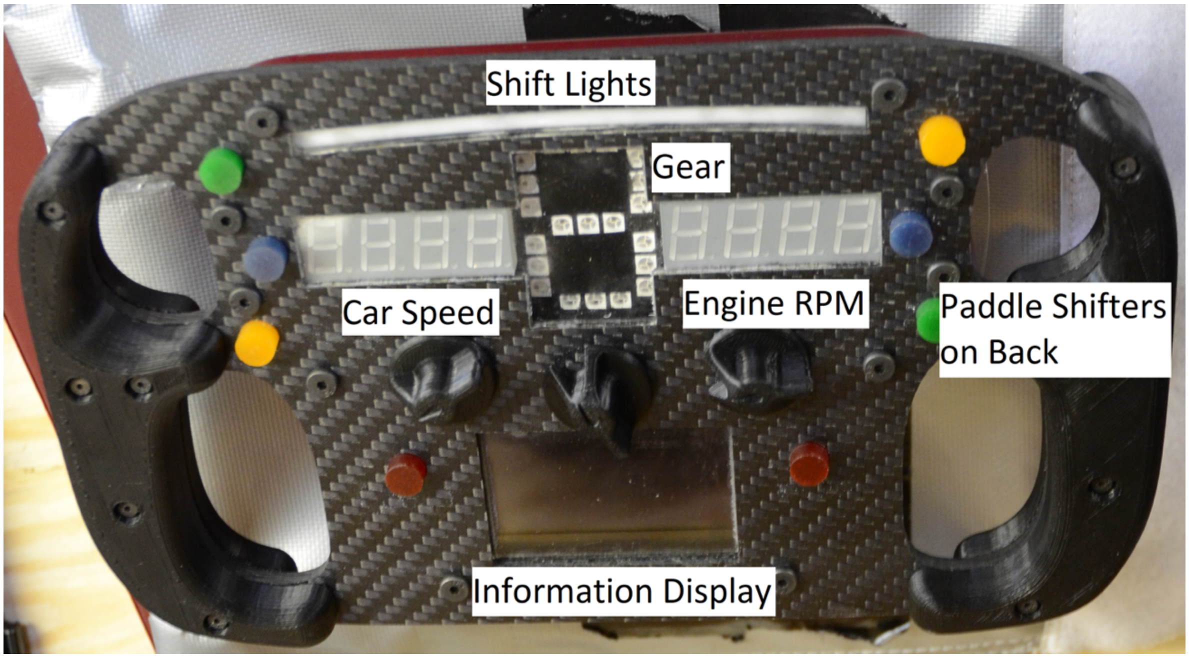


Figure 9: 2016 FSAE MQP steering wheel

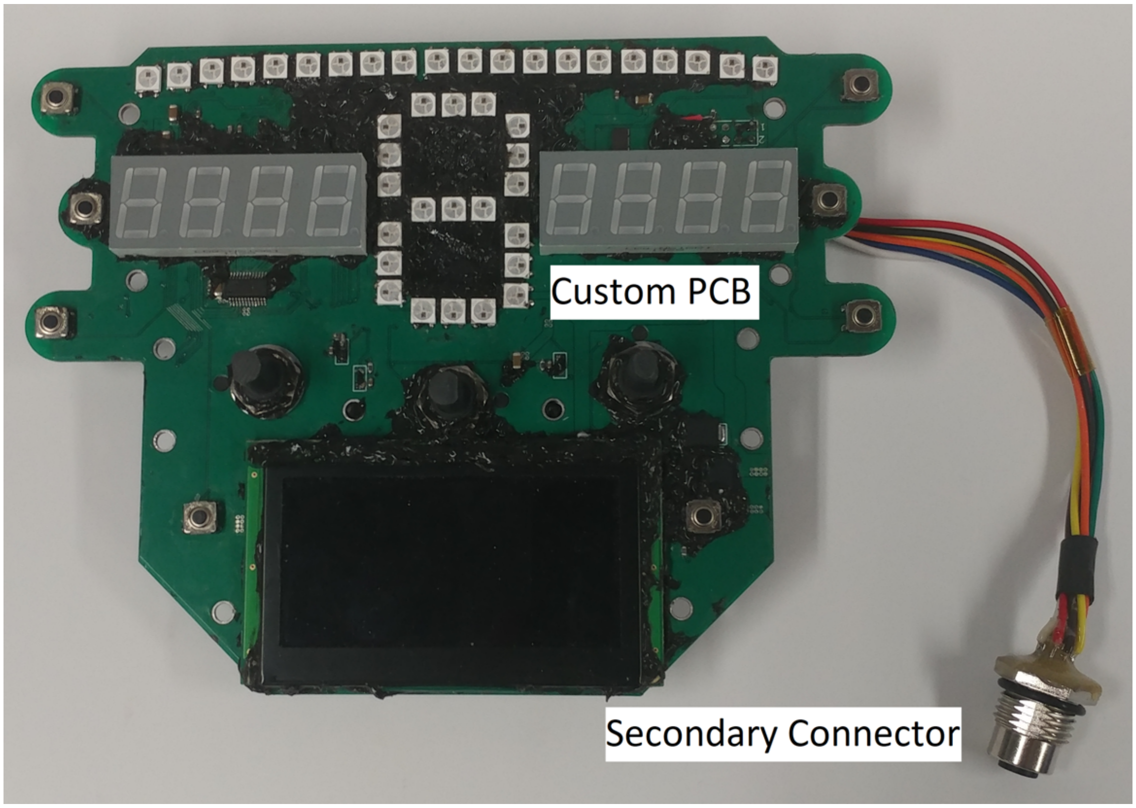


Figure 10: Steering wheel PCB

While the many systems of the car were impressive, there was insufficient time to finalize the work and the team did not perfect the critical systems such as shifting and engine operation. This resulted in an unreliable vehicle overall. Additionally, lack of proper documentation of the many systems resulted in an electrical system resembling a “black box” where the exact operation of each circuit is unknown and not replicable.

1.4 Challenges

There were a few major challenges of this project the team had to overcome. First, the previous vehicle had to be analyzed to understand every possible critical electrical system. This analysis included wiring connections, circuit protections, sensors and actuators, and packaging on the vehicle (how wires were routed and protected from heat). Next, the team had to fully understand the engine and transmission we were working with. We had to reach out to Yamaha for specific model information and electrical wiring diagrams. It was quickly determined the charging system is much weaker on the WR450F engine and is not upgradable, so power management became a major challenge.

The shifting system was highlighted as a challenge from the initial onset of the project. The previous pneumatic system was heavy, required a significant amount of electrical power, took up a substantial amount of space, and was overcomplicated. The new shifting system had to be lightweight, small, and use as little power as possible.

The FSAE ECE MQP team was also new to FSAE competition and rules requirements. Studying, interpreting, and designing systems to satisfy these rules was a major challenge. The rules significantly governed the direction our MQP went. Proper documentation was also required by FSAE in order to compete in the 2018 competition. The same was true for setting up future teams for success: providing clear, understandable, and detailed documentation was a great challenge in finishing the project.

1.5 Proposed Novelty/ Contribution

In order to alleviate the issues outlined on the previous vehicle, simplifying all electrical systems and increasing modularity were critical. Therefore, the 2018 competition car's engine management system (EMS) consists of one central unit being the Haltech ECU and a single additional microcontroller for auxiliary tasks the ECU is not allowed to perform per the FSAE competition rules [4].

This team developed a three-fold approach to solving issues the WPI FSAE experienced in the past with the electronic vehicle management system. The first tier of this solution was to provide the team with a dedicated engine test harness not to be used in the car, but for running the Yamaha WR450F engine on an engine test stand. This gave the team the ability to test the engine outside of the car with ease, which is critical for the early design stages. This harness is designed to be drive-by-wire capable and has the minimal amount of connections required. The tier one harness provided a proof of concept for the electrical signals for the EMS and ensured that the proposed electrical design was practical to implement in the car.

Once the engine management design was verified, a new, longer harness was designed with modular connection provisions for subsystems such as the Brake Plausibility Device, engine shifting management system, and additional sensory systems such as brake pressure sensors.

This introduced the third tier of the project, which involved using the remainder of the time the team had available to add modular sensor and information systems to aid in driver training and improve racing performance of the car. The most important systems included a gear indicator sensor as well as steering wheel paddle shifters.

As final deliverables, this team produced two engine harnesses, with one being used for engine testing and the other being used for the 2018 competition car with a modular yet critical harnesses for shifting as well as a Brake Plausibility Device, and a non-critical sensor harness for the vehicle. Additionally, the documentation for this project included a comprehensive explanation as to why connections were chosen with the intent being to make future wiring projects simpler for future teams in addition to the schematics themselves.

1.6 Report Organization

This report is designed to act as both a reference for the detailed design work completed by the team, as well as a tutorial for future FSAE teams working on the electrical system. In the Tutorial section, an electrical overview is given of the general wiring harness design as well as descriptions of all sensors and actuators used on the vehicle. It also discusses the requirements of SAE International for competition. The purpose of Chapter 2 is to outline everything the future team is expected to encounter in building a vehicle was basic operational and rules compliant systems.

Chapter 3 describes the team's initial ideas for solving all the issues found with the previous FSAE vehicle. It describes the concept of the solution before the solution was designed as a tool to help future teams begin the design process.

Chapter 4 provides a detailed description of all design work from start to finish. It covers design successes as well as failures and how the team adapted to arrive at the final solution. It also discusses how each system was installed on the vehicle and how each system was tested to verify proper operation to help future teams.

Chapter 5 describes what this project accomplished and how we believe future teams can use this platform to design an even more advanced vehicle. This is followed by the references, which are given not only for credit where ideas stem from, but as a list of resources the team used to assist with the project design that future teams can benefit from. The appendices include highly detailed information about electrical connections, schematics, parts orders, and FSAE requirements. This report should be thoroughly reviewed by future FSAE teams before work begins, and we hope it is helpful for years to come.

2. Automotive Electrical Systems Overview

Vehicles equipped with electronic fuel injection (EFI) utilize many sensors and actuators to control combustion events via the engine control unit (ECU). Sensors take information such as intake air temperature, intake air pressure, crankshaft position, exhaust oxygen levels, and accelerator pedal position and send this information to the ECU for processing. In turn, the ECU decides how much fuel to provide via the electronic fuel injector and when to actuate the spark plug to initiate combustion. All sensors and actuators are connected to the ECU via an engine wiring harness. Other common vehicle sensors used today such as blind spot detectors and crash avoidance radar are typically placed in a separate wiring harness. A diagram of a simple EFI system found is seen in Figure 11.

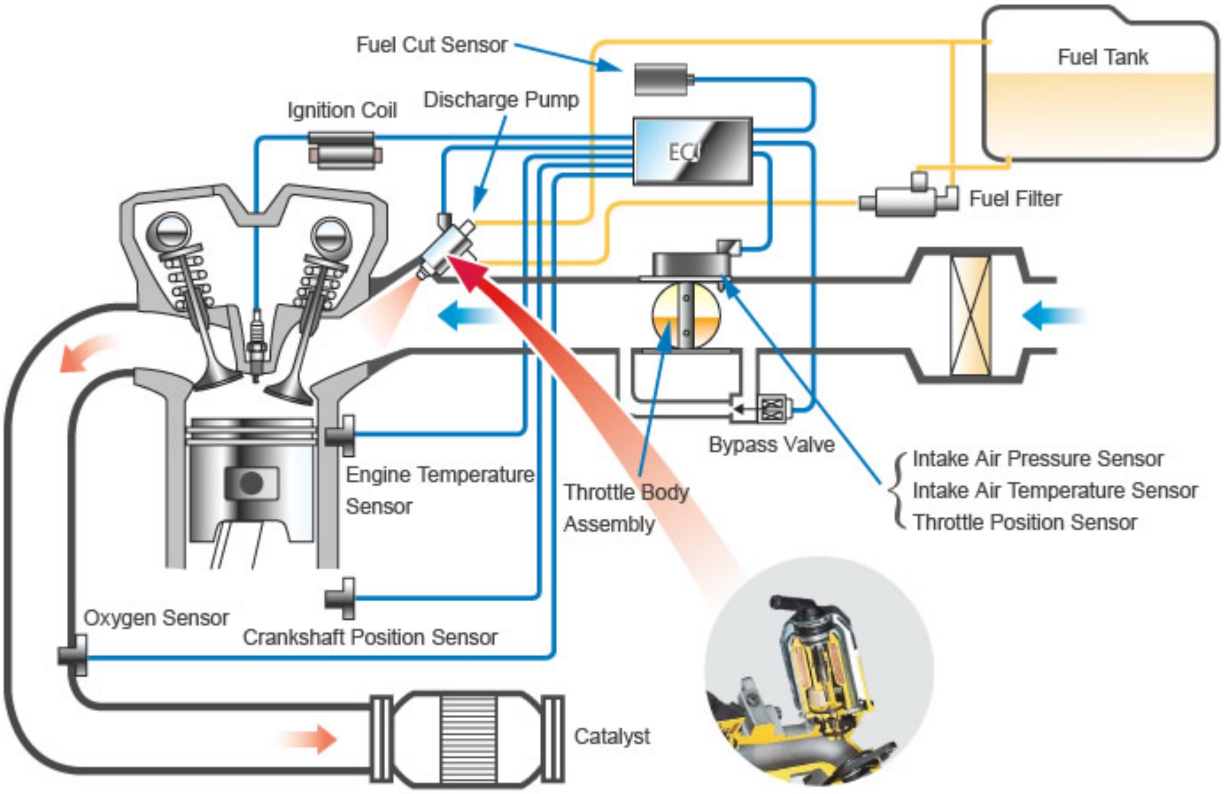


Figure 11: Electronic fuel injection engine feedback diagram [7]. This image includes additional sensors and components not utilized in the Yamaha WR450F configuration such as the fuel cut sensor and the catalytic converter. Other sensors such as camshaft position sensors are not included.

2.1 FSAE Electrical System Overview

The electrical system of the 2017-2018 WPI Formula SAE race car is designed as a modular system that allows for the easy expansion of the current harness and troubleshooting by isolating individual problems that may arise. The modularity is three-fold, starting with a primary harness that handles engine function and management. A secondary harness is them layered on top of the primary harness that serves systems such as shifting and proprietary safety circuitry required by SAE in order the reach the criteria required for competition. The tertiary harness allows for noncritical functions such as telemetry and other sensors that may be desired for racing applications but are not critical for the basic function of the car.

The idea of using this design is that the harness will both provide the team basic functionality of the vehicle for not only the 2018 competition but for future years if there is no opportunity to create a new harness for new vehicles. It will also allow future MQPs to build new harnesses on the secondary or tertiary level to replace and expand the non-critical functions of the car without needing to completely rebuild from an initial harness. This means that new harnesses on the secondary and tertiary level can be designed, prototyped, and implemented into the car while the basic function of the vehicle remains unaffected.

It was decided at the beginning of the project that all electrical subsystems of this vehicle needed to be designed and implemented with racing principles in mind. Therefore, in addition to the rules and regulations that needed to be met in order to compete, critical components needed to be easily accessible for quick and easy replacement in the event of failure at the race track. Thus, the harness was designed to allow circuits and components to be easily isolated and failures to be quickly identified due to the extensive use of connectors and the simplification of design.

All of the levels of the harness are centralized at the Haltech ECU as well as the microcontrollers that are necessary to fully run the vehicle. The primary harness consists of all of the engine control circuitry, including the accelerator pedal, throttle body, manifold absolute pressure sensor, crank position sensor, injector, air temperature sensor, coolant temperature sensor, cooling fan, relay box, power management circuitry, starter motor, and O2 controller.

The secondary harness consists of the shifting motor, shift motor controller, gear indicator circuit, brake plausibility circuit, brake pressure transducers. These all communicate with the Haltech when necessary but are designed in order to allow these subsystems to be easily removed, troubleshot, or redesigned without disabling the basic, primary harness.

The tertiary harness is central to telemetry and non-critical functions. This harness may be implemented partially on the 2017-2018 FSAE vehicle but will be the point of heavy modification for any future project work related to future vehicle iterations. A summary of the vehicle wiring is seen in Table 1.

Table 1: Wiring harness organization

Primary Harness	Engine Sensors
	Engine Actuator
	Charging
	Main Power
	Thermofan Control
Secondary Harness	Safety Systems (Brake Plausibility)
	PiShifter
	Brake pressure sensors
Tertiary Harness	Telemetry sensors
	Monitoring

2.2 Wiring Harness

A vehicle wiring harness connects all of the electrical sensors, actuators, and controllers required for a particular vehicle to function. In the average road-going vehicle, there are a variety of harnesses that all connect in order to provide function for different subsystems of a vehicle. This includes the lighting systems, entertainment systems, and various other subsystems that are common in modern vehicles. In order for all of the components to be in their respective locations for sensing and actuation, a wiring harness is required to make connections and provide power [8]. In order to make a harness that is both robust and durable, connectors and a wiring loom are used to increase reliability and prevent wires from becoming cut, shorted, or melted in abrasive and high heat environments [9]. On the 2017-2018 WPI Formula SAE vehicle, the wiring harness was implemented with a modular design that manages all of the engine sensors and actuators as well as non-critical safety and telemetry devices. Without the wiring harness, the WPI 2018 Formula SAE vehicle would be incapable of functioning other than as a rolling and steering mechanical design. All engine function and power distribution relies on the wiring harness to properly allow signals and connections to interface with the actuators.

The entire harness was designed and implemented to take into consideration both and heat constraints. All of the harness was physically created by following a wiring procedure designed to make sure that all work was double checked and continuity tested multiple times before initial energizing and testing. Wires were grouped together and sleeved to resist abrasion and aid harness installation and removal. The primary harness was entirely laid out before adding connectors, which were crimped, soldered, and labeled. This ensured that all similar wires were the same length and that most cables were able to be placed in as little looming as possible. Heat shrink added at the end of wires for improved aesthetics and provided clean looming terminations. Special care was taken in order to maintain distance from heat sources and ensure reliability of the harnesses. The final wiring in the car will also have heat resistant wrapping around various parts of the harness in order to further ensure reliability.

2.3 Sensors

Coolant Temperature Sensor

The coolant temperature sensor is dependent on the casting of the Yamaha WR450FF engine block. Therefore, the stock temperature sensor is used and wire pigtails had to be attached to the sensor with a connector of our choice. The resistance curve then had to be extrapolated in order to build a curve for the Haltech software. This was done through values provided in the Yamaha service manual initially and then through tested values from the sensor itself at various heat levels. An image of a coolant temperature sensor is shown in Figure 12.

Figure 12: Coolant temperature sensor [10]

Air Inlet Temperature Sensor

For the air inlet temperature sensor, a Delphi unit (Delphi 25036751 [11]) was chosen based on the ability to get a resistance curve data sheet. The unit chosen is fully capable of a full engine inlet temperature range and is powered from the 5-volt sensor supply voltage. An image of an air inlet temperature sensor can be seen in Figure 13 and the Delphi resistance curve is shown in Table 2.

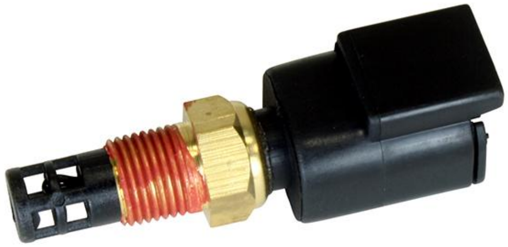
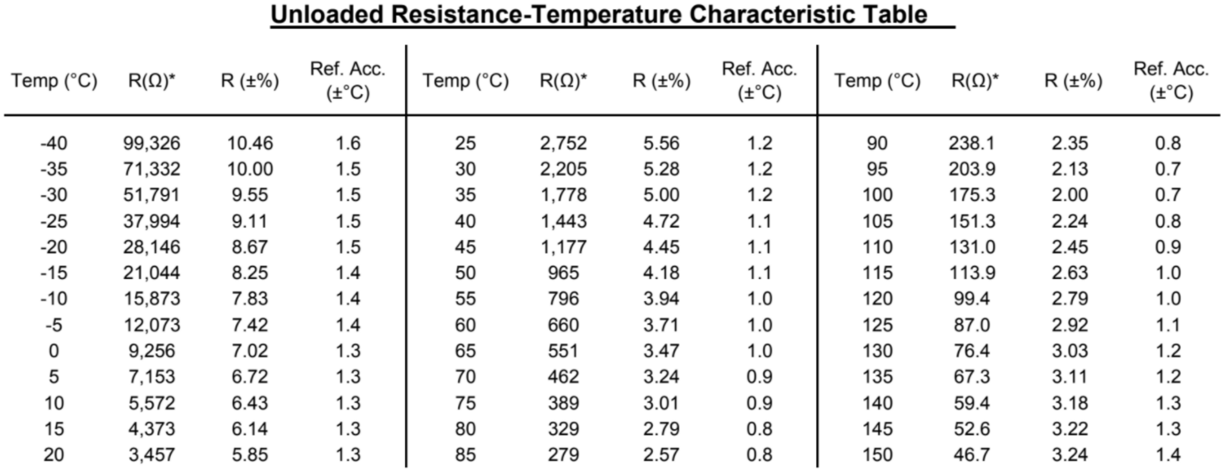


Figure 13: Air inlet temperature sensor [12]

Table 2: Air inlet temperature sensor transfer function [[13]]



Unloaded Resistance-Temperature Characteristic Table

Temp (°C)	R(Ω)*	R (±%)	Ref. Acc. (±°C)	Temp (°C)	R(Ω)*	R (±%)	Ref. Acc. (±°C)	Temp (°C)	R(Ω)*	R (±%)	Ref. Acc. (±°C)
-40	99,326	10.46	1.6	25	2,752	5.56	1.2	90	238.1	2.35	0.8
-35	71,332	10.00	1.5	30	2,205	5.28	1.2	95	203.9	2.13	0.7
-30	51,791	9.55	1.5	35	1,778	5.00	1.2	100	175.3	2.00	0.7
-25	37,994	9.11	1.5	40	1,443	4.72	1.1	105	151.3	2.24	0.8
-20	28,146	8.67	1.5	45	1,177	4.45	1.1	110	131.0	2.45	0.9
-15	21,044	8.25	1.4	50	965	4.18	1.1	115	113.9	2.63	1.0
-10	15,873	7.83	1.4	55	796	3.94	1.0	120	99.4	2.79	1.0
-5	12,073	7.42	1.4	60	660	3.71	1.0	125	87.0	2.92	1.1
0	9,256	7.02	1.3	65	551	3.47	1.0	130	76.4	3.03	1.2
5	7,153	6.72	1.3	70	462	3.24	0.9	135	67.3	3.11	1.2
10	5,572	6.43	1.3	75	389	3.01	0.9	140	59.4	3.18	1.3
15	4,373	6.14	1.3	80	329	2.79	0.8	145	52.6	3.22	1.3
20	3,457	5.85	1.3	85	279	2.57	0.8	150	46.7	3.24	1.4

O2 Sensor

In order to properly configure and tune the engine, a wideband oxygen (O2) sensor was required. Due to the fact the Haltech 1500 does not have a wideband O2 controller, it was necessary to have a dedicated O2 controller that is capable of properly interpreting the signal and sending the signal to the ECU. The Innovate LC-2 O2 controller used in the previous year's car was also chosen for this year's vehicle since the Innovate controller has a very simple input-output configuration that does not require any further design work [14]. Additionally, it is available in a lightweight, minimalistic package that maximizes space savings. The LC-2 controller must be calibrated both between the sensor and controller and then between the controller and the ECU. An image of an O2 sensor is shown in Figure 14.

Figure 14: Wideband oxygen sensor [15]

Manifold Absolute Pressure Sensor

The manifold absolute pressure sensor (MAP) serves the purpose of allowing the engine management system to interpret the amount of air that is being taken into the engine by measuring the vacuum or negative pressure inside the intake. This sensor has a direct impact on how the engine operates and functions through tuning and is responsible for various. In order for this sensor to operate properly it must be calibrated using datasheet tables that can be found from various places on the internet. These tables convert the manifold pressure to a voltage that can then be interpreted by the Haltech ECU. The MAP sensor that was chosen for this application was a General Motors 1 bar MAP sensor since it is readily available and is extremely common in aftermarket applications. The 1 bar model was also chosen since our engine is not in a boosted application but instead in a naturally aspirated mode where there can be greater voltage resolution of the sensors representation of manifold pressure with a 1 bar sensor versus a 2 or 3 bar sensor that must achieve a greater range of manifold pressures over the same voltage range. The manifold pressure sensor data is shown in Figure 15, Table 3, and Figure 16.

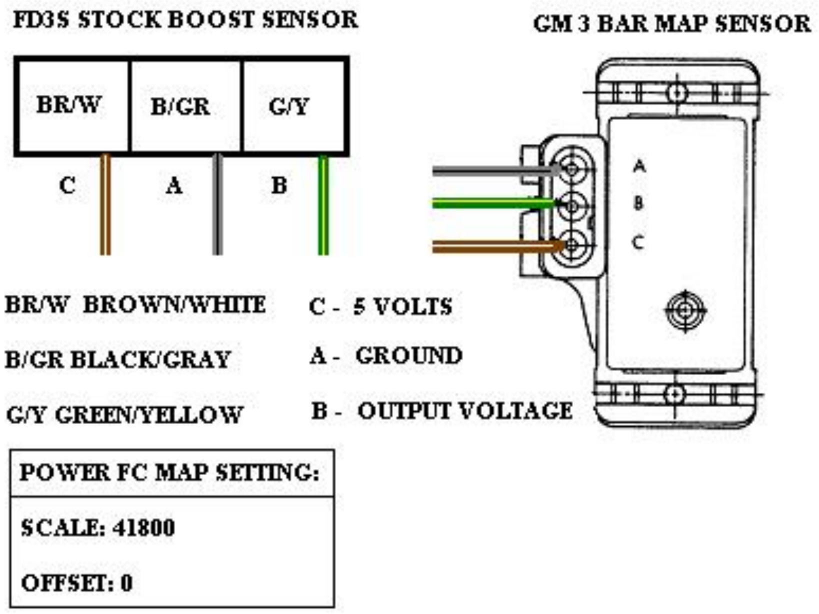
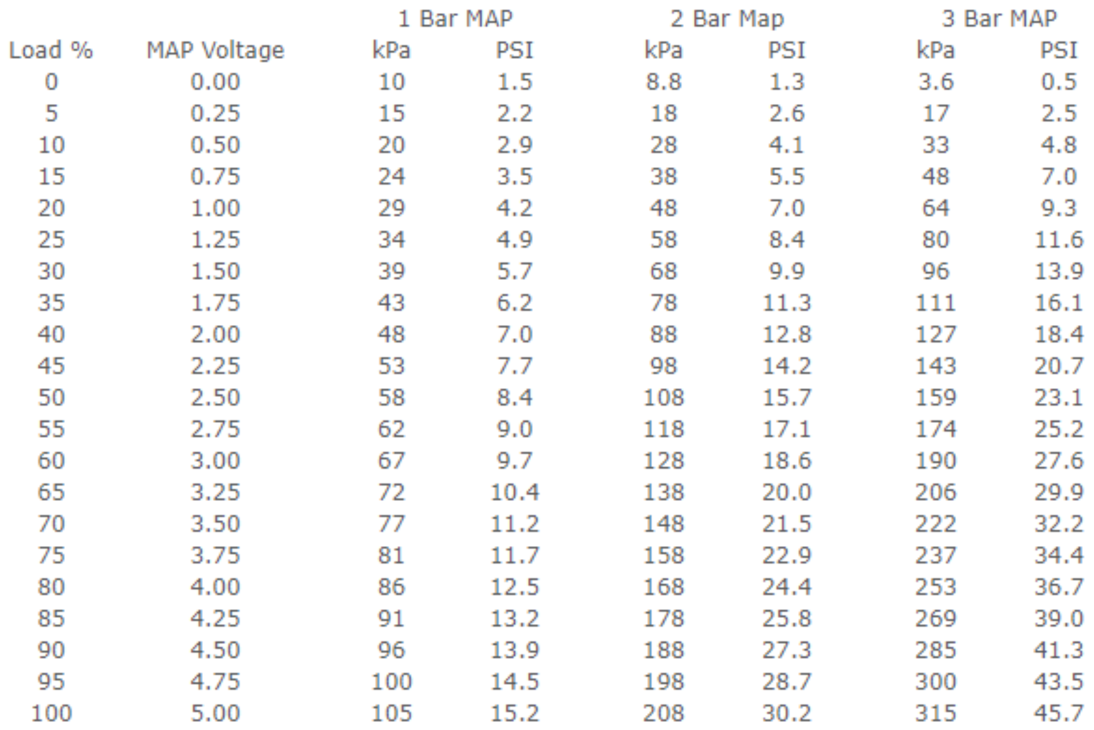


Figure 15: Manifold absolute pressure wiring diagram [16]

Table 3: MAP sensor transfer function [17]



		1 Bar MAP		2 Bar Map		3 Bar MAP	
Load %	MAP Voltage	kPa	PSI	kPa	PSI	kPa	PSI
0	0.00	10	1.5	8.8	1.3	3.6	0.5
5	0.25	15	2.2	18	2.6	17	2.5
10	0.50	20	2.9	28	4.1	33	4.8
15	0.75	24	3.5	38	5.5	48	7.0
20	1.00	29	4.2	48	7.0	64	9.3
25	1.25	34	4.9	58	8.4	80	11.6
30	1.50	39	5.7	68	9.9	96	13.9
35	1.75	43	6.2	78	11.3	111	16.1
40	2.00	48	7.0	88	12.8	127	18.4
45	2.25	53	7.7	98	14.2	143	20.7
50	2.50	58	8.4	108	15.7	159	23.1
55	2.75	62	9.0	118	17.1	174	25.2
60	3.00	67	9.7	128	18.6	190	27.6
65	3.25	72	10.4	138	20.0	206	29.9
70	3.50	77	11.2	148	21.5	222	32.2
75	3.75	81	11.7	158	22.9	237	34.4
80	4.00	86	12.5	168	24.4	253	36.7
85	4.25	91	13.2	178	25.8	269	39.0
90	4.50	96	13.9	188	27.3	285	41.3
95	4.75	100	14.5	198	28.7	300	43.5
100	5.00	105	15.2	208	30.2	315	45.7

Figure 16: MAP sensor [18]

Crankshaft Position Sensor

The crankshaft position sensor utilizes a magnetic pickup on a reluctor wheel in order to determine the position of the crankshaft on the engine. This sensor is integral to the engine as it tells the ECU the positioning of the crankshaft in order to properly trigger the EFI system. The voltage value induced by the sensor at various rotational speeds of the engine is important to the function of the electronics system as well. As the engine spins, the speed at which the sensor passes the pickup determines the level of voltage that is induced. A higher rotational speed induces a greater voltage. To measure this value, the sensor wires must be probed with minimal intrusion from the probes in order to not distort the signal. A picture of a motorcycle crankshaft position sensor can be seen in Figure 17.

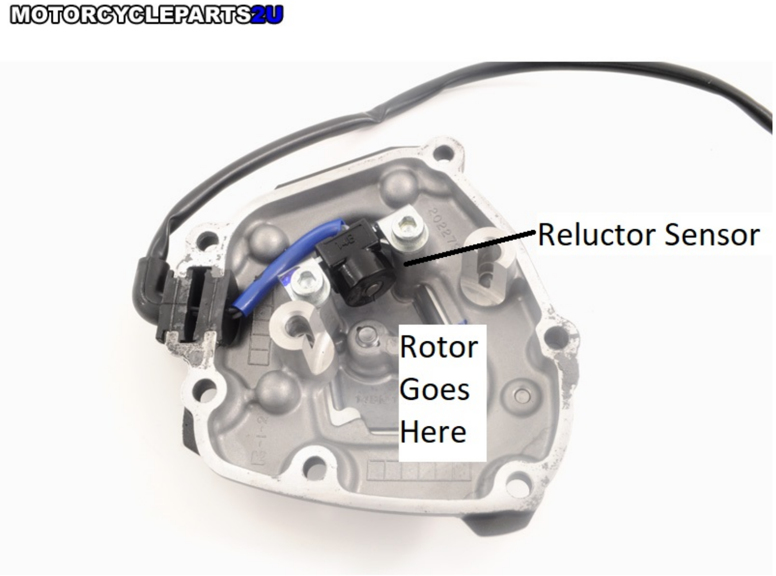


Figure 17: Crankshaft position sensor (installed) [19]

In our testing, it was found that many issues arose from having an extended unshielded cable for testing with an oscilloscope. Having an unshielded cable caused the engine to not start at all as the crank position was misread in this case. Probing directly in the plug of the cable resolved this issue and demonstrated the importance of a shielded cable when installed on the vehicle permanently.

Sensor values were captured on an oscilloscope in order to determine the peaks of the voltage spikes at various engine speeds ranging from cranking to 9000 RPM, seen in Figure 18.

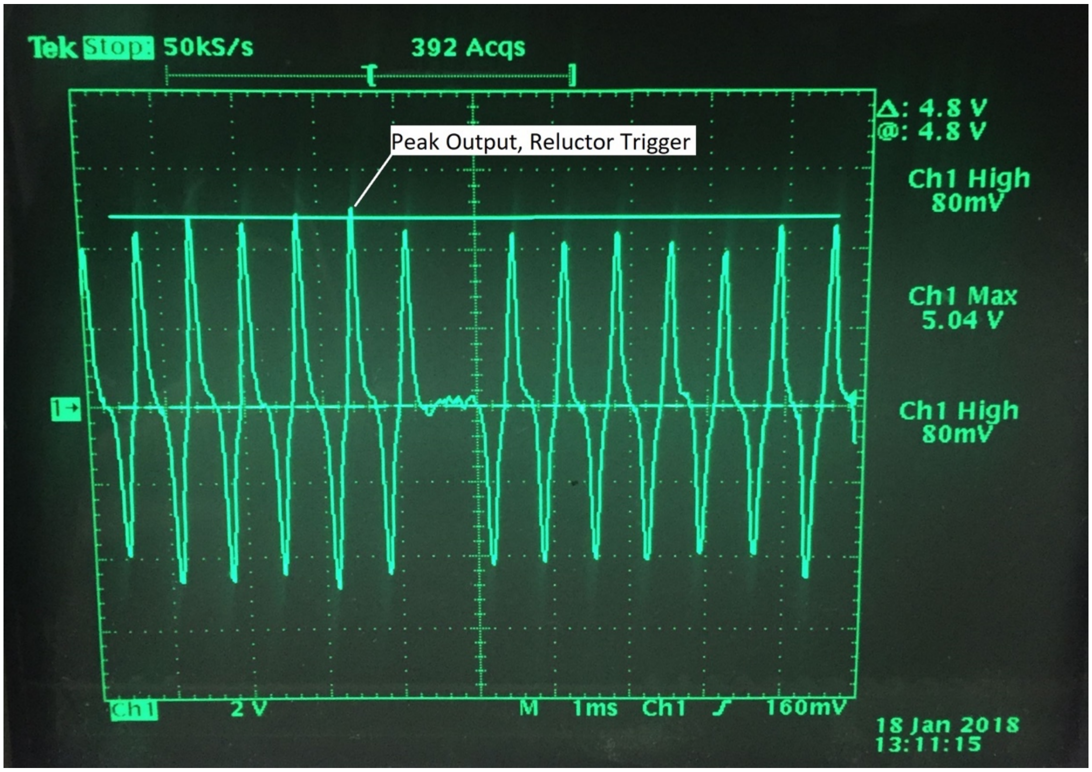


Figure 18: Crankshaft position sensor voltage output

It was found that the stock values by Haltech were in many cases far higher than what the sensor was producing which had potential to prevent the Haltech from triggering fuel injection and spark events in order to make the engine run.

Future research and development should be done regarding creating a camshaft position sensor for the engine. A crankshaft and camshaft position sensor combination will further refine the fuel injection timing and enable the engine to only fire the injector and spark events on one of the four strokes of the engine, as opposed to the current configuration that only provides half of the relevant data for efficient injection. The addition of this sensor into the camshaft could be made by positioning a metal pickup on the gear of one of the camshafts and a sensor mounted and sealed through the valve cover. This would greatly increase accuracy of the system.

Throttle Position Sensors and Accelerator Pedal Position Sensors

The throttle position sensors (TPS) and accelerator pedal position sensors (APPS) are sourced through the throttle body assembly and the throttle pedal assembly that were chosen for the application. A change from previous years is a new 40mm Bosch throttle body that was sourced for this application. Bosch provides a full line of throttle bodies in various bore sizes in order to meet the requirements of any mechanical application. All of the throttle bodies available through Bosch are electrically driven and in compliance with FSAE rules. The use of a new throttle body increases reliability and removes the need to prove safety functionality as it is a pre-sealed OEM throttle body. A picture of a TPS can be seen in Figure 19.

Figure 19: Throttle position sensor [20]

An image of the same type of APPS we used can be seen in Figure 20.

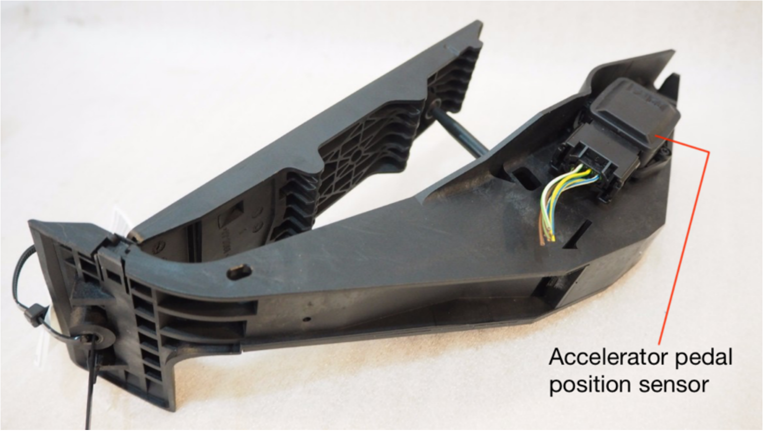


Figure 20: Accelerator pedal with accelerator pedal position sensor [21]

Both the TPS in the throttle body and the APPS in the accelerator pedal are designed with redundancy for safety in the event of signal mismatch. In the case of the throttle body, the sensors provide opposite and opposing readings. The oscilloscope photograph in Figure 21 demonstrates this principle. In the closed position one sensor reads the positive rail voltage and the other reads the negative rail voltage. As the throttle plate is opened the voltages cross each other.

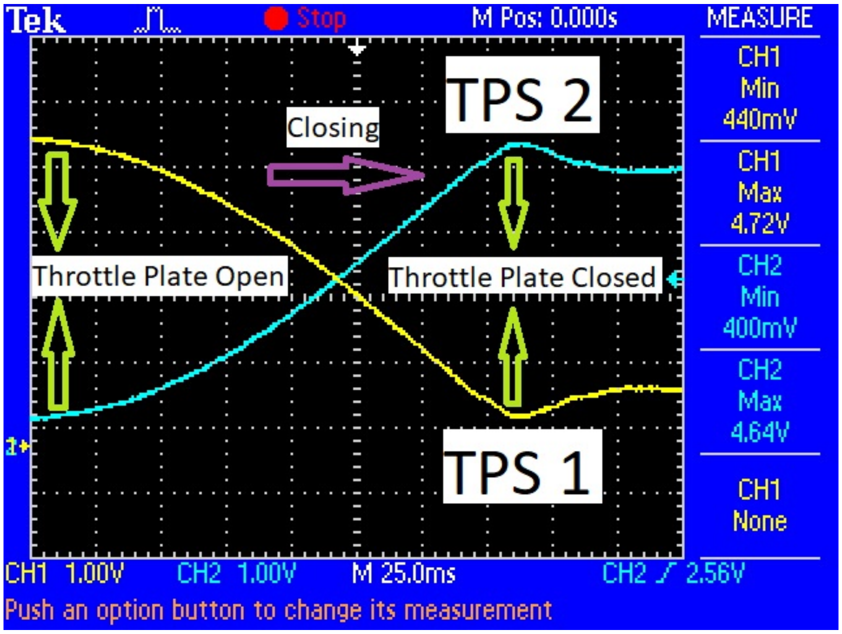


Figure 21: Redundant throttle position sensor response

The APPS are designed to be redundant as well, but they function differently than the TPS. In the case of the APPS, each potentiometer has a different lower rail voltage and different full-scale voltage. Their responses to driver input of various types can be seen in Figure 22 and Figure 23.

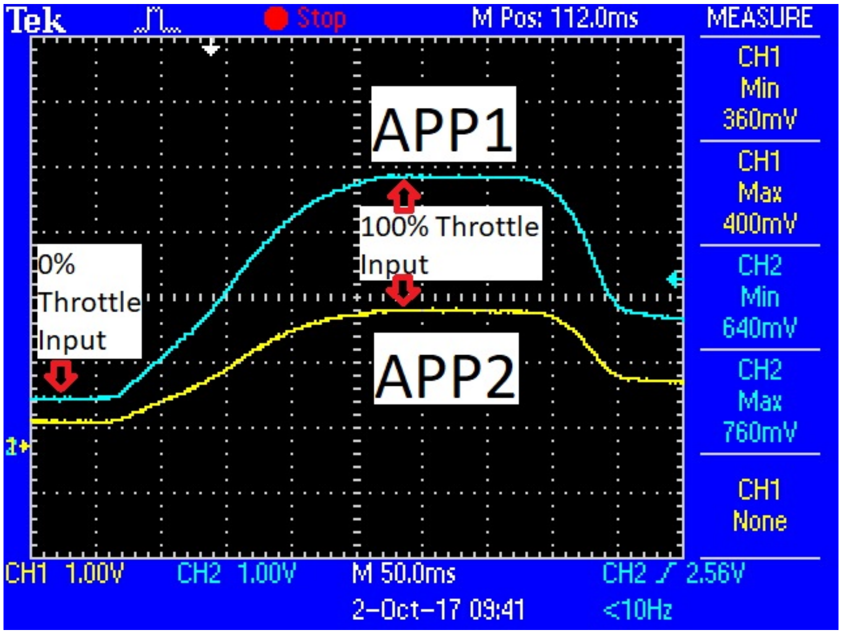


Figure 22: Redundant accelerator pedal position sensor response

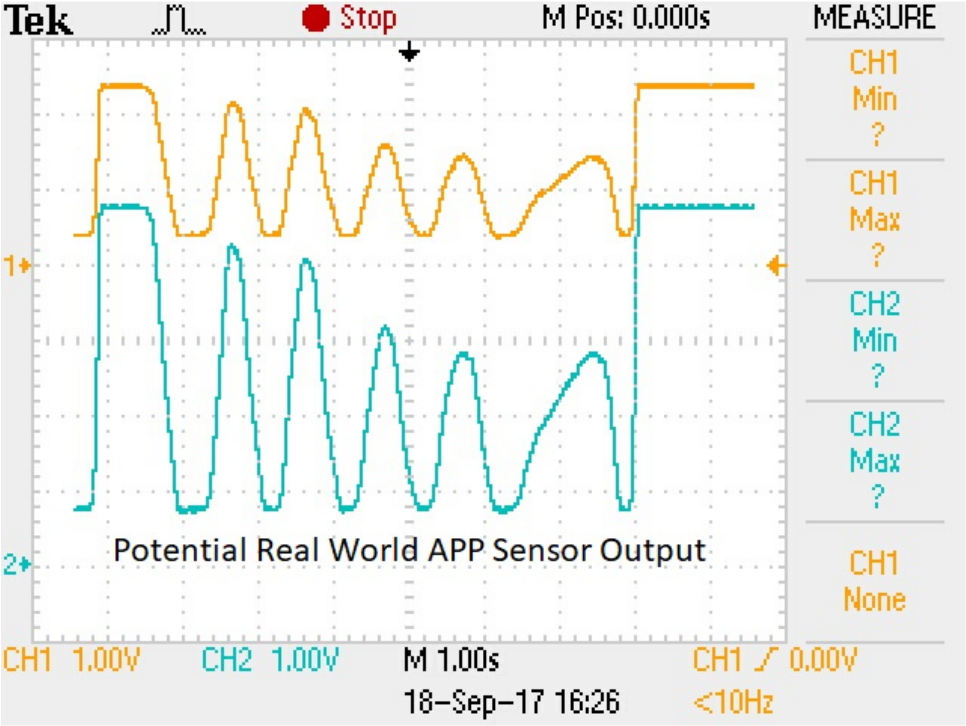


Figure 23: APPS response to quick throttle actuation

One of the major concerns regarding this system was ensuring the pedal would function properly in this custom application. The components used in this project needed to be capable of reacting fast enough to driver input in a standalone environment without any signal processing that would be present in a fully integrated OEM engine control system. It was determined that the sensor reacted instantaneously to the user and that the reaction time was therefore satisfactory for the application and no perceivable latency would be present to the driver. These tests were all performed in the component selection process and are representative of the sensor in a standalone configuration, with no control unit for the device.

In this series of testing, no anomalies were found in how the sensors operated in a standalone configuration and it was determined that no signal processing was needed in order to allow the APP sensors to be read by the ECU. The following scope photos verify the functionality of the APP sensor. Figure 24 shows the maximum voltage values which are present when the pedal is depressed, while Figure 25 shows the voltage values for the two sensors when the pedal is at idle.

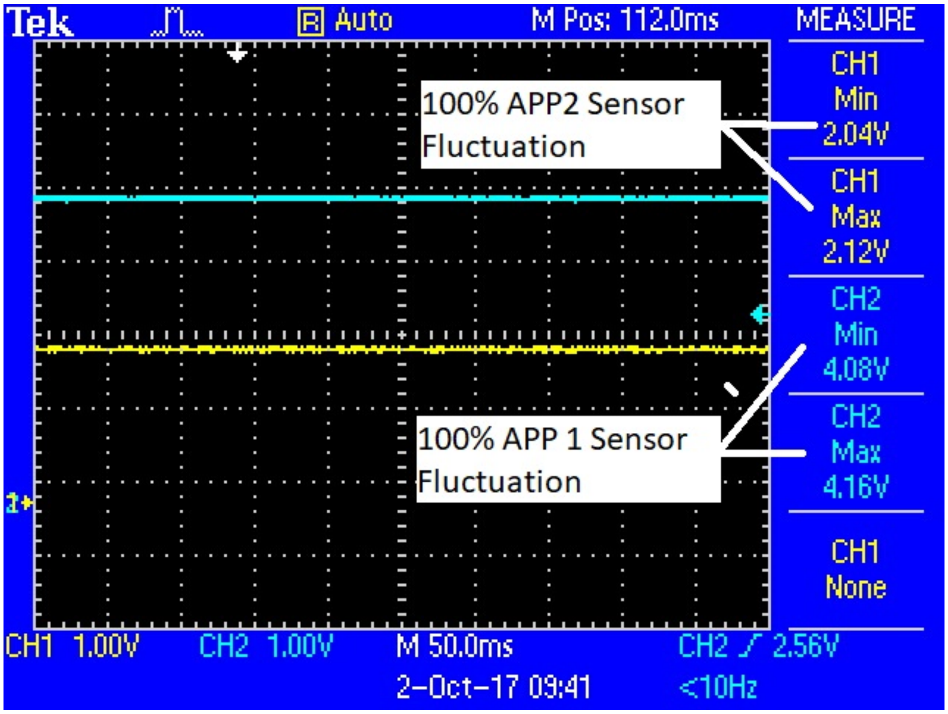


Figure 24: APPS full-scale voltages

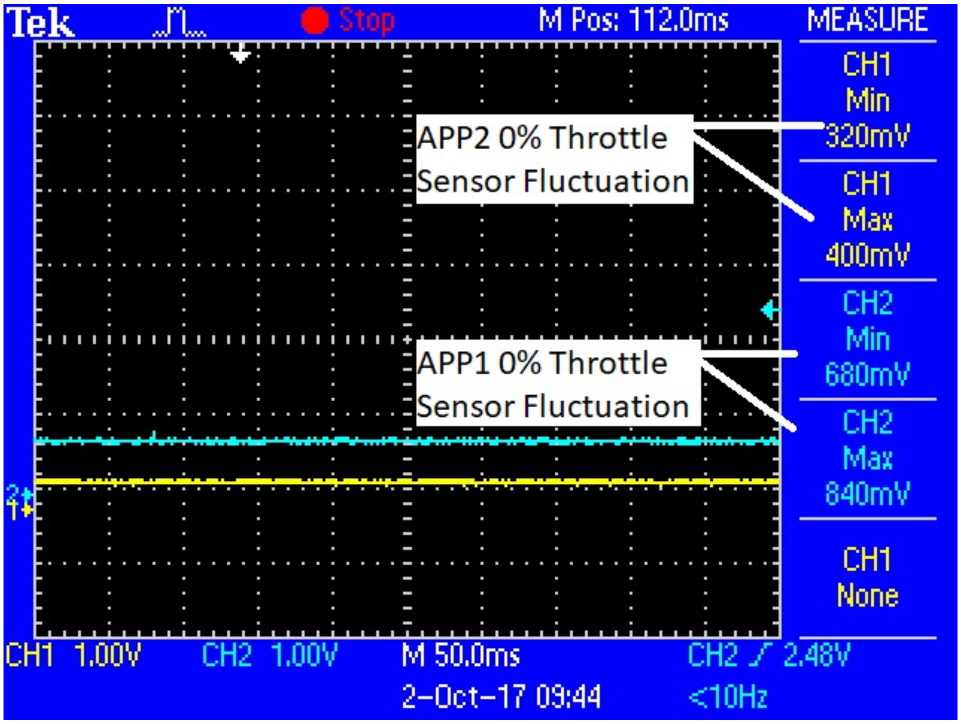


Figure 25: APPS zero-scale voltages

Neutral Indicator Sensor/Gear Indicator Sensor

The WR450F engine is equipped with a neutral indicator sensor. The purpose of this sensor is typically to tell when the transmission is in neutral for electric start purposes. In the OEM dirt bike application, the system is designed so that the electric starter is not allowed to engage unless the bike is in neutral, preventing transmission and starter damage. The neutral indicator sensor from Yamaha has a single metallic contact that is stationary. When the gear is changed, a metallic ball contact rotates in the transmission housing, eventually making contact with the sensor contact when in the neutral position. This type of single contact sensor can be seen below in Figure 26.

Figure 26: Neutral indicator sensor [22]

In this year's FSAE design, the neutral indicator sensor was re-manufactured to provide additional data for more powerful subsystems. The final design had stationary contacts - one for each gear in addition to neutral as seen in Figure 27. As the transmission is shifted, the ball contact rotates and makes contact with one metallic contact for each gear. This allows the driver to know which gear the vehicle is in at all times which is very helpful in a racing scenario with the sequential gearbox in the WR450F.

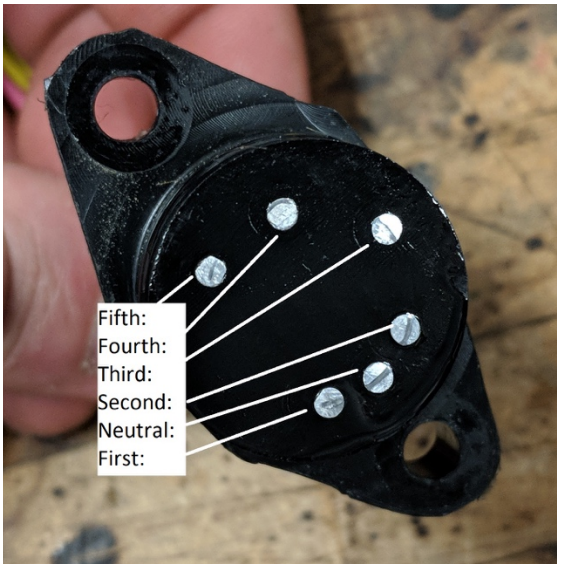


Figure 27: Custom gear indicator sensor

2.4 Actuators

Engine Control Unit (ECU)

The Engine Control Unit is the center of the electrical system for any vehicle management system. Designed to be user friendly and achieve a high level of functionality, the Haltech Elite 1500 ECU that was chosen for the 2018 WPI Formula SAE car since it has the functionality to run a variety of engines up to 8 cylinders and supports a modern drive-by-wire throttle control. In this system, the throttle plate inside of the throttle body is controlled indirectly from the pedal through an electrical connection.

The Haltech Elite 1500 ECU has been used previously in the WPI Formula SAE vehicles. This ECU allows for a variety of generic input output as well as basic functions that can be configured in a graphical user interface. From the perspective of competition, the benefits of this ECU are that it eliminates less reliable mechanical systems while providing the team with the ability to easily configure, troubleshoot, and make adjustments to the vehicle. An image of a Haltech Elite 1500 ECU can be seen in Figure 28.

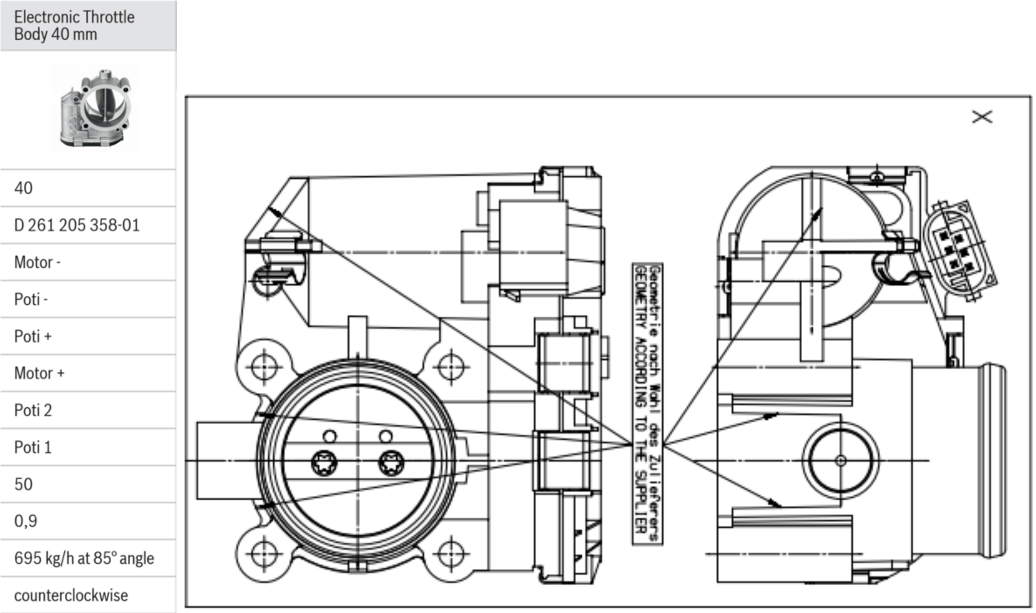
Figure 28: Haltech Elite 1500 ECU [23]. Two connectors are used: A 26-pin connector and a 34-pin connector. Various connections on each are used.

The tuning system of the Haltech is a self-learning system that relies heavily on the wideband oxygen sensor in the car. Assuming proper intake design and injector placement, this means a rough tune of the fuel and air into the vehicle will be self-adjusted by the ECU in order to increase the power and torque potential of the vehicle. All of this functionality is built into the ECU and requires no coding or electrical engineering expertise from the team. The extent of the design for the ECU first entails designing the electrical system to properly meet the needs of the sensors and actuators chosen, then using the ECU software in order to properly specify the functionality that is intended to be used, and finally wiring of all the electrical components that are connected to the ECU.

In the case of resistive sensors and those that require calibration, the Haltech Elite 1500 ECU allows the team to input resistance curves and sensing equivalent of these values in addition to the calibration software that coordinates components in the device to function properly. The ECU also provides a suggested wiring diagram that is robust and will allow almost any engine to be operated from the management system. This ECU features a number of options that make it ideal for our application. First, this ECU enables a drive-by-wire system which allows for key safely features that have been utilized previously in WPI FSAE cars and enables the throttle system to be electronically driven minimizing mechanical linkages. The ECU has a variety of options for injector and crank position sensors that match the configuration of the Yamaha WR450FF engine that was chosen for this application.

Throttle Body

The throttle body chosen was a Bosch 40mm throttle body [24] that is designed for the intent of OEM applications. The throttle body uses proprietary automotive electrical connectors. Use of an OEM throttle body has the benefit of being easily configurable through the Haltech software. It also passes FSAE rules for competition without further technical evaluation from competition rule makers due to the industry standards in place that the product used already is compliant with. A technical drawing of the throttle body can be seen in Figure 29.



Electronic Throttle Body 40 mm
40
D 261 205 358-01
Motor -
Poti -
Poti +
Motor +
Poti 2
Poti 1
50
0,9
695 kg/h at 85° angle
counterclockwise

Figure 29: Bosch 40mm throttle body technical drawing [25]

Wiring the throttle body is done as suggested in the specification sheet and in accordance with the ECU signal requirements. Once wiring is specified to the ECU in software, the ECU is able to self-calibrate the unit by actuating the throttle plate motor and reading the sensors to develop a curve as to how the signals react to the input. This allows the throttle body selected to be plug-and-play compatible with the ECU. A picture of our throttle body is shown in Figure 30.

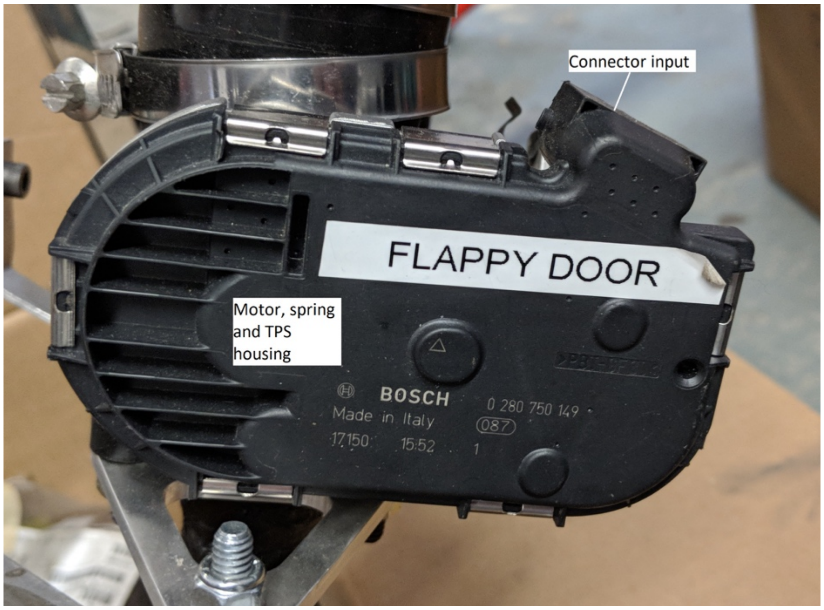
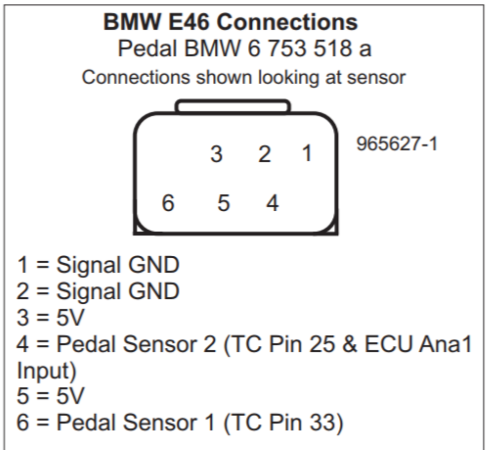


Figure 30: Bosch 40mm ETC throttle body

Accelerator Pedal

The throttle pedal was chosen with the same ideas in mind as the throttle body. Responsible for housing and facilitating the actuation of the APPS, the pedal chosen was a BMW E46 accelerator pedal that is common on a number of automobiles and is readily available. There are various revisions of the pedal used in many model years, yet the function remains the same. The pedal that was used in this application was similar to the pedal that was used in the previous year's car because ergonomically, the pedal works well for the driver and is a minimalistic design that fits well in the vehicle. In addition, the pedal is very light with an all-plastic construction and has a dual return spring system that complies with FSAE rules. The previous FSAE vehicle used a BMW pedal that had an integrated transmission kick down switch that an automatic vehicle uses to bring the transmission down a gear in order to increase acceleration at wide open throttle. Due to the fact the FSAE car uses a manually actuated transmission at the discretion of the driver, the transmission kick-down function is unnecessary and provides a mechanical feel to the end of the pedal travel that is undesirable to the driver in a racing condition.

This pedal meets all of the FSAE requirements including the need for dual pedal return springs as specified in the 2018 competition rules. The sensors in the pedal act differently than those in the throttle body by output but serve the same basic function. Wiring the pedal to analog inputs and feeding the required voltages for sensor reading allows the ECU to calibrate the pedal with the assistance of a user pushing on the pedal when asked by software, in order to achieve different sensor readings. Once complete, the drive-by-wire setup is calibrated and pressing the pedal will directly correlate to the movement of the throttle body when both are connected to the ECU. This can be tested by actuating the pedal and observing the throttle plate in the throttle body move. The pinout of the APPS is provided in Figure 31 and our accelerator pedal can be seen in Figure 32.



1 = Signal GND
2 = Signal GND
3 = 5V
4 = Pedal Sensor 2 (TC Pin 25 & ECU Ana1 Input)
5 = 5V
6 = Pedal Sensor 1 (TC Pin 33)

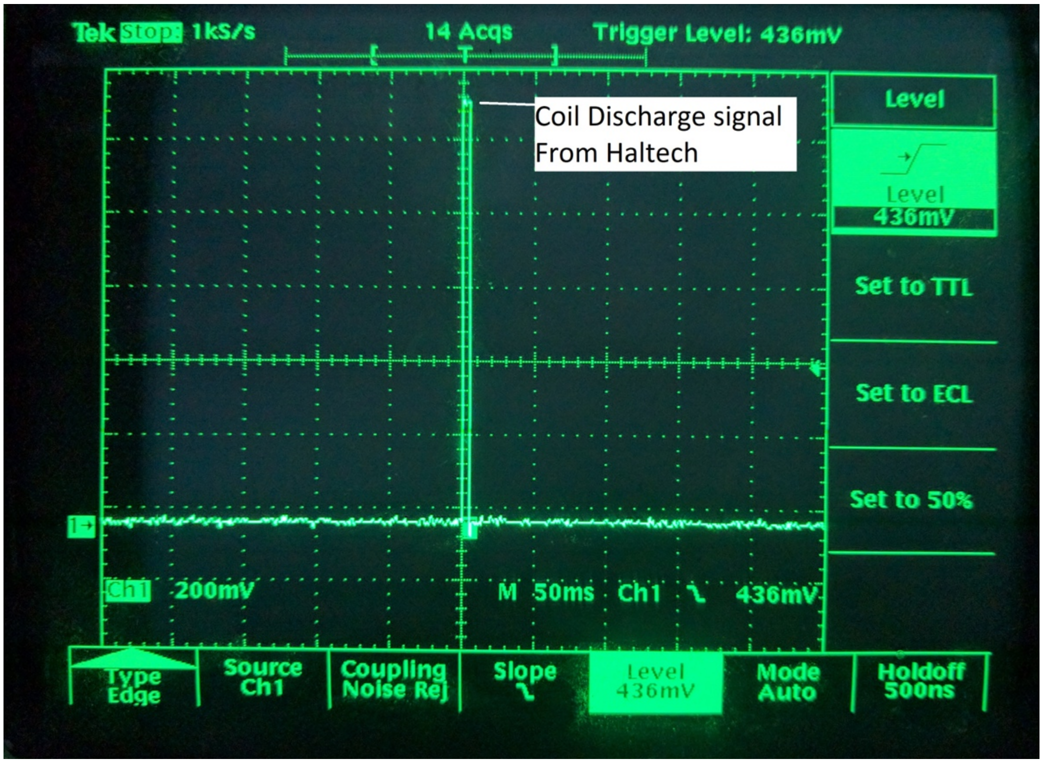
Figure 31: APPS wiring diagram [26]

Figure 32: BMW accelerator pedal

Ignition Module

The ignition coil is necessary in order to generate a spark and therefore initiate combustion in the combustion chamber of the engine. The ECU is compatible with a number of ignition modules but does not have an onboard ignition module. In the case of most modern vehicles, ignition modules that drive the ignition coil are built into a single unit minimizing space and creating an all-around easier implementation of the components. Additionally, most modern vehicles have separate modules for each of the cylinders on the vehicle which minimizes large current carrying spark plug wires seen on a variety of older vehicles.

The Haltech 1500 ECU provides a 12-volt supply, sensor ground, and a signaling wire to the ignition module and coil. When a small signal is sent from the ECU to the module, the coil is used as a transformer in order to build voltage far beyond that capable of being provided from the battery. This voltage is discharged by the spark plug, thus generating a spark and initiating combustion. The ECU signal to the coil was captured in Figure 33 as a pulse.



Coil Discharge signal
From Haltech

Figure 33: ECU coil trigger signal

Any modern coil will provide the benefits stated above. In previous years, General Motors LS2 coil packs were used for their easy availability. Spare coils were already purchased for previous vehicles and also provided continuity between various iterations of our competition vehicles. Therefore, an LS2 coil pack was used on the 2018 competition vehicle and can be seen in Figure 34.

Figure 34: GM LS2 ignition coil [27]

2.5 Shifting, Power Management, and Circuit Protection

The two most commonly used engine families in the competition, the YFZ Yamaha and CBR Honda engines, both have transmissions built into the crate engine package. In standard usage, these engines are mounted in a motorcycle or ATV, which allows them to use a kick shifter to change gears. For FSAE, the engine is mounted rearward of the driver, which means the normal shifting method is unavailable and a replacement must be designed. Many teams adapt a cable to the stock shift arm and place a hand shifter near the driver; the 2014 Engineering Excellence Award winner is shown in Figure 35. This solution is straightforward to build but requires the driver to remove their hand from the steering wheel every time they need to change gears. A system with fewer requirements of the driver affords them more concentration for other aspects of the race.

Figure 35: Lafayette College's award winning 2014 shifter design [28]

The 2015 WR450F engine used in the FSAE vehicle uses an AC magneto to generate power for the vehicle's electrical systems in addition to charging the battery. The AC magneto consists of a stationary coil called a stator and permanent magnets that rotate with the engine called a rotor. This rotor-stator system is a more compact and lighter alternative to an alternator found on today's modern passenger vehicles. The magneto generates alternating current, but when paired with a rectifier/voltage regulator unit, this alternating current is converted to DC which the vehicle's systems require. The 2015 WR450F generates 160 watts of power at an engine speed of 5500 RPM [29]. A stator and rectifier/regulator module can be seen in Figure 36.

Figure 36: Stator and rectifier/regulator unit [30]

Circuit protection devices were used in order to protect the driver, the wiring, and all components used on the vehicle. A fuse box was designed into the system per Haltech's guidelines for ECU and vehicle protection in an over-current event.

A 200-amp circuit breaker was used in series with the main power distribution line. This is the main source of protection for any short that may occur in the vehicle's wiring or electronics. The value of 200 amps was selected as it is above the starter motor rating of 180 amps. This allows the maximum protection without tripping when starting the vehicle. In the event the 200-amp circuit breaker does trip, it should not be reset until the cause of the high current event has been verified or eliminated. The circuit breaker used can be seen in Figure 37.

Figure 37: 200A circuit breaker protecting entire vehicle electrical system [31]

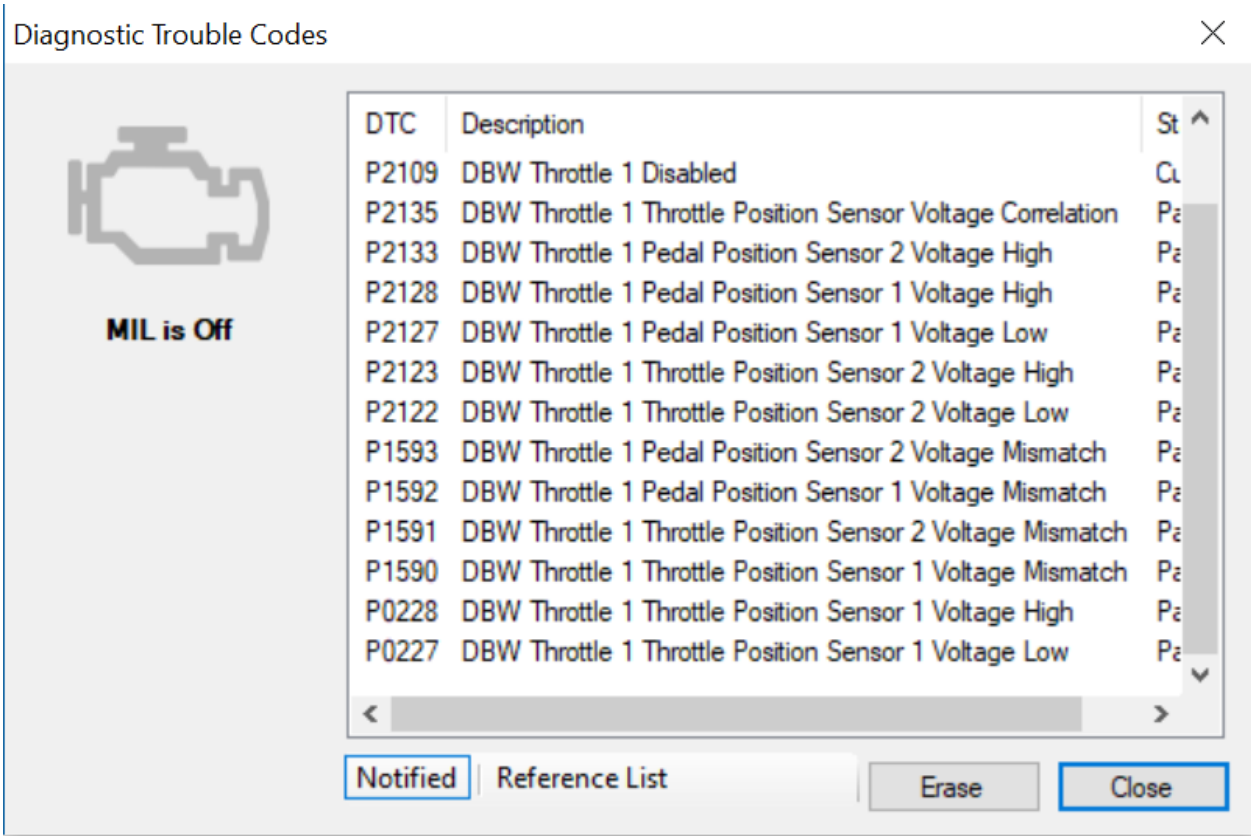
2.6 Safety Compliance

SAE International requires competitors to adhere to a strict set of rules ensuring fair competition and safety. The requirements cover all systems of the vehicle, but this project focused on the electrical systems only. At the beginning of the project, members of this team were unfamiliar with how FSAE operates, and the rules guided the focus of the project far more than initially anticipated.

The strictest regulations are placed on the electronically controlled throttle system. While some teams opt for a mechanically operated throttle using a cable to connect the accelerator pedal to the throttle body, this team decided to implement a drive-by-wire system. The electronic system can be safer than the mechanical counterpart, but only if done correctly. The ETC is governed by rules IC1.11 - IC1.16 in the 2018 official FSAE rulebook [4]. Designing this system to be effective and compliant with the SAE rules requires a strong background in Electrical Engineering, specifically in analog electronics. SAE requires a notice of intent for teams building an ETC system, including proof that members on the team have the technical knowledge required for completing the task. This team's notice of intent can be found on the FSAE website and our completed document can be found in Appendix D.

Once designed and built, a failure mode effect analysis (FMEA) must be submitted to FSAE as confirmation that the team has covered every requirement. The FMEA is a lengthy document with 46 different failure modes requiring analysis. The template is in a separate Excel document submitted with this report.

Rules IC1.11 - IC1.16 covers a wide variety of failure modes of the ETC. Fortunately, most of these failure modes are automatically handled by the Haltech Elite 1500 ECU. This ECU was chosen because it is the least expensive model that includes ETC failure handling. According to Haltech, various failures such as a broken throttle return spring or a butterfly valve jam or breakage are covered by the ECU. The ECU also has two separate processors that constantly check the status of each other and prompt the ECU to enter a safe mode if an internal fault is detected. Additionally, sensor failures and broken electrical connections trigger the ECU to shut down the vehicle [32]. The team tested broken TPS signal connections by inserting a connector in series with the data line. When the engine is running and these connectors were separated, the engine promptly shuts down. Figure 38 shows the diagnostic trouble codes (DTC) that are triggered when an error occurs. These codes proved the ECU was capable of handling this safety requirement.



DTC	Description	St
P2109	DBW Throttle 1 Disabled	Cu
P2135	DBW Throttle 1 Throttle Position Sensor Voltage Correlation	Pa
P2133	DBW Throttle 1 Pedal Position Sensor 2 Voltage High	Pa
P2128	DBW Throttle 1 Pedal Position Sensor 1 Voltage High	Pa
P2127	DBW Throttle 1 Pedal Position Sensor 1 Voltage Low	Pa
P2123	DBW Throttle 1 Throttle Position Sensor 2 Voltage High	Pa
P2122	DBW Throttle 1 Throttle Position Sensor 2 Voltage Low	Pa
P1593	DBW Throttle 1 Pedal Position Sensor 2 Voltage Mismatch	Pa
P1592	DBW Throttle 1 Pedal Position Sensor 1 Voltage Mismatch	Pa
P1591	DBW Throttle 1 Throttle Position Sensor 2 Voltage Mismatch	Pa
P1590	DBW Throttle 1 Throttle Position Sensor 1 Voltage Mismatch	Pa
P0228	DBW Throttle 1 Throttle Position Sensor 1 Voltage High	Pa
P0227	DBW Throttle 1 Throttle Position Sensor 1 Voltage Low	Pa

Figure 38: DTC codes thrown by the ECU upon sensor/connection failure conditions

Full documentation of failure handling can be found in the FMEA.

Brake Plausibility Device

The Brake Plausibility Device is an additional safety subsystem required by SAE International for all vehicles equipped with ETC. The operation of the device is such that engine power is shut down if the throttle body butterfly valve and brake pedal are actuated simultaneously over a certain threshold for a specified amount of time. More specifically and additionally, the device shuts down the engine if the throttle position sensors (TPS) and brake pressure sensors return values indicative of throttle and brake pedal actuation even if the pedals are not actuated, therefore protecting against faulty sensors that cause unpredictable engine acceleration. The purpose of the device is to protect the driver should the accelerator pedal or throttle body stick open, or should a sensor or connection fail, causing the vehicle to accelerate unpredictably and uncontrollably. When this unrequested acceleration occurs, the driver's instinct is usually to actuate the brake pedal. Thus, the device is in place to shut down the engine in order to prevent the engine from fighting the driver's attempt to slow the vehicle using the brakes. The specific requirement, IC1.16, found in the 2018 FSAE competition rules [4] follows:

> A standalone non-programmable circuit must be used on the car such that when braking hard (for example >0.8g deceleration but without locking the wheels) and when the TPS shows that the throttle is greater than 10% open, the power to the electronic throttle and fuel pump must be completely shut down and this must result in the electronic throttle closing to the idle position. The action of removing power to the electronic throttle and fuel pump must occur if the implausibility is persistent for more than one (1) second. This device must be provided in addition to the plausibility checks which are carried out in the ETC which interprets the drivers throttle request and controls the engine throttle position. The Brake Plausibility Device may only be reset by power cycling the Primary Master Switch. The team must devise a test to prove this required function during Technical Inspection. However, it is suggested that it should be possible to achieve this by sending an appropriate signal to the non- programmable circuit that represents a throttle position of more than 10% whilst pressing the brake pedal to a position or with a force that represents hard braking.

In addition to ETC regulations, other rules governed how vehicle systems were designed. These rules ensured the vehicle could be shut off by various mechanical means. The greatest protection of the vehicle's electrical system is a master shutoff switch, often referred to as a battery disconnect switch or boat switch. All power distributed to the vehicle must feed through this switch which is required to be mounted on next to the driver at shoulder height so that team members or competition officials can shut down the car in an emergency. Additionally, the driver has a resettable push button switch next to the steering wheel that shuts off the ECU, however the vehicle remains energized. The same is true for a required brake over-travel switch. This was wired in series with the EMG cut line and shuts down power to the ECU if the brake system loses hydraulic pressure and the pedal reaches the floor of the vehicle.

2.7 Summary

All of the sensors and actuators in this section reflect the choices made by the team in order to ensure that components were readily available, easily troubleshot and compatible with each other in order to integrate the system together. The research and testing done in this section reflect the desire to make this system replicable for future iterations of the car with minimal component change and seeks to provide lasting information on the system in order for it to be referenced by future teams and allow significant progress on the currently implemented setup instead of the backtracking that has been done previously by this team and by others in order to make a functioning vehicle.

3. Proposed Approach

The proposed approach to this project included three main components: the engine wiring harness, the electric shifting system, and driver interface components such as the gear indicator sensor. Citing documentation shortcomings and reliability issues with the previous vehicle, our approach sacrificed non-critical sensing features such as suspension angle and GPS tracking for reliability and replicability of the main engine functions.

3.1 Wiring Harness

The engine wiring approach taken was very forward-looking, with the objective that people of other disciplines can understand and utilize the wiring for future years without the assistance of this MQP team. For this reason, the team decided to develop two engine wiring harnesses. The first wiring harness, known as the test-stand wiring harness, is meant to be used this year and in all future years as the basis for engine tune development. The second wiring harness, known as the vehicle wiring harness, is application specific in its dimensions and routing and is only designed for use on one vehicle. This competition year, the wiring harnesses were to be designed in parallel with the mechanical design of the vehicle which allowed electrical design work to be completed before the engine was installed in the chassis of the car.

The wiring harnesses were designed to be modular, using quick release electrical connectors seen in modern vehicles. Engine sensors and actuators should only need to be installed once, so the wiring should be done such that cutting and soldering is never needed after first installation, regardless of removal of the wiring harness. Therefore, proprietary connectors were sourced for engine sensors and actuators with their own quick release receptacles, and pigtails were attached to all other sensors and actuators. At the end of each pigtail, a quick release connector was installed such as the one seen in Figure 39.

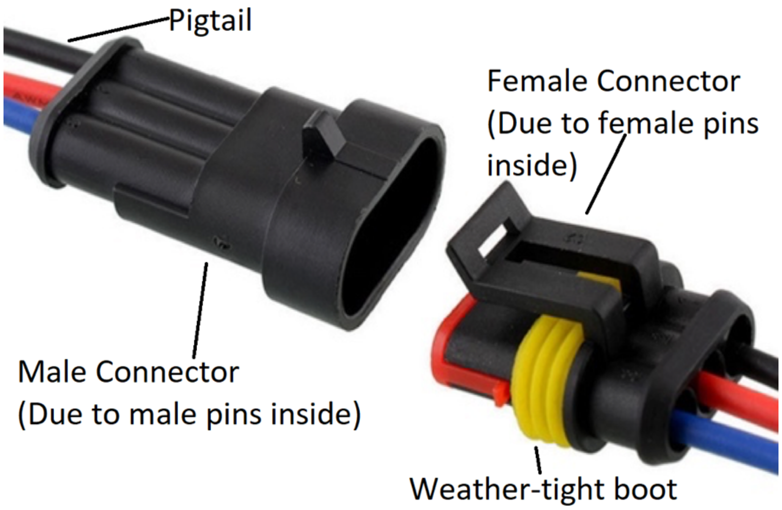
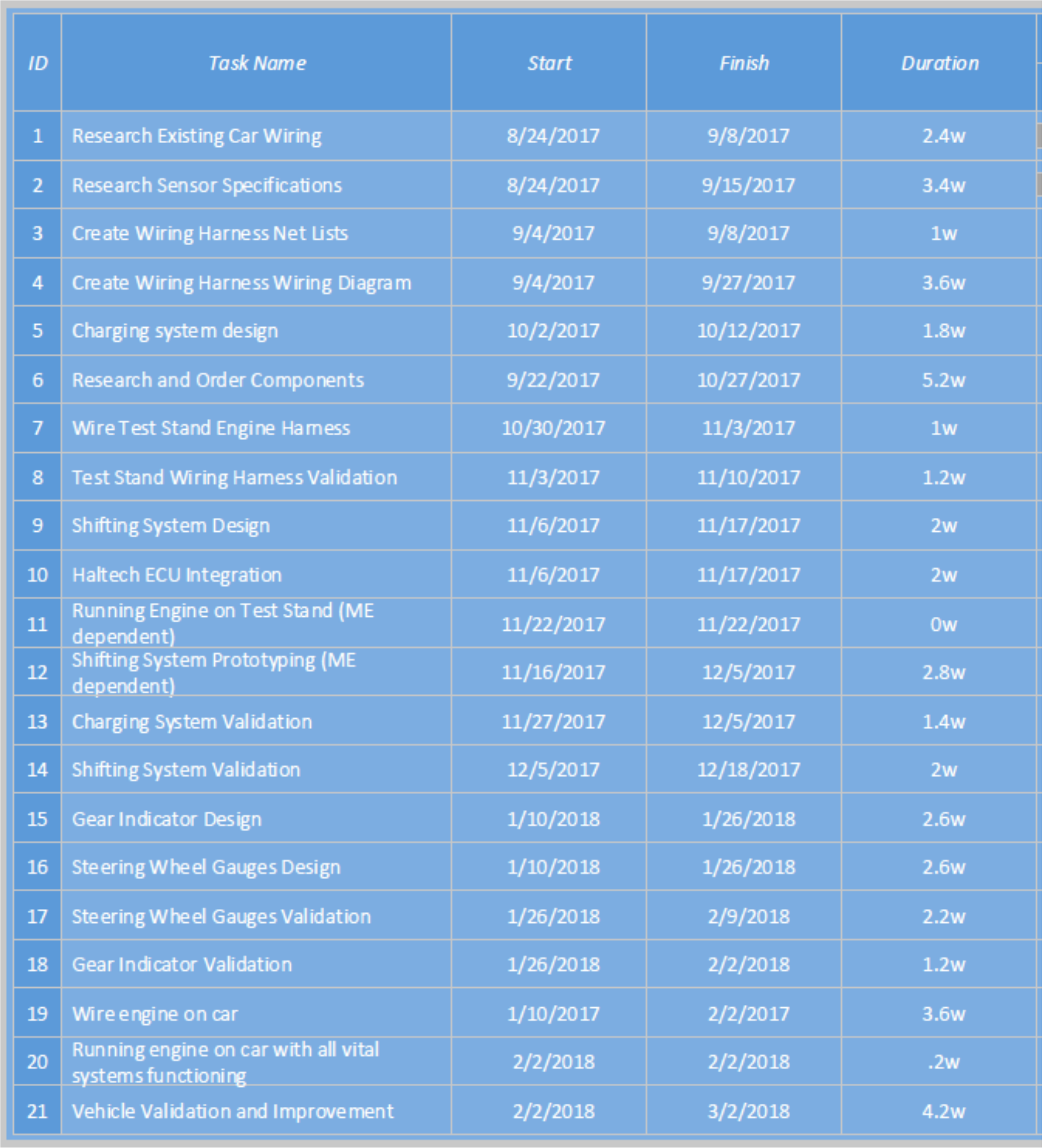


Figure 39: Waterproof electrical connector [33]

With this design, the engine wiring harness is quickly and easily detachable from the engine.

The function of the test stand wiring harness is to allow for quick plug-and-play installation for future FSAE teams to test the functionality of the engine. Due to the relatively short timeline of the vehicle's development, it is imperative to get the engine running as quickly as possible - even before the chassis of the vehicle is complete. The proposed timeline which was largely followed, excluding delays with our partner team, is seen in Figure 40.



ID	Task Name	Start	Finish	Duration
1	Research Existing Car Wiring	8/24/2017	9/8/2017	2.4w
2	Research Sensor Specifications	8/24/2017	9/15/2017	3.4w
3	Create Wiring Harness Net Lists	9/4/2017	9/8/2017	1w
4	Create Wiring Harness Wiring Diagram	9/4/2017	9/27/2017	3.6w
5	Charging system design	10/2/2017	10/12/2017	1.8w
6	Research and Order Components	9/22/2017	10/27/2017	5.2w
7	Wire Test Stand Engine Harness	10/30/2017	11/3/2017	1w
8	Test Stand Wiring Harness Validation	11/3/2017	11/10/2017	1.2w
9	Shifting System Design	11/6/2017	11/17/2017	2w
10	Haltech ECU Integration	11/6/2017	11/17/2017	2w
11	Running Engine on Test Stand (ME dependent)	11/22/2017	11/22/2017	0w
12	Shifting System Prototyping (ME dependent)	11/16/2017	12/5/2017	2.8w
13	Charging System Validation	11/27/2017	12/5/2017	1.4w
14	Shifting System Validation	12/5/2017	12/18/2017	2w
15	Gear Indicator Design	1/10/2018	1/26/2018	2.6w
16	Steering Wheel Gauges Design	1/10/2018	1/26/2018	2.6w
17	Steering Wheel Gauges Validation	1/26/2018	2/9/2018	2.2w
18	Gear Indicator Validation	1/26/2018	2/2/2018	1.2w
19	Wire engine on car	1/10/2017	2/2/2017	3.6w
20	Running engine on car with all vital systems functioning	2/2/2018	2/2/2018	.2w
21	Vehicle Validation and Improvement	2/2/2018	3/2/2018	4.2w

Figure 40: Project timeline

In order to run the engine before it is installed, it can be placed on a test stand complete with fuel, a radiator and fan, a battery, an intake, and an exhaust, such as the one seen in Figure 41.

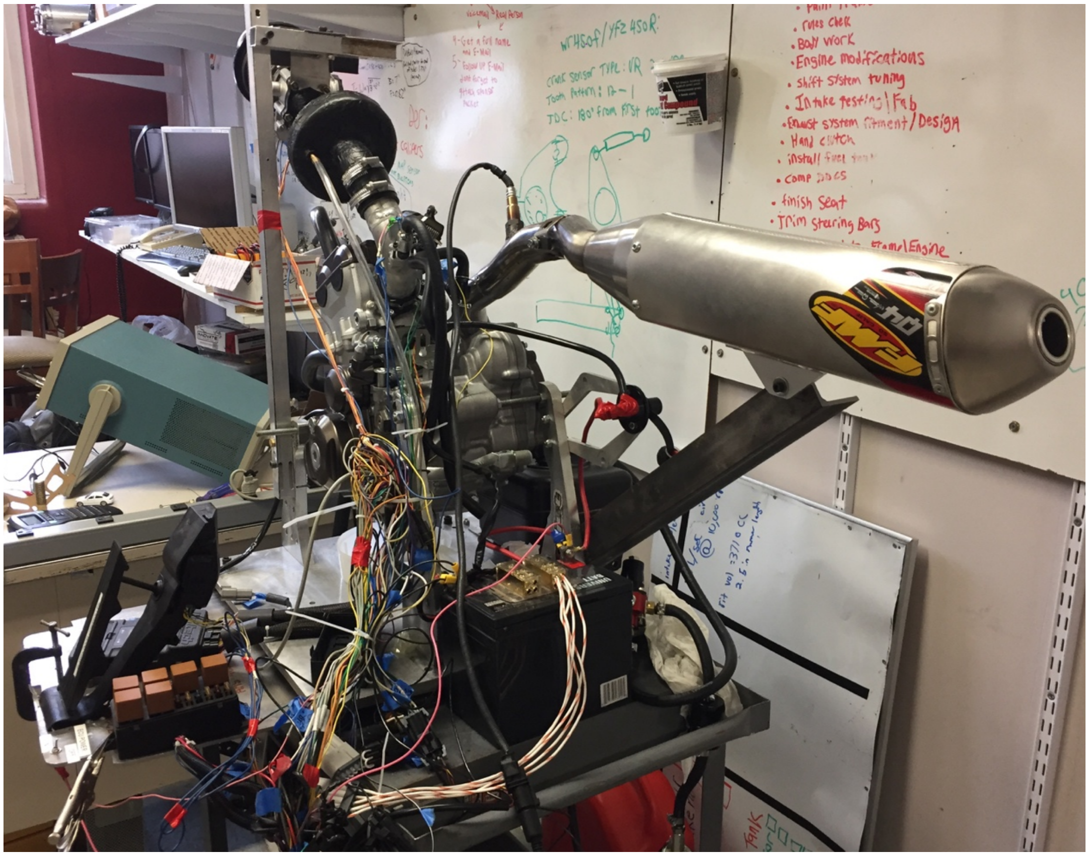


Figure 41: Engine on test stand with test stand wiring harness

With the standalone test stand wiring harness, the only wiring necessary is for the initial installation of the engine sensors and actuators. Once this is complete, the connectors can be plugged into the engine and the ECU, and the engine is ready to be started and tuned. All of this is able to be done in parallel with but separate from any chassis work.

The vehicle wiring harness is separate from the test stand wiring harness and is custom for every vehicle. For each vehicle, the length and routing of the wires will be different, but the electrical connections will be the same as the test stand harness. This is assuming that all electrical design work necessary was completed using the test stand wiring harness as intended. Therefore, the vehicle wiring harness can be directly modeled after the test stand wiring harness and is a carbon copy of the test stand wiring harness.

3.2 Shifting System

The 2016 FSAE team took the unique approach of using an electrically controlled pneumatic system for the shifting. Momentary switches mounted on the steering wheel allowed the driver to change gears without removing their hand from the wheel, which earned the design positive comments from judges at competition. However, the design has two major drawbacks. Though faster than a hand shifter, the system is not quick to change gears due to a lack of timing optimization on top of limitations of the design itself. The system actuates the clutch for every shift which is not required, introducing delays. The larger issue with the system is the associated weight cost to the vehicle. The system includes an onboard air tank, compressor, plumbing, three separate pneumatic cylinders, and all the associated electrical components, seen in Figure 42. In a competition where added weight is highly detrimental, reusing the design of the pneumatic system should be avoided if possible, while keeping the advantages of electrically controlled gear changes.

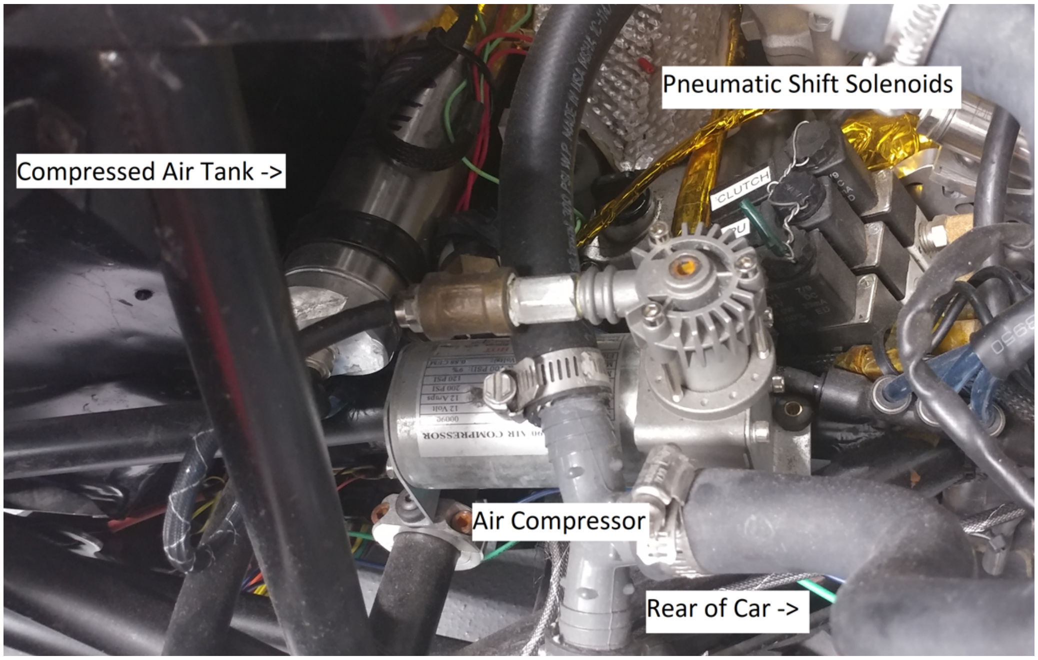


Figure 42: 2016 FSAE pneumatic shift system

The built-in shift mechanism of the transmission requires relatively high torque for a small amount of time and distance to complete a gear change. This suggests that a DC motor could be used as an actuator, since they have high stall torque, especially given the low duty cycle requirements. Even though the motor itself is dense, the overall system weight is lower than the pneumatic system and has potential for greater adjustability using different motors. The DC motor system also offers great simplification over the pneumatic design, increasing reliability. Considering this, our team decided to design a shifting system for this year's car based on a DC motor. We initially looked at servos for position data, but torque was insufficient.

3.3 Gear Indicator Sensor

The gear indicator sensor idea was proposed early in the project, but the first design revision was drafted when team member James Beucler was posed a design question in a job interview with Analog Devices (ADI). With guidance from Mr. Paul Blanchard, an ADI employee, a design was formed using only one signal wire and one power wire. The design utilized a resistor divider network between each contact on the sensor. At the first contact, gear 1, the measured voltage is zero volts as the point of measurement is ground. As gears are upshifted, the measured voltage becomes higher as there are more resistors between the point of measurement and ground. At the last contact, gear 5, the measured voltage is highest. Each measured voltage between the voltage divider resistors is representative of the current gear. This data is easily digitally processed using an analog-to-digital converter (ADC) in order to light a seven-segment display on the driver's steering wheel with the corresponding gear; a critical piece of information for the driver during a race.

3.4 Summary

The approach made by this team represents a significant increase in the consistency, modularity, and reliability of the vehicle. The attempt of these practices was to ensure electronics maintain function for a prolonged period of time over previous vehicles and therefore are capable of being used and modified for years to come on test vehicles or in future iterations of the Formula SAE vehicle. By increasing the simplicity over previous vehicles and using connectors this team hopes to provide a more practical electrical design.

4. Implementation & Methodology

The design and implementation of electrical systems had to be performed in parallel to meet the strict competition attendance deadlines. The design of the engine wiring harness was prioritized. Once the design was finished, the wiring harness was installed while design work began on the shifting system. Special care was taken to document all design details and all problems encountered as future teams will likely encounter similar setbacks. This section should be reviewed by future teams before design work begins.

4.1 Critical Vehicle Systems

The design of the test stand wiring harness began with many unknowns. The first unknown was which engine sensors and actuators were needed to run the engine. This was determined by the team's knowledge of electronically fuel injected engines and by research into previous WPI FSAE designs. Once these components were selected, the next unknown was the pinout of each engine sensor and actuator. These were determined through research of datasheets from the manufacturer or implementations on previous years' designs [6]. The LS2 coil pinout, seen in Figure 43, was highly valuable as it is wired backwards compared to the LS1 coil which has been used previously.

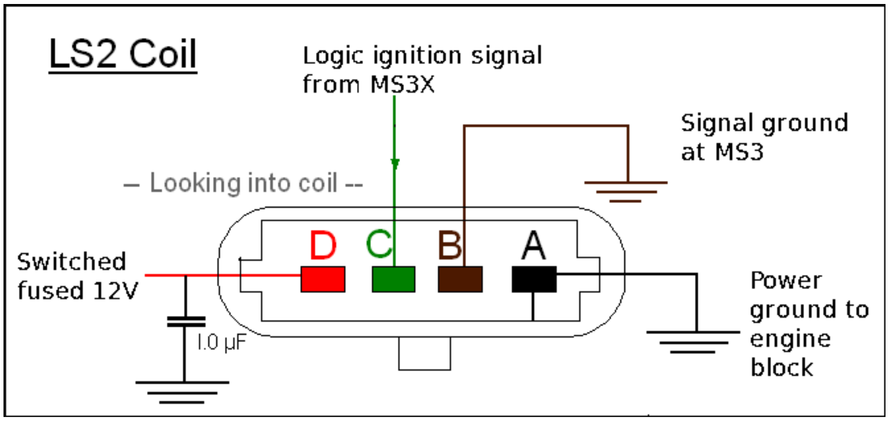
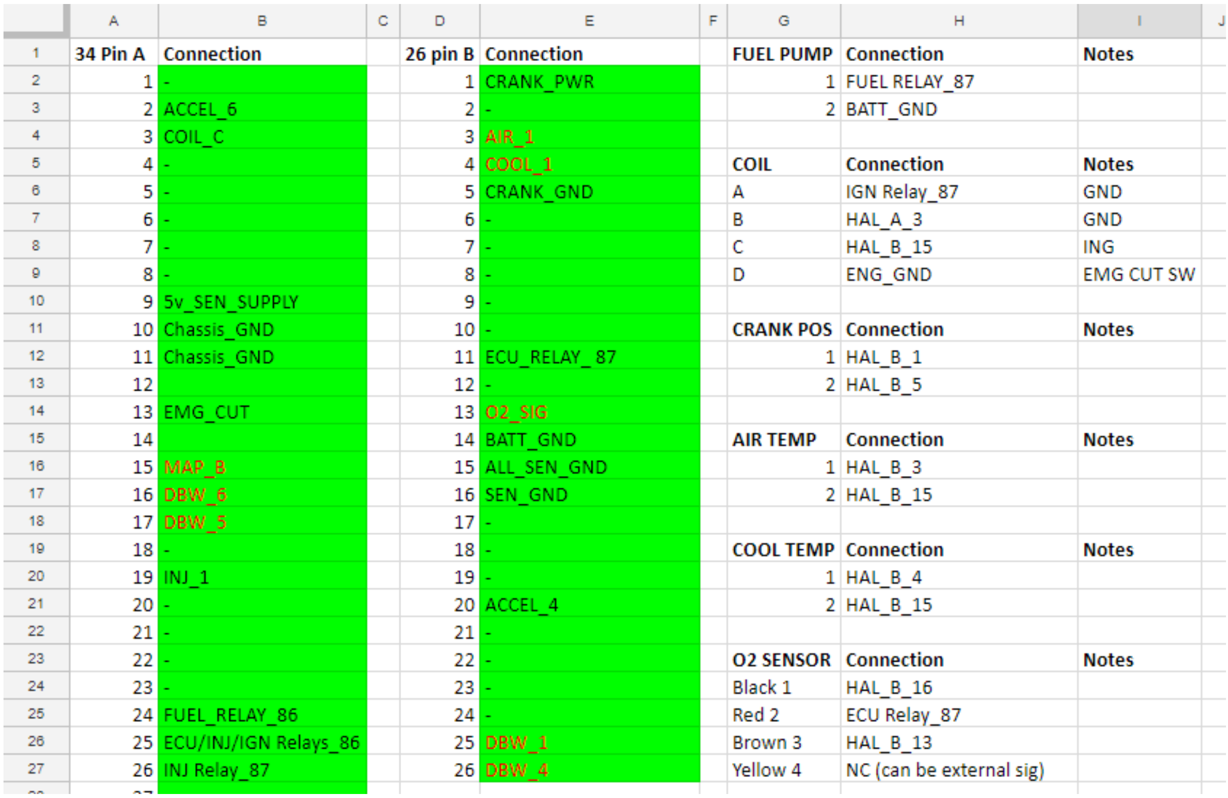


Figure 43: LS2 ignition coil wiring diagram [34]. Note the tab on the bottom showing the orientation

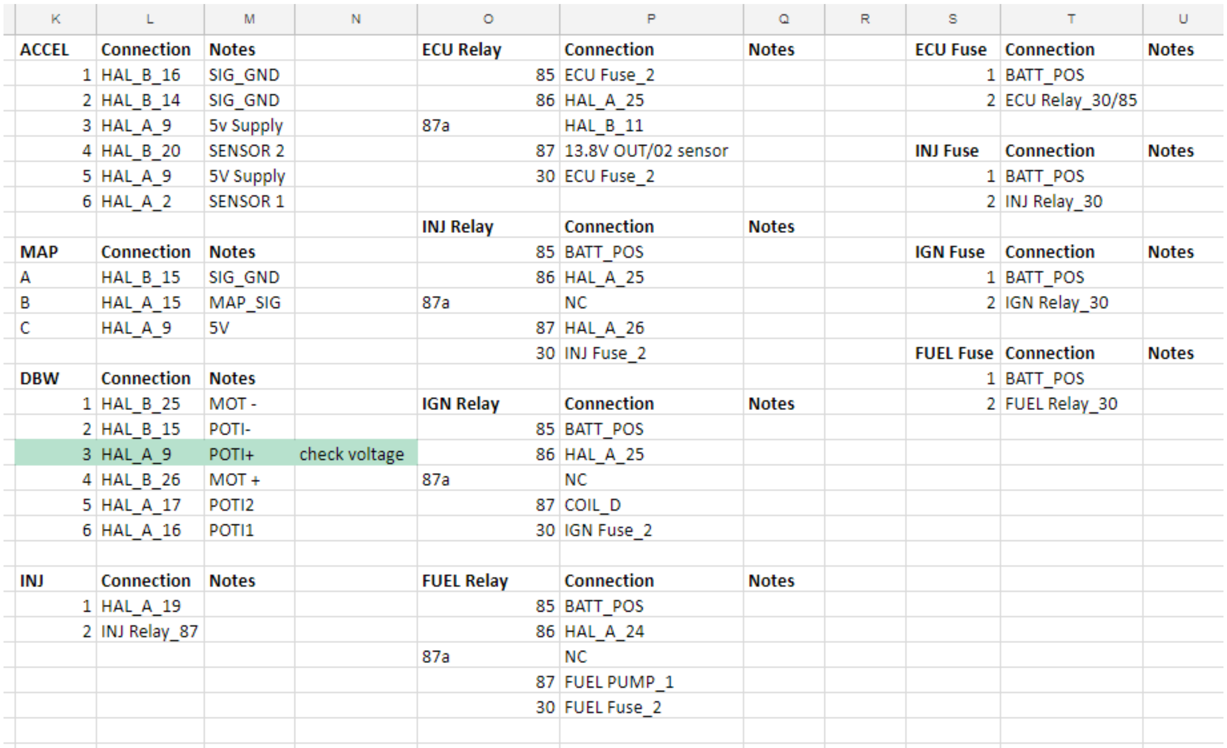
Since the inputs and outputs (I/O) of the Haltech ECU were given, the next major unknowns were which ECU I/O port could be used for each sensor or actuator and how to make this connection.

The Haltech ECU includes 60 electrical connections to tie to various sensors and actuators on the engine. Although the 1-cylinder engine used in this vehicle did not require the use of all 60 connections, organization was still critical. The first tool used to organize the task was Microsoft Excel, where the researched pinouts of each sensor and actuator were documented. Next, another spreadsheet was used to assign the Haltech ECU pin to be used with each sensor/actuator pin. This was done at each end of the wiring harness, the ECU side and the engine side, and then cross-checked in order to ensure accuracy. Our Excel sheet can be seen below in Figure 44 and Figure 45.



	A	B	C	D	E	F	G	H	I
1	**34 Pin A**	**Connection**		**26 pin B**	**Connection**		**FUEL PUMP**	**Connection**	**Notes**
2	1	-		1	CRANK_PWR		1	FUEL RELAY_87	
3	2	ACCEL_6		2	-		2	BATT_GND	
4	3	COIL_C		3	AIR_1				
5	4	-		4	COOL_1		**COIL**	**Connection**	**Notes**
6	5	-		5	CRANK_GND		A	IGN Relay_87	GND
7	6	-		6	-		B	HAL_A_3	GND
8	7	-		7	-		C	HAL_B_15	ING
9	8	-		8	-		D	ENG_GND	EMG CUT SW
10	9	5v_SEN_SUPPLY		9	-				
11	10	Chassis_GND		10	-		**CRANK POS**	**Connection**	**Notes**
12	11	Chassis_GND		11	ECU_RELAY_87		1	HAL_B_1	
13	12			12	-		2	HAL_B_5	
14	13	EMG_CUT		13	O2_SIG				
15	14			14	BATT_GND		**AIR TEMP**	**Connection**	**Notes**
16	15	MAP_B		15	ALL_SEN_GND		1	HAL_B_3	
17	16	DBW_6		16	SEN_GND		2	HAL_B_15	
18	17	DBW_5		17	-				
19	18	-		18	-		**COOL TEMP**	**Connection**	**Notes**
20	19	INJ_1		19	-		1	HAL_B_4	
21	20	-		20	ACCEL_4		2	HAL_B_15	
22	21	-		21	-				
23	22	-		22	-		**O2 SENSOR**	**Connection**	**Notes**
24	23	-		23	-		Black 1	HAL_B_16	
25	24	FUEL_RELAY_86		24	-		Red 2	ECU Relay_87	
26	25	ECU/INJ/IGN Relays_86		25	DBW_1		Brown 3	HAL_B_13	
27	26	INJ Relay_87		26	DBW_4		Yellow 4	NC (can be external sig)	

Figure 44: Sensor and actuator pinout spreadsheet



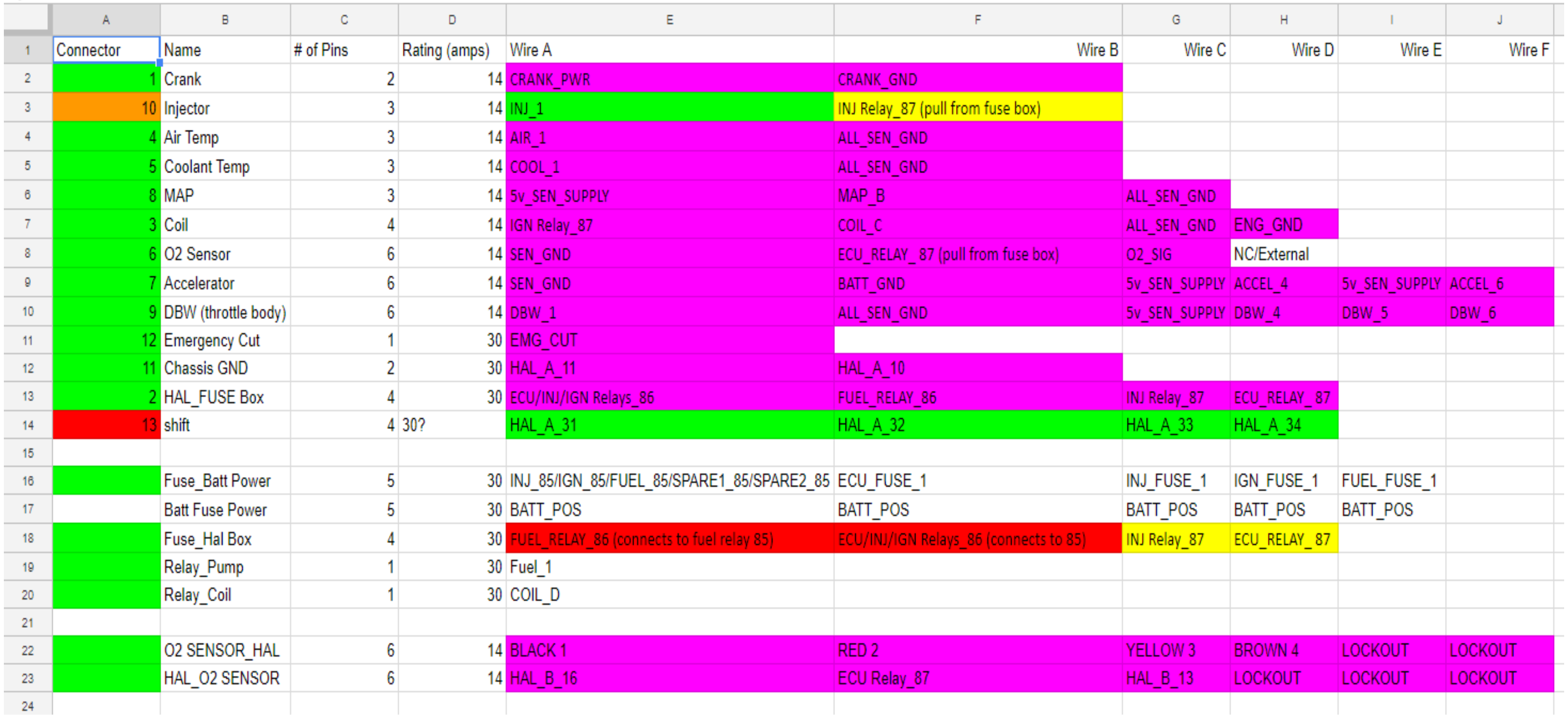
K	L	M	N	O	P	Q	R	S	T	U
ACCEL	Connection	Notes		ECU Relay	Connection	Notes		ECU Fuse	Connection	Notes
1	HAL_B_16	SIG_GND		85	ECU Fuse_2			1	BATT_POS	
2	HAL_B_14	SIG_GND		86	HAL_A_25			2	ECU Relay_30/85	
3	HAL_A_9	5v Supply		87a	HAL_B_11					
4	HAL_B_20	SENSOR 2		87	13.8V OUT/02 sensor			INJ Fuse	Connection	Notes
5	HAL_A_9	5V Supply		30	ECU Fuse_2			1	BATT_POS	
6	HAL_A_2	SENSOR 1						2	INJ Relay_30	
				INJ Relay	Connection	Notes				
MAP	Connection	Notes		85	BATT_POS			IGN Fuse	Connection	Notes
A	HAL_B_15	SIG_GND		86	HAL_A_25			1	BATT_POS	
B	HAL_A_15	MAP_SIG		87a	NC			2	IGN Relay_30	
C	HAL_A_9	5V		87	HAL_A_26					
				30	INJ Fuse_2			FUEL Fuse	Connection	Notes
DBW	Connection	Notes						1	BATT_POS	
1	HAL_B_25	MOT -		IGN Relay	Connection	Notes		2	FUEL Relay_30	
2	HAL_B_15	POTI-		85	BATT_POS					
3	HAL_A_9	POTI+	check voltage	86	HAL_A_25					
4	HAL_B_26	MOT +		87a	NC					
5	HAL_A_17	POTI2		87	COIL_D					
6	HAL_A_16	POTI1		30	IGN Fuse_2					
INJ	Connection	Notes		FUEL Relay	Connection	Notes				
1	HAL_A_19			85	BATT_POS					
2	INJ Relay_87			86	HAL_A_24					
				87a	NC					
				87	FUEL PUMP_1					
				30	FUEL Fuse_2					

Figure 45: Sensor and actuator pinout spreadsheet (continued)

To assist with organization of these spreadsheets, a naming convention was developed. First, following Haltech's naming convention of the ECU connectors, the 34-pin connector was called connector A and the 26-pin connector was called connector B. At the ECU side, the names of each sensor/actuator pin were entered at the corresponding ECU pin as the name of the sensor/actuator used, followed by an underscore and the sensor/actuator pin number. For example, pin 19 of the ECU connector A was for pin 1 of the fuel injector, so INJ_1 was listed at pin 19. The same was true for the sensor/actuator end. Pin 1 of the fuel injector was named HAL_A_19.

The wiring net list was now complete, but it included a lot of information and was hard to read. To alleviate this issue, an electrical schematic was developed. Cadence Design Entry, a part of the Cadence's suite of design software, was the industry standard schematic capture software tool chosen to create the main schematic of the wiring harness. This schematic, displaying ECU connections, sensor/actuator connections, as well as fuse and relay box connections, can be seen in Appendix E. The schematic served as a critical reference for performing the physical wiring of each wiring harness in the implementation of the design plan.

The implementation of the test stand wiring harness design involved connecting the ECU to the engine sensors/actuators in such a way that the harness could be quickly removed or installed without the need for cutting or soldering wires. For the test stand wiring harness, a Haltech ECU wiring pigtail was used, purchased from Haltech in a previous year's project. This included all 60 connections the Haltech is able to make. The first step in adapting this wiring pigtail to create the test stand wiring harness was labeling each wire with its intended function, following the convention mapped out in the schematic. The method chosen was slow but accurate and involved first testing for continuity using a multimeter, then wrapping each wire with a masking tape tag and manually writing each connection. At the end, each wire without a label was not to be used and labeled as "NC" for "no connect," a standard convention in electrical engineering. Next, with all wires labeled, each of the sensor or actuator connections was grouped together with a zip tie. A document was created that reflected what connections were being put in each connector in order to maintain continuity between connectors and make sure signals were not mismatched, seen in Figure 46.



	A	B	C	D	E	F	G	H	I	J
1	Connector	Name	# of Pins	Rating (amps)	Wire A	Wire B	Wire C	Wire D	Wire E	Wire F
2	1	Crank	2	14	CRANK_PWR	CRANK_GND				
3	10	Injector	3	14	INJ_1	INJ Relay_87 (pull from fuse box)				
4	4	Air Temp	3	14	AIR_1	ALL_SEN_GND				
5	5	Coolant Temp	3	14	COOL_1	ALL_SEN_GND				
6	8	MAP	3	14	5v_SEN_SUPPLY	MAP_B	ALL_SEN_GND			
7	3	Coil	4	14	IGN Relay_87	COIL_C	ALL_SEN_GND	ENG_GND		
8	6	O2 Sensor	6	14	SEN_GND	ECU_RELAY_87 (pull from fuse box)	O2_SIG	NC/External		
9	7	Accelerator	6	14	SEN_GND	BATT_GND	5v_SEN_SUPPLY	ACCEL_4	5v_SEN_SUPPLY	ACCEL_6
10	9	DBW (throttle body)	6	14	DBW_1	ALL_SEN_GND	5v_SEN_SUPPLY	DBW_4	DBW_5	DBW_6
11	12	Emergency Cut	1	30	EMG_CUT					
12	11	Chassis GND	2	30	HAL_A_11	HAL_A_10				
13	2	HAL_FUSE Box	4	30	ECU/INJ/IGN Relays_86	FUEL_RELAY_86	INJ Relay_87	ECU_RELAY_87		
14	13	shift	4	30?	HAL_A_31	HAL_A_32	HAL_A_33	HAL_A_34		
15										
16		Fuse_Batt Power	5	30	INJ_85/IGN_85/FUEL_85/SPARE1_85/SPARE2_85	ECU_FUSE_1	INJ_FUSE_1	IGN_FUSE_1	FUEL_FUSE_1	
17		Batt Fuse Power	5	30	BATT_POS	BATT_POS	BATT_POS	BATT_POS	BATT_POS	
18		Fuse_Hal Box	4	30	FUEL_RELAY_86 (connects to fuel relay 85)	ECU/INJ/IGN Relays_86 (connects to 85)	INJ Relay_87	ECU_RELAY_87		
19		Relay_Pump	1	30	Fuel_1					
20		Relay_Coil	1	30	COIL_D					
21										
22		O2 SENSOR_HAL	6	14	BLACK 1	RED 2	YELLOW 3	BROWN 4	LOCKOUT	LOCKOUT
23		HAL_O2 SENSOR	6	14	HAL_B_16	ECU Relay_87	HAL_B_13	LOCKOUT	LOCKOUT	LOCKOUT
24										

Figure 46: Pinout verification spreadsheet

The colors represented each check of the wiring in accordance with the engine wiring harness procedure in Appendix B. Green meant one person had checked it off in addition to the person who wired it, and purple meant the connection had been verified by two additional team members. Red showed potential issues that were either incorrect or required other attention. After all wires in the pigtail were organized, the connector installation began. It is important to note that the best practice involves completing one sensor or actuator connection at a time to avoid losing track of wires.

The connector assembly procedure was straightforward but took great dexterity to be done correctly. First, the correct connector was chosen based on the number of wires going to the sensor or actuator. Some connectors used as few as one wire, and some used up to six wires. Once selected, the first wire was stripped or removed of insulating material about ⅜ inch in length. Next, the easiest step to miss was to insert the rubber moisture seal onto the wire and pushed out of the way with the smaller end facing the stripped end of the wire. Next, the metal pin or receptacle (male or female, depending on the connector side) was crimped onto the bare wire with the connector crimping tool. All of these components can be seen in Figure 47.

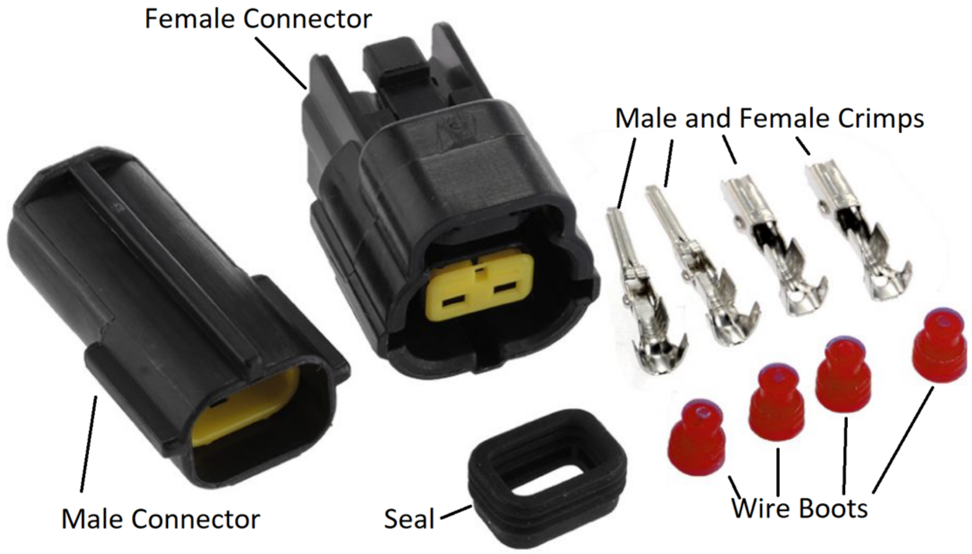


Figure 47: Electrical connector components [35]

Crimping on the metal connection required a few steps itself: first, the wire was inserted into the metal pin or receptacle. Next, the rubber moisture seal was slid to the end of the metal pin or receptacle, where it was crimped with the wire using the largest crimp size. This step was important as it held the metal pin or receptacle in place for the additional crimping. The middle of the pin or receptacle has two metal fins that stick up - the next step was to crimp these to the wire carefully using smaller and smaller crimp sizes until the crimp was tight. The open end lined up with the “w” shaped side of the crimping tool, and the closed end lined up with the rounded side of the crimping tool. To get started, however, sometimes the rounded side could be used on the closed end of the metal pin or receptacle.

Once the metal pin or receptacle was crimped firmly, the wire was soldered to the pin or receptacle at the point of the crimp. This is not always performed on vehicles but adds strength and ultimately reliability to the connector. In cases of misuse, the wire is sometimes pulled on rather than the plastic connector when disconnecting the wiring harness. This small step protects the crimp from coming undone in this case. Once the solder cools, the wire can be inserted into the its corresponding location in the plastic connector, mapped in the schematic. Once a small click is heard or felt, the wire is secure. This procedure is repeated for each wire on each side of the connector.

The vehicle-specific wiring harness was built in a methodical manner. First, a color-coding system was created for organizational purposes. While color coding simplifies initial installation, its main purpose is to make troubleshooting easier in the future in the event of a system malfunction or broken connection. Three main colors were chosen for power and ground: red for +12V, pink for +5V, and black for all grounds. All sensor and actuator wires followed Haltech’s coloring convention as closely as possible, which can be seen in their wiring diagram found in Appendix A. Haltech’s convention designated different colors for each data line which makes installing multi-pin electrical connectors much easier and also allows for faster troubleshooting.

Wiring placement was planned and debated extensively. Special care was taken to protect the wires from damaging conditions on the vehicle. For example, areas of high heat such as the exhaust pipe and engine were avoided. Areas with sharp edges, high friction, or potential for driver interference were also avoided. Some collaboration with the mechanical engineering team was necessary to confirm proper and safe fitment. This included crossing the frame of the vehicle near the drive chain. If the chain were to break, the wires would be damaged causing dangerous shorting while taking the vehicle’s electrical systems out of commission. For this reason, a simple steel chain guard was constructed to fit around the chain with the wires safely crossing on top.

Using the Cadence wiring map created for the test stand wiring harness as a guide found in Appendix E, the wires were organized and laid. When laying wires, the general area of each sensor placement relative to the ECU must be known. Every wire should have a minimum of six inches of extra length at each end if exact placement is known; otherwise wires should be left as long as necessary until final placement of sensors is known, without wasting too much wire. The best way to simulate wiring position is to run the wires through loose zip ties on the frame simulating because final zip tie installation can cause wires to be just a few inches too short when wires are pulled in on corners. After each wire for a single sensor or actuator was run and cut, the wires were bundled together with another zip tie and labeled with the sensor or actuator name. The color of each wire identified its location in the connector, but each wire was numbered with its pin number to make it perfectly clear.

Once the base of the wiring harness was constructed, consisting of basic sensors and actuators for engine operation only, the wires were fed through expandable wire loom for protection. The other layers were assembled similarly, following the modular design plan of the vehicle's electrical systems. The purpose of this method of assembly was so that non-critical subsystems can be altered for future years' projects while the base wiring harness always allows engine operation.

In 2012, Yamaha's WR dirt bike lineup was upgraded to use electronic fuel injection (EFI). An electronically fuel injected engine requires a variety of sensors and actuators as well as an engine control unit (ECU) in order to operate, all requiring more electrical power. In order to keep up with the increased electrical demand, Yamaha upgraded the stator (the stationary coil of wire used to generate electricity as the permanent magnets rotate around it) to a larger design while also utilizing three phase power generation. By using a three-phase design, more power is able to be generated for the same diameter rotor used in the generator.

The upgraded design is capable of producing 160 watts of power at an engine speed of 5500 RPM, and an estimated 60 watts at 1700 RPM [29]. The voltage is regulated between 14.1V and 14.9V (both unloaded) by the voltage regulator. Unfortunately, this power output is over 100 watts less than the previous year's design. The previous design used a YFZ450R sport ATV (all-terrain vehicle) engine which used a larger stator because space and weight savings are not as critical on ATVs as on dirt bikes. In addition, the previous year's design used an aftermarket stator upgrade, capable of exceeding the stock rating of 266 watts at 5500 RPM [5].

After much research including consulting various aftermarket stator manufacturers including TrailTech and Ricky Stator as well as the original manufacturer Yamaha, it was determined that the stator in the 2015 WR450F is not currently upgradable. When Yamaha upgraded the charging system in 2012, the stator size was increased by the maximum allowable amount to fit in the same size crank case. Therefore, the power budget of the 2017-2018 FSAE competition vehicle is limited to 160 watts at 5500 RPM. In the future, it is recommended to use the YFZ ATV engine instead of the WR450F engine due to this limitation.

The given power budget was workable but not ideal. Therefore, additional electrical system upgrades were considered in the event that the electrical load exceeds the power output of the AC generator momentarily. The single greatest upgrade possible was a battery with increased energy storage. Starting with greater storage gives a greater buffer in available energy during race time. In a racing vehicle, however, this greater storage is not ideal as a higher capacity battery usually means larger size and much greater weight. It was determined that the solution to this issue was to purchase a lithium-ion battery of the same size which has a much higher energy capacity, but a much lower weight than the comparable lead-acid battery of the same energy capacity. The battery chosen was manufactured by Battery Tender and had an impressive 96 watt-hours of storage while weighing only 3.75 pounds [36].

Another upgrade performed was the rectifier/regulator unit. For dirt bikes and ATVs, the rectifier that turns AC to DC is packaged with the voltage regulator that does not allow the voltage to go over ~14-15 volts in high RPM operation. The 35-amp OEM unit from Yamaha was considered as it was designed to work with the OEM stator. However, if a stator upgrade ever becomes available for the WR450F, the team decided it would be best to use a rectifier/regulator that can handle the additional power to avoid any necessary rewiring. The unit used is capable of handling 50 amps of current [37]. While this does not increase the power output of the magneto, it gives the ability to replace the stator in the future on the fly for one with a higher power output without other wiring considerations.

The wiring of the charging system is very simple. The three-phase AC output of the magneto is connected to the AC input of the rectifier/regulator. The positive and negative DC outputs of the rectifier connect to the positive and negative terminals of the battery, respectively. A wiring diagram can be seen in Figure 48.

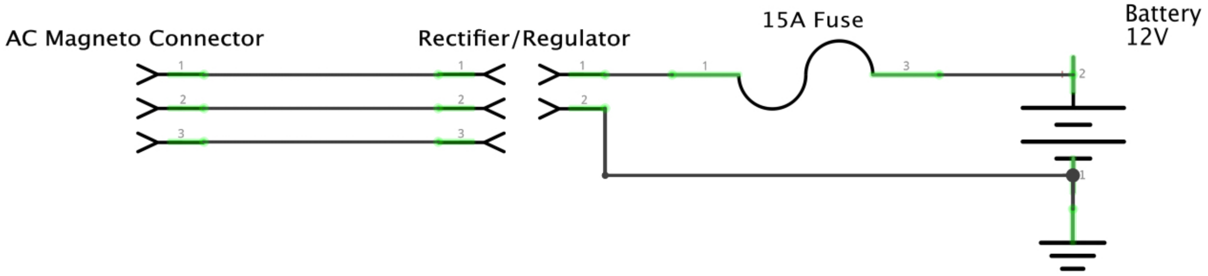


Figure 48: Charging system schematic

The shifting system was completely overhauled for the 2018 vehicle to use a DC motor. To select an appropriate motor, we first assumed the linkage between the motor output and the shifter input was frictionless and did not change torque. We then measured three parameters of the transmission: the maximum torque on the selector shaft to change gears, the return to center torque of the selector shaft, and the angular displacement of the input shaft to change gears. To do this, we attached the standard shift arm to the input shaft. We measured the length of the shift arm and pulled on it with a scale to calculate torques. We were also able to measure angles at the same time; this data is given in Table 4. Using the ATV and dirt bike riding experience of some team members as a guideline, we also set an ambitious but achievable goal for shift speed. From these data points we were able to calculate minimum performance characteristics for the motor we needed. We made sure to source a motor that exceeded our minimum requirements to account for linkage friction and other non-idealities of the system.

To narrow the scope of search for a specific model of motor to buy, we decided to start with a supplier commonly used for FIRST Tech Challenge (FTC) hardware. We chose to start with them because FTC robots have similar system requirements: low weight, high power density, and high torque. In their catalog we found a number of units that met or exceeded our performance requirements. We picked the lightest of the options available, which allows us to upgrade to a more powerful unit in the future if we need to. Shortly after we purchased the motor the gearbox output shaft was changed, meaning that future teams may need to modify the linkage slightly.

Table 4: Shifting system requirements and specifications

	Measured	Motor Requirements	775 Motor, PG75 gearbox [38]
Angle to Next Gear	15 degrees	N/A	N/A
Time to Next Gear	100 ms	38 rpm	75 rpm free speed
Torque to Next Gear	10 lb-ft	12 lb-ft	16.6 lb-ft stall torque

To change gears, the motor needs to rotate one way for a higher gear and the other way for a lower gear. Two momentary switches are used to control the system, one for upshifts and one for downshifts. The circuit needs to operate the motor in the correct direction when one of the switches is pressed but not both. The team member designing the control circuitry realized this is very similar to the wiring for a dual controlled house light: the light is on when one of the switches is flipped, but not both or neither seen in Figure 49.

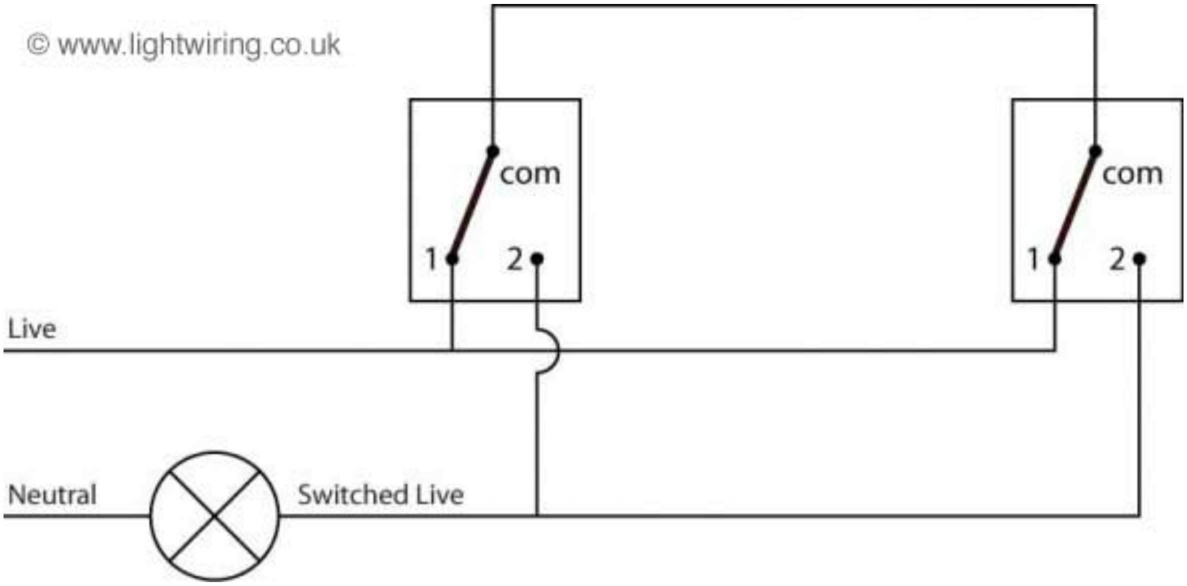


Figure 49: Shift button wiring top-level diagram, similar to dual light switch wiring [39]

The first wiring design is very similar to the house wiring; the motor is grounded on both sides at steady state. When a button is pressed the associated relay flips, applying rail voltage to that side of the motor. When both buttons are pressed, both sides of the motor are held high and the motor does not rotate. This meets many of the design requirements of the goal circuit seen in Figure 50.

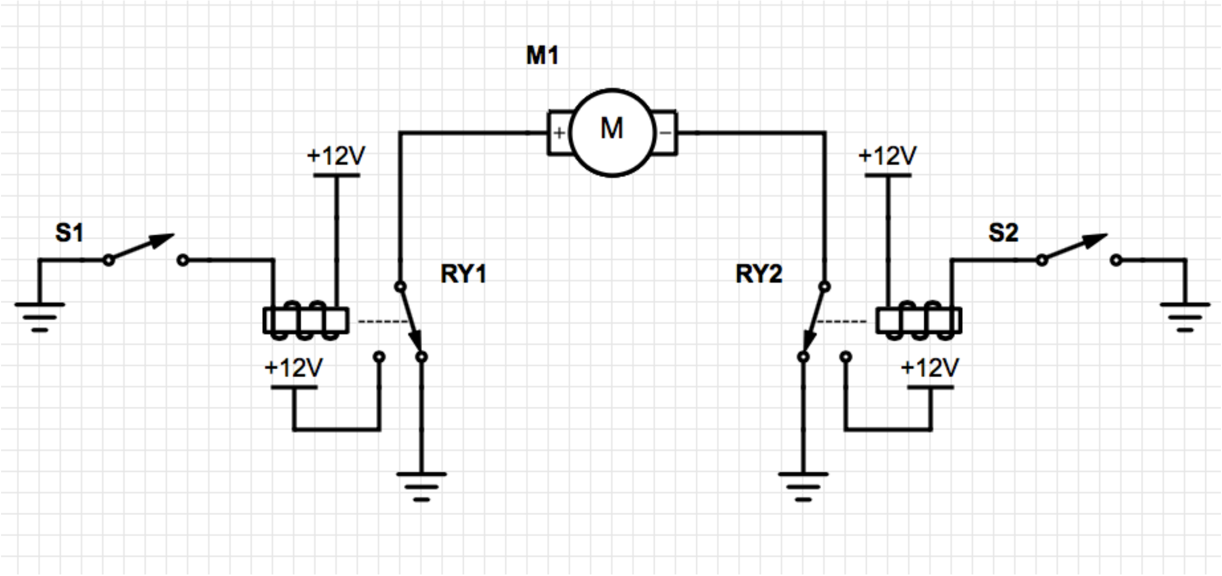


Figure 50: Relay-based shift system schematic

After the initial design was completed, we asked the mechanical engineering team for feedback. They pointed out a major drawback of the proposed design: the driver would have to hold down the shift button until the shift was completed, or the transmission would fail to change gears. In a racing competition it is highly likely that the driver would not hold the button for enough time, especially in the case of repeated downshifts. On the other hand, the driver may instinctively be holding the button longer than necessary, artificially slowing gear changes. With this in mind, our team decided to keep the same basic idea for the shift circuitry, since it meets most of the requirements, and add a timer circuit between the button and the relay to prevent incomplete gear changes.

For the timer circuit, the designer decided to use a 555 timer IC, due to ease of configuration and familiarity. In the circuit the 555 is wired as a one shot. In this mode, the output goes high for a controlled amount of time after triggered, then drops and waits for the next trigger signal seen in Figure 51. The designer also made sure the timer could source enough current to trip the relay so that the control like of the relay could be tied directly to the output.

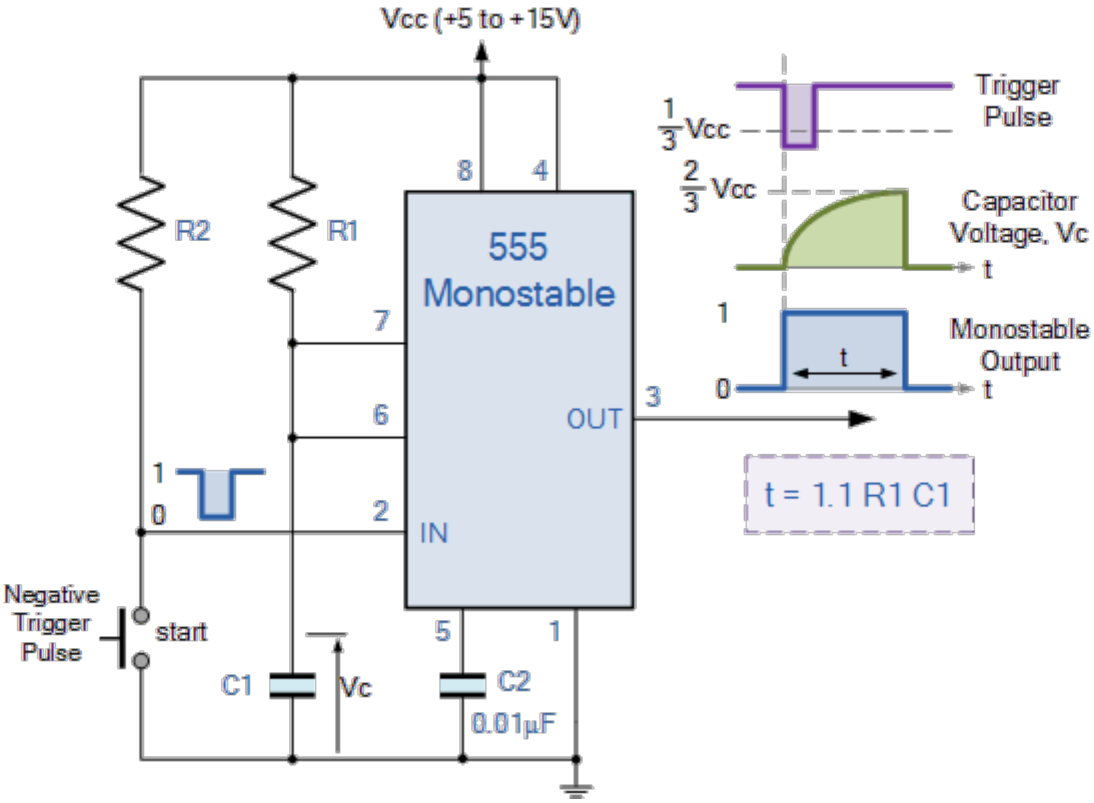


Figure 51: One-shot (monostable) circuit built with a 555 timer [40]

The prototype design included a potentiometer to change the on-time of the circuit. This allowed us to test the circuit in real world conditions to determine the fastest reliable shift time. We could then measure the potentiometer value and replace it with resistors to prevent issues caused by accidental adjustment. In testing the first physical prototype seen in Figure 52, we discovered that the timer would trigger the output to go high correctly but never reset.

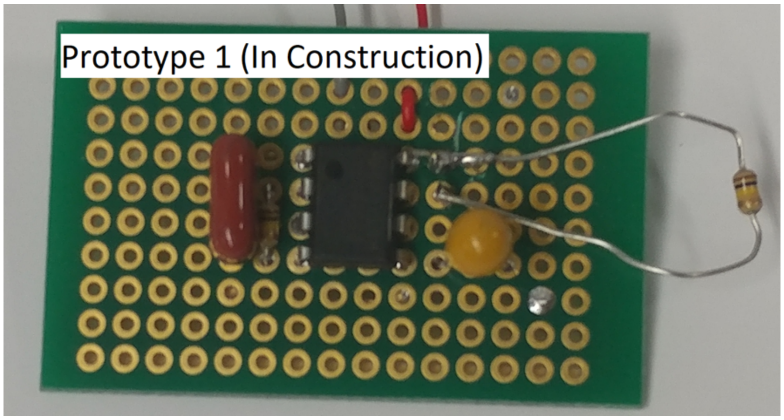


Figure 52: Early shifting prototype without potentiometers or buttons

Through research we found that using the wrong type of capacitor could cause this issue by introducing non-negligible amounts of leakage current.

For the second prototype, we switched to an electrolytic capacitor. These are not recommended for timing applications due to value instability over temperature, however they are accurate enough for prototype testing. This revision was done on a breadboard to make changing components easier which allowed us to prove that capacitor leakage current was the issue in the previous circuit. The second prototype confirmed operation of the circuit design for a single 555 timer controlling half of the shift circuitry.

The third and fourth prototypes, seen in Figure 53 and Figure 54, were built with the 556 dual timer for testing dual ended output. The P3 layout was designed to fit within the small area of the proto-boards we used. The space constraint caused issues with proper attachment of the output lines which caused significant strain during testing. We believe the timer chip shorted out after reattaching an output wire that had pulled off due to a weakened solder joint, necessitating another prototype layout. For the P4 the circuit designer used smaller potentiometers and redid the layout, placing high priority on side-to-side symmetry and avoiding crossing wires.

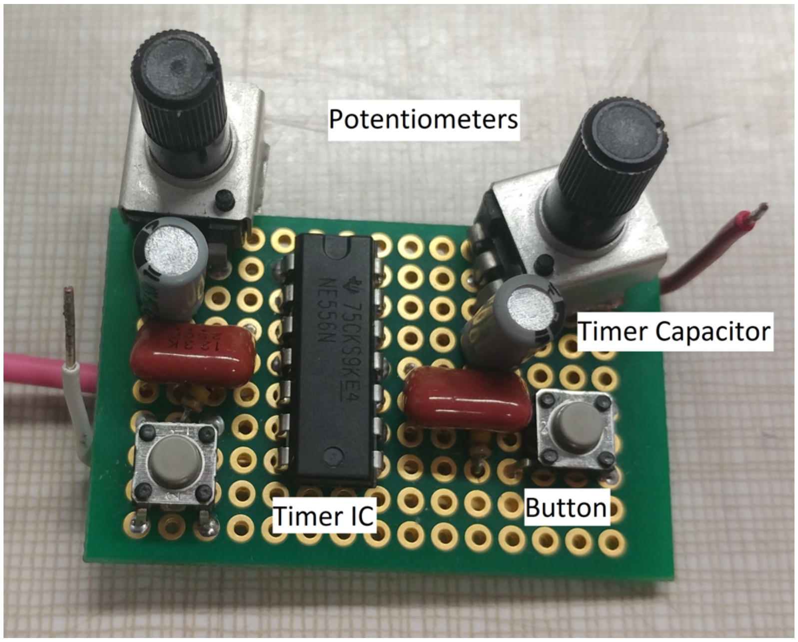


Figure 53: Relay-based shift system testing prototype, version 3

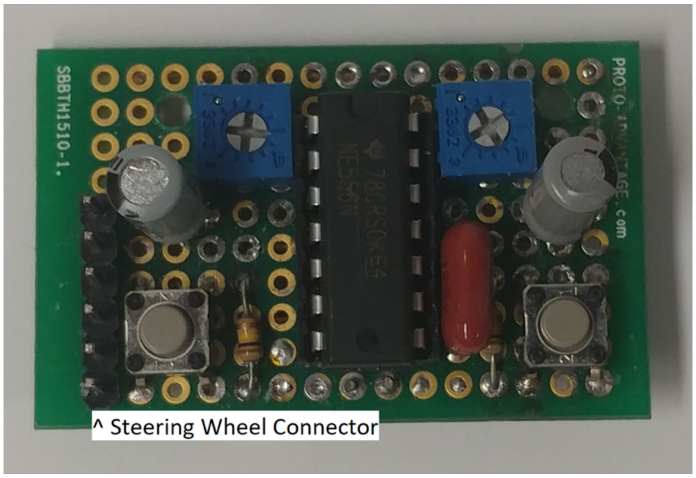


Figure 54: Relay-based shift system testing prototype, version 4

Both P3 and P4 were designed to be installed in the steering wheel of the car. The circuit inputs were two tactile buttons mounted in the steering wheel underneath paddle shifters, with redundant buttons on the face of the steering wheel in case a paddle broke while driving. The steering wheel connects to the wiring harness through four pogo pins inside the steering shaft itself. This allows the steering wheel to be removed, necessary to meet FSAE mechanical rules, without having an additional cable like previous WPI cars. The steering wheel housing is seen in Figure 55.

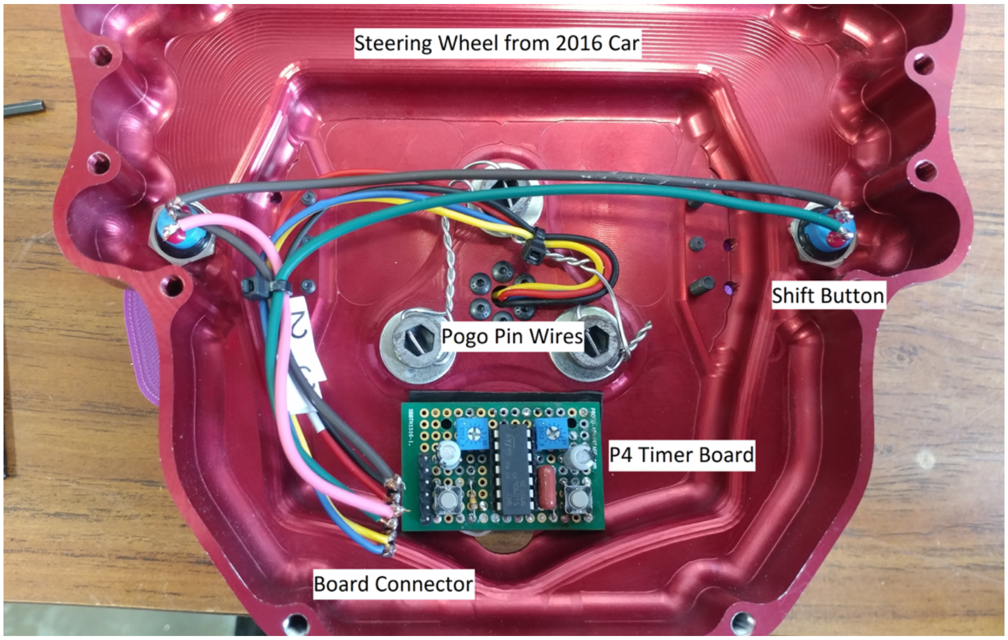


Figure 55: Version 4 shifting prototype installed in steering wheel

Testing of P3 and P4 revealed a number of potential problems with the design. The first major problem was momentary dips in the output voltage. This resulted in the output never returning to ground and staying there, causing the relay to stay closed. When we tested with a motor attached, the relays had a tendency to cycle at a very high frequency as seen in Figure 56. We believe the relays cycled because they did not have freewheeling diodes across the coil. When we added diodes, the cycling issues largely went away. In addition, when testing with a single channel DC supply, the motor would hit the current limiter, reducing the output voltage and causing the timer circuit to lose power. The test setup can be seen in Figure 57.

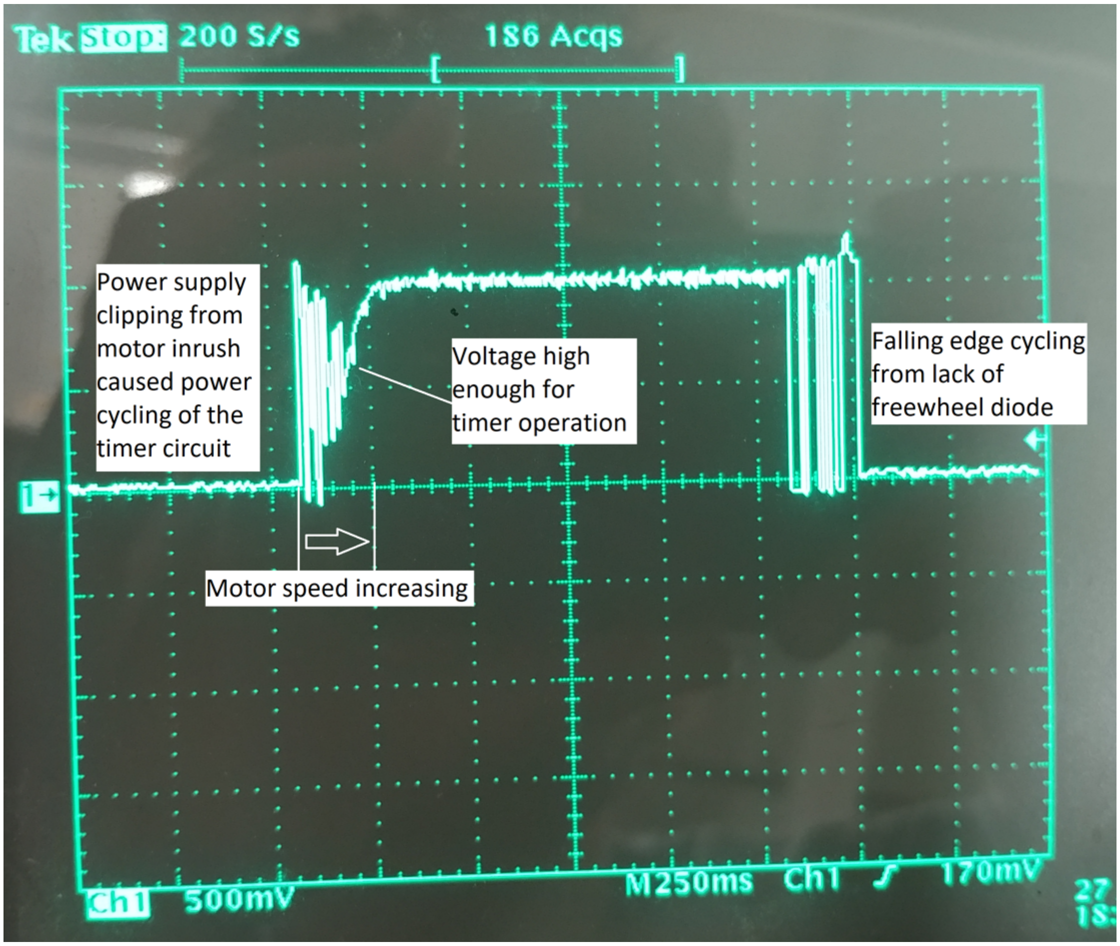


Figure 56: Relay chatter due to timer brownout and lack of freewheel diodes

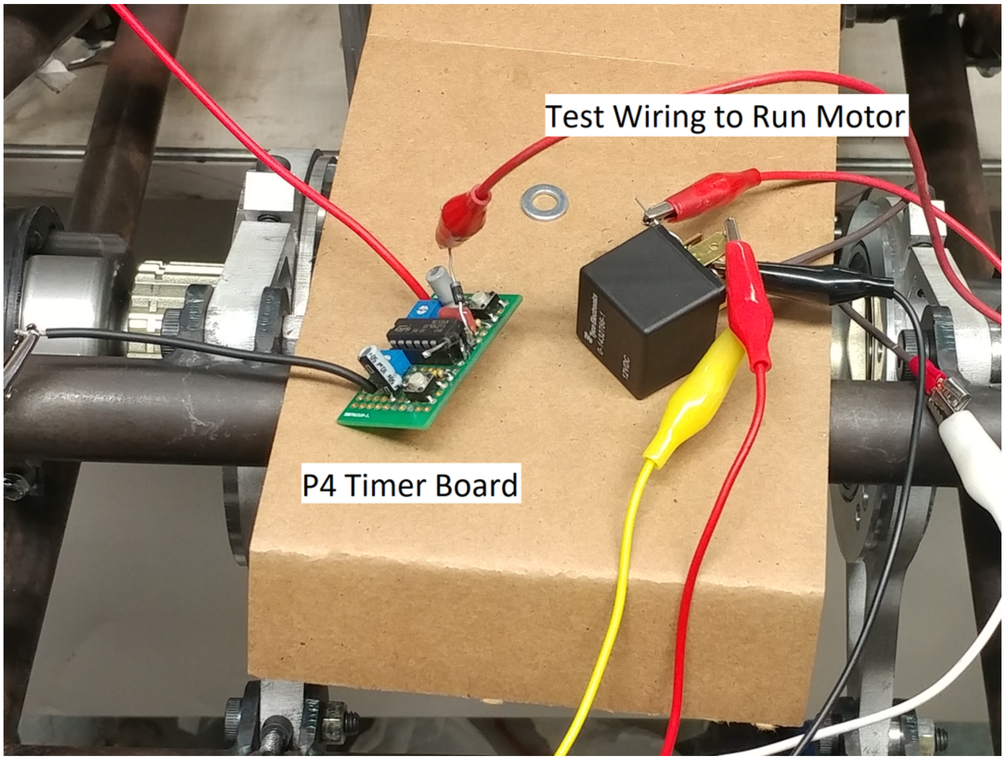


Figure 57: Testing the relay-based shift system on the vehicle

The fourth prototype was installed into the steering wheel for onboard testing of the circuit. Power was supplied by an 8V line from the ECU. Testing with the steering wheel not installed in the car worked as intended, but the circuit did not function when the steering wheel was installed in the car. Our team could not discover the cause of the failure, and the circuit designer was not confident that the timer circuit would operate well enough for a competition setting, especially given previous bench testing failures. We decided to wire the steering wheel so that the buttons had direct control of the relays like our proposed design, which worked well enough to drive the car in non-competitive settings. We then started on a contingency plan for a better overall transmission controller.

4.2 Contingency Design: Raspberry Pi Shifter

The original timer circuit did not have much functionality - it did not “know” anything about the system it was controlling and could not act differently in the event of a failure to make the next gear. In other words, the initial design had no feedback loop. The team decided that the new controller design should have a number of additional features to improve upon the previous design instead of just repeating it. At a minimum, we wanted the new design to be aware of what gear it is in - this allows for multiple extra features, including error detection and the ability to run a 7-segment display showing the current gear.

With these features in mind, team members came up with two ideas for the replacement controller design. The options were using the Arduino controller originally intended for the safety systems and using the GPIO port on a Raspberry Pi. We decided to use the Raspberry Pi because it is easier to modify later, especially for non-programmers. Additionally, the Raspberry Pi can be programmed in Python; the system designer is more comfortable with Python than C/C++ and the hardware team member in charge of the system wanted to learn Python. In addition to the above features, the Pi can use the encoder already attached to the motor. This allows for positional control of the motor instead of timing control used previously and can be used for a powered return to center operation instead of relying on springs to back drive the motor. A final advantage of this system is, with slight changes to the wiring harness, the Pi can be swapped out for the relays extremely quickly in case of failure.

We initially tried to minimize budget usage since the design change came late in the project. We looked at the available Raspberry Pi models and settled on the Raspberry Pi Zero, available for $5. The Zero has a single core ARM processor at 1GHz and 512MB of RAM, more than enough to meet our design goals. We bought a Zero starter kit, a spare Zero, and a number of other parts from Adafruit, one of the main Raspberry Pi suppliers. Once the parts arrived we began setting up the Zero; the system designer had drafted the shifter control code while waiting for the parts to arrive but the Zero needed to boot to a Linux system first.

We needed to interface the Pi with the wiring harness for the rest of the car. The main data inputs to the Pi are the motor encoder and the gear indicator. We sourced a motor encoder cable from AndyMark, but we needed to build the gear indicator in house. The gear indicator was built from Delrin with aluminum contact pins. This caused unforeseen issues because we are not able to solder to aluminum; we ended up using butt connectors to crimp wires to the pins. Our initial design used a Pi Zero which has a current requirement of at most 350mA [41]. The 5V supply from the Haltech does not support this much current, necessitating a dedicated voltage converter. Almost all the 12V-5V buck-boost converters available on Amazon did not support that little current [42], so we bought a 12V to USB converter that supports anything up to 3.1A.

The last harness change was driving the motor with a solid-state h-bridge driver instead of relays, since the Pi did not support voltage high enough (around 7.5V) to trip the relays. We sourced a small driver capable of 25A continuous and 60A peak, more than enough the drive the motor (0.6A no load, 22A stall). The motor driver and input headers were wired onto an expansion board that plugged into the Pi's GPIO header. A picture of this configuration can be seen in Figure 58.

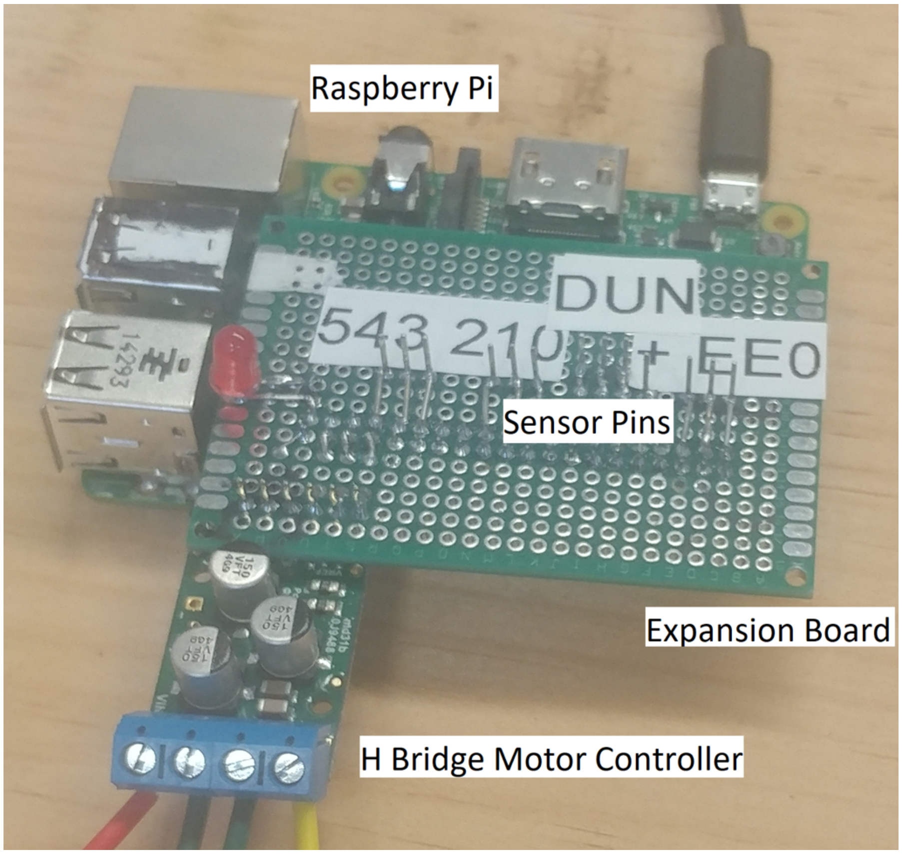


Figure 58: PiShifter test setup

We encountered system failures before shifter code testing. We encountered failures before reliably getting the Zero to boot to a Linux desktop using the provided system image. We also fried both Raspberry Pi Zeros. In an attempt to avoid blowing out a third Zero, the system designer did some testing to figure out what exactly went wrong - one failure could have been an accident, two in a row is very likely a system flaw. The 5V and 3V3 lines are exposed on the GPIO header and can be checked with a multimeter. Using the same power supply as during setup, included with the starter kit, we measured 5.4V on the 5V rail. The supply itself is listed as 5.25V output, which is already the upper edge of the USB specification. In addition, we learned that the Zero was designed without any 5V rail voltage regulation presumably due to cost concerns [43], which makes the problem even worse. We measured 1.5V and 0.8V output on the 3V3 rail, and the 3V3 regulator on both boards is significantly above operating temperature (very hot to the touch), indicating a component failure. Lastly, other people encountered the same failure under very similar circumstances, indicating this is not an issue with our system specifically [44]. We believe an out of spec power supply, possibly in combination with a bad USB hub, caused 3V3 regulator failure on both Pi Zeros.

At this point the team had no functional Raspberry Pis. The system designer wanted to order more, but orders of Raspberry Pi Zeros are limited to one unit per account per order. We ordered one Zero and one Raspberry Pi 3B, the most powerful and up-to-date model. This has the additional advantage of on-board USB ports, allowing us to avoid using the suspect hub. To perform testing before the replacement Pis arrived, we used a team member's Raspberry Pi 2B. The Zero, 2B, and 3B models all use the same system image, so switching units is as easy as moving the SD Card boot disk from one board to another. This avoided any testing delays caused by incompatible systems.

Once we had a system booting reliably, we started testing the transmission control code. Errors encountered and causes are tabulated below in Table 5, approximately in order of appearance during testing.

Table 5: Transmission control code errors

Error	Cause
Warnings against using some GPIO Pins	Some warnings merely informative, others caused by invalid pin configuration. See Encoder Testing.
No data from motor encoder	Encoder incorrectly supplied 3V3 instead of 5V
Motor unstable shifting through neutral	Noise on Gear Indicator in addition to control code that did not ignore invalid inputs
Motor does not stop, only reverses	Encoder operation incorrect. See Encoder Testing.
Encoder counters change semi-randomly	Encoder output voltage constant.

Some initial problems were due to overlooking a potential error when developing the beta code. Due to noise in the system caused by the motor, the gear indicator would sometimes trigger the wrong gear. Since the original code did not have sanity checking on the gear inputs this would cause unpredictable motor behavior, such as reversing prematurely. A similar issue occurred when trying to go to neutral from first or second gear. Neutral is a half shift between these gears, meaning the spacing between indicator pins is minimal. The motor hub often had enough momentum to move the indicator past neutral enough to trigger the next gear. The original code design told the motor to reverse direction when a new gear was detected to re-center the motor. For example, shifting from first to neutral turns the motor towards second gear. If the gear indicator position was slightly past neutral towards second gear when the motor reversed, it would hit neutral again while re-centering. This would cause a second reversal, sending the motor towards second gear. Once it reached second gear it would reverse back to neutral. This resulted in the motor vibrating between the edges of neutral and second gear, sometimes indefinitely. This could have been mitigated by using encoder data, but at this point the encoder was not working properly and could not be relied on. We solved this by updating the code to only accept inputs from the destination gear, which removed the possibility of getting trapped between the destination and a neighboring gear.

Final testing of the proof of concept revealed an additional problem. Most of the encoder testing was done with the motor hub set screws removed, so that the shift linkage was disconnected from the motor allowing it to spin freely. Reinstalling the set screws required the motor position to be adjusted since the hub did not rotate freely. The hardware team member in charge of shifting did not realize the ECU needed to be on to run the relays, since it provides power to the relays through the steering wheel. The harness wiring will be changed to trigger the relays on a falling edge from the steering wheel so that the Pi and the relays can be interchanged on the fly - The Pi cannot drive the relays over GPIO. This will mean the car will shift with the ECU turned off, which is desirable from a maintenance perspective. The Raspberry Pi is seen in Figure 59.

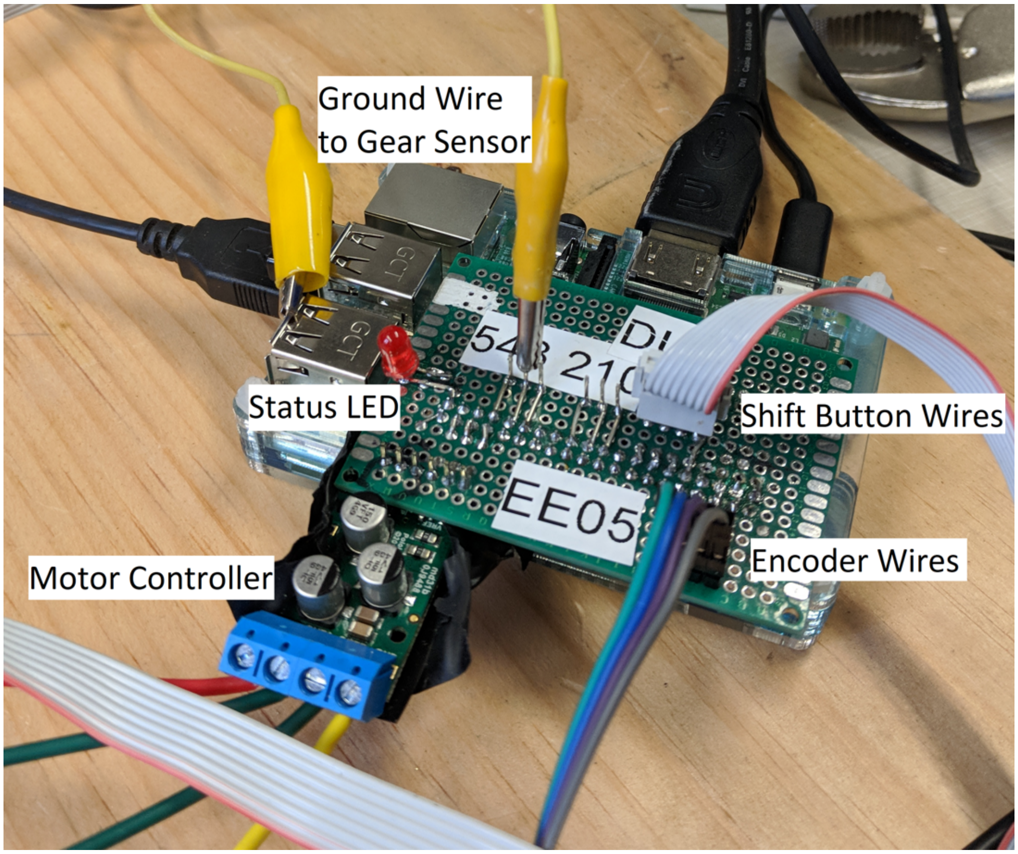


Figure 59: Raspberry Pi with motor controller circuit

We destroyed a Pi 3B during final testing - the headrest panel which the Pi attaches to was not secured and moved due to engine vibration. This shorted the motor controller board against the case. The motor controller survived but the 3B's processor was likely exposed to 12V over the GPIO lines and no longer works. After that, we tested with a spare Pi Zero, which promptly stopped accepting USB inputs, likely due to the same USB issues encountered before. We covered the back side of the motor controller in electrical tape and ordered another 3B for testing V2 code.

During initial testing of the code, we ran into a number of code flow problems that needed to be fixed. Some internal counters did not change value, due to namespace handling in Python. We solved this by using "global [name]" when referencing global counters. Additionally, the gear indicator would trigger an interrupt when it should not have due to AC noise from the engine on the analog lines. The prototype code solved most of the issues by ignoring triggers from non-adjacent gears, but this still left the Pi accidentally changing gears when it should not have.

The Pi will run headless on the car, meaning we have no way to dynamically tell it to start the transmission control program. To run the program every time, we set up a CRON job at boot to run a Python script, based on instructions from [45]. We can change which script it runs by editing a bash script that starts the Python program. We wrote a short script for testing that lights an LED, which allows us to measure boot time of the device, representing the minimum time between when main power is turned on and when the transmission is usable. We measured 35s boot time for the 2B, 25s for the 3B; we attempted to time the Zero but we stopped timing after two minutes. This means the Zero is either glacially slow or does not properly run CRON at boot, both of which disqualify it from use in the final system. Future teams may want to switch to systemd instead of CRON - it will likely start the control program sooner and might restart the script if it exits unexpectedly.

Confirming functionality of the base system - buttons, motor control, motor timeout, gear indicator - did not take much time. Most of the debug time was spent working on the motor encoder. Initially, only one of the encoder line counters changed, and almost exclusively in one direction. By using an oscilloscope, we discovered that the encoder data lines were at 3V3 and did not change. The counter was triggering on AC noise on top of the data signal caused by interference from the motor. We assumed the encoder ran on 3V3 input; this was incorrect. We switched to 5V supplying the encoder and checked the output lines, since the Pi's GPIO is not 5V tolerant. The encoder outputs a 0-5V square wave, which is ideal for edge triggering. We also measured the maximum frequency of the encoder output, which is roughly 250Hz per line as seen in Figure 60.

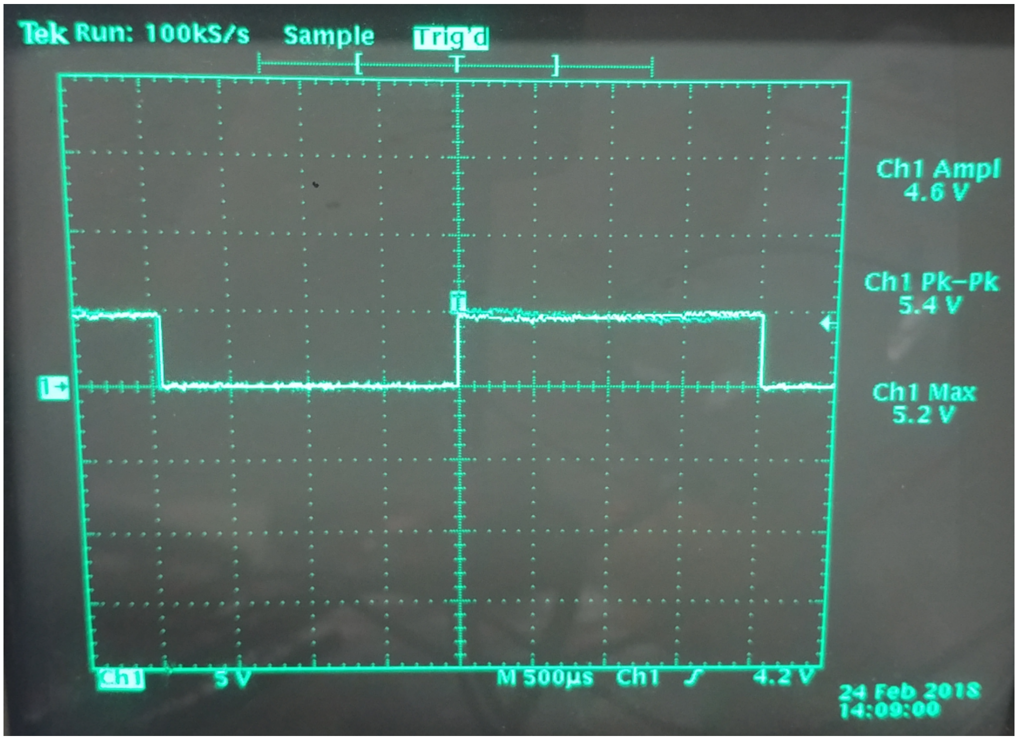


Figure 60: Motor encoder output

Since the Pi does not tolerate 5V inputs, we wired in a 2kΩ/3kΩ resistor divider into each input line. This did not improve how the code was interpreting the input. We thought the issue might have been the ISR code taking too long - the GPIO package we use does not support queued software ISRs. However, we performed timing tests on the ISR code itself and got an average run time of less than 10μs, well within the smallest possible encoder timing of 1ms using both edges of both encoder lines. This does not account for the time between the interrupt trigger and the beginning of the ISR. A researcher [46] tested this delay on a Pi Zero running Python and measured an average delay of 212μs and a maximum of 377μs. In the worst case the entire interrupt routine takes 400μs, leaving 600μs between interrupts from the encoder. In this configuration, a Pi Zero is fully capable of running the shift system and the 3B is likely to process even faster. This meant that the error stems from the Pi incorrectly reading the encoder inputs, and not from missing them entirely. By probing the Pi directly with an oscilloscope, we found that the input was a square wave ranging from 1.6-3V. We thought the resistor divider may be at fault, so we changed to a diode setup that reduces the input voltage to roughly 4V3 [47]. This changed the upper bound of the input slightly but did not change the lower bound. By doing more research, we stumbled upon the cause of the problem. The two input lines we chose for the encoder are the only two on the Pi with 1.8kΩ pull up resistors to 3V3, which caused the voltage at the pin to be 1.6V when the input was ground, since we used a 2kΩ input resistor.

This issue potentially could have been caught earlier because the programmer had muted GPIO warnings during testing. Most of the warnings were notices that we had reassigned pins normally used for an SPI interface, which we could safely ignore. The warnings that would have told us anything said that some pins had hardware pull up resistors. For the first version of the code, all the GPIO lines were specified to run pulled up anyway, so the programmer did not think those were relevant either. Muting the warnings made the terminal debug output significantly easier to read, which sped up debugging the rest of the system.

Initial testing of the Pi was done by wiring the motor controller into the relay sockets. This allowed us to revert back to the direct control design quickly, however that design is rising edge triggered and the Pi is falling edge triggered. After implementing the V2 code, we updated the wiring of the relays and steering wheel so that the Pi and relays could be swapped out in case of Pi failure. The first version of the script used no objects and encountered significant issues with edge triggering the gear indicator. As with the encoder, this caused spurious inputs due to noise on the lines. Lastly, the beta code did not use both encoder channels to derive rotation direction.

The second version of the code made significant improvements to the prototype script, and is available in Appendix H. The largest improvement is the change from a pure script to a program with objects, broken down into an encoder, a gear sensor, and a motor. The flowchart for this code can be seen in Appendix G. This allows easier updating of sensor implementation and avoids global variables entirely. Additionally, it allowed very easy implementation of a seven-segment gear display for the driver and an upshift indicator line for the Haltech.

The encoder attached to the motor is a quadrature encoder, meaning the two output lines are 90 degrees out of phase from each other. This allows the motor controller to determine motor direction by the order and edge direction of the A and B channels. The encoder attached to the motor we are using outputs 7 pulses per revolution per channel [38]. Using the 71:1 gearbox and updating position on both edges of both lines, this gives a position resolution of .72 degrees of the output shaft. In testing with nothing attached to the motor shaft, the momentum caused an overrun of about 84 pulses, representing 59 degrees. This will be significantly reduced by the return springs attached to the shift linkage and other friction in the system. Small amounts of drift in the zero position may be possibly caused by the same AC noise issues as before but given the small output resolution, we do not anticipate that it will cause problems. Complete failure of the encoder will still allow shifting, although the motor will not have a powered return to center and will turn off based on the override timer.

Preventing AC noise from accidentally triggering the gear indicator presents significant challenges, although noise could be mitigated by shielding the data lines. Solving the issue relies on the difference between a "falling edge" and a "low" reading on a pin. The GPIO package we use has a very low threshold for falling edge detection, which causes the noise issues. The version two code still triggers on falling edges on all gears. However, it ignores what indicator line triggered the interrupt, and reads all the gears to find the low state - the correct gear. This sacrifices processing efficiency but ensures the Pi always has the correct gear. In the event of a gear indicator failure, the driver will not know what gear the car is in, but the car will still shift into non-neutral gears. If the failure was momentary, the gear indicator will resume intended operation the next time it properly reads gear state.

The motor control code remained largely the same in overall organization. We updated the selection code for inputs to the motor controller itself, which saved approximately 30 lines of code and made including the upshift indicator significantly easier. Additionally, the code was configured such that incorrect inputs to the selector itself cause the motor to stop. Hardware failure of the motor controller is unpredictable and may result in the motor burning up. Shifting would be unavailable in this case, until the relays are swapped in and motor replaced if necessary.

The gear display for the driver is a seven-segment display in the dashboard. We decided to use a binary seven segment decoder chip SN7447A [48][49], both to reduce the number of GPIO lines used and improve potential for modification later. The V2 code changes made updating the gear display significantly easier than it would have been in the prototype implementation.

4.3 FSAE Safety Requirements

The design work of the Brake Plausibility Device began with accurately interpreting the FSAE competition rule IC1.16 [4]. Initially, the team considered using a microcontroller and restricting the ability to program the device once installed in the vehicle in order to satisfy the non-programmable requirement. Unsure of the legality of this approach, a rules clarification question was submitted to FSAE through their website. A rules representative by the name of Peter Kuechler informed the team that a microcontroller is not allowed, and that the device must use analog circuitry: “The plausibility device must be discrete analog circuitry. A digital circuit or microcontroller is not permitted.”

With analog circuitry in mind, the rule was broken down into the most important phrases. First, “braking hard” means braking greater than some threshold. This suggests the use of a comparator. Next, “and” suggests some logic function, specifically an and-gate. The throttle threshold “throttle is greater than 10% open” is similar to the braking hard phrase and also suggests use of a comparator. Later in the paragraph, “implausibility is persistent for more than one (1) second” suggests two requirements are necessary. For the combination of the hard braking and throttle conditions covered by the first AND gate *and* for this to be true for greater than one second, this suggests a second AND gate is required. Additionally, the one-second requirement suggests some type of timing circuit is necessary. A one-shot device configured for a one-second output pulse would satisfy this. The final requirement, “completely shut down, may only be reset by power cycling,” suggests latching is needed, and a simple SR-type latch would fulfill this. Without latching, the Brake Plausibility Device would allow the engine to be restarted without cycling master power after an implausibility occurs. FSAE does not allow this because the root cause of the problem must be identified and corrected before the engine is to be restarted.

With a general idea of the required components for proper signal processing, a block diagram was drawn. A few iterations of revising and redrawing were necessary until all design constraints were met. The final block diagram, seen in Figure 61 displays the general construction of the circuit.

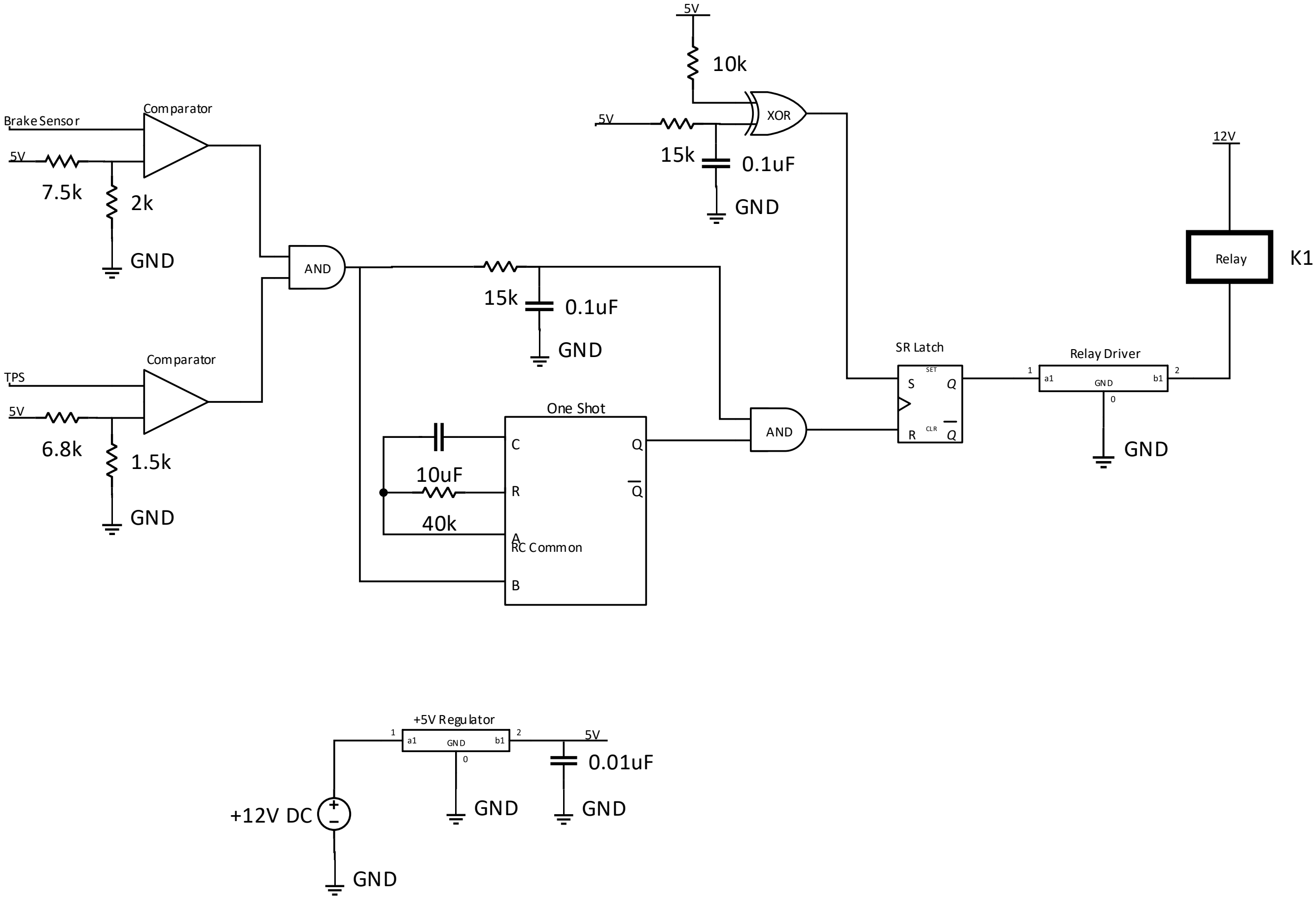


Figure 61: Brake Plausibility Device block diagram

Beginning on the left side, there are two comparators; one for the brake pressure sensor and one for the TPS. As with any standard comparator operation, the output signal is logic high when the input signal is greater than some threshold. In this case, the brake pressure sensor and TPS signal were fed to the positive inputs of the comparators in order to trigger a logic high output when their signals were greater than the reference voltage at the negative inputs set by voltage dividers. Two small capacitors were placed between the inputs of the comparators for noise rejection purposes.

The outputs of the comparators went into each input of the first and-gate. According to AND logic, the output of the AND gate is high when the implausibility is present. In order to satisfy the timing requirement, the output of this and-gate went into the positive-edge-triggered input of a one-shot device. This device was configured with a resistor and a capacitor to give a logic low pulse for one second before returning to logic high. If the implausibility is still present at the time the one-shot device returns to logic high, the engine must shut down. Therefore, this output pulse was fed to a second and-gate along with the output of the first AND gate that tells whether or not the implausibility is present. If both inputs of the second AND gate are high, the engine must shut down. There was a slight issue with the timing of this circuitry, however. The one-shot device does not go low instantaneously, so there could be a moment in time that both inputs to the second and-gate are high before the one-shot device has a chance to function as intended, shutting down the engine prematurely and without reason. Therefore, a small delay in the form of an RC network was inserted to prevent this timing condition. A consequence of inserting this delay means the shutdown of the engine will be delayed if the implausibility is present when the one-shot returns high, but this is allowable given that the delay is on the order of microseconds and no figure of accuracy is given by FSAE in the rules description. A timing diagram was developed to help identify race conditions with assistance of Brian Beucler from Analog Devices, seen in Figure 62.

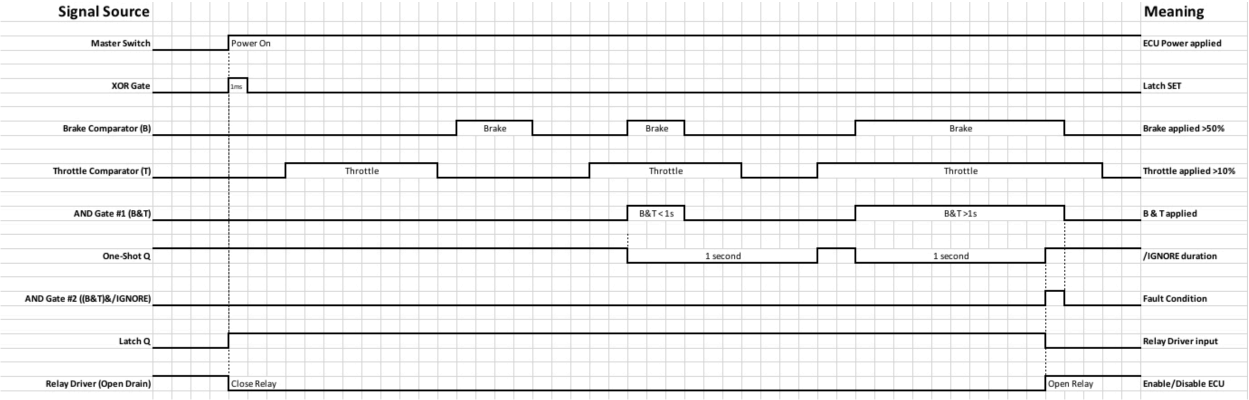


Figure 62: Brake plausibility device timing diagram

Various driver inputs were tested in this diagram, including brake and throttle separately, brake and throttle at the same time for less than one second, and brake and throttle at the same time for greater than one second. The circuit was carefully analyzed for each case with individual component outputs using a simulation tool. This tool helped significantly in designing the device correctly in the first iteration, with minimal design changes after circuit assembly.

In order to understand the latching functionality of the circuit, the engine shut-off mechanism must first be visited. The most efficient way to shut down the engine is to remove power to the ECU. The ECU has an emergency cut line (EMG cut) that turns off the ECU when grounded. The Brake Plausibility Device utilizes this EMG cut line with a relay to control the shutdown of the engine. The relay is connected to 12V and ground and is held closed when the engine is supposed to be running. When opened, the EMG cut signal is grounded and the engine shuts off. A relay driver IC drives the relay from the logic-level signal of the circuit.

The SR latch is tasked with providing a logic-high output until the implausibility occurs. Therefore, the S or "set" input must be high when master power is turned on. When the implausibility occurs, the second AND gate sends a logic high signal to the R or "reset" input of the latch, effectively providing a logic-low output to the relay driver, opening the relay, and shutting down the engine. The method of setting the S input high upon master power on is of great interest. This pin cannot simply be tied to the positive rail, as the latch would always be set for a logic-high output. Instead, a momentary logic-high pulse must be provided to the S input on power on. In order to do this, a pulse generator circuit was needed. A simple pulse generator circuit was made using an RC delay and an exclusive-or logic gate. One input of the gate is tied high, and the other input is tied high through a small delay. According to XOR logic, the output of the gate is high for all times when the inputs differ in logic levels. Therefore, as the RC circuit charges according to the time constant τ, the logic levels temporarily differ, sending a short pulse to the S input of the latch, allowing for reliable master power-on reset as the FSAE requirement specifies. It is important to note that all unused logic gate inputs are grounded for the purpose of chip stability.

The circuit was first assembled on a breadboard for functional verification. Due to time limitations, the circuit was soldered on a perf-board for use on the vehicle rather than creating a custom PCB. An image of the bread boarded circuit can be seen in Figure 63 and an image of the final perf-boarded circuit can be seen in Figure 64.

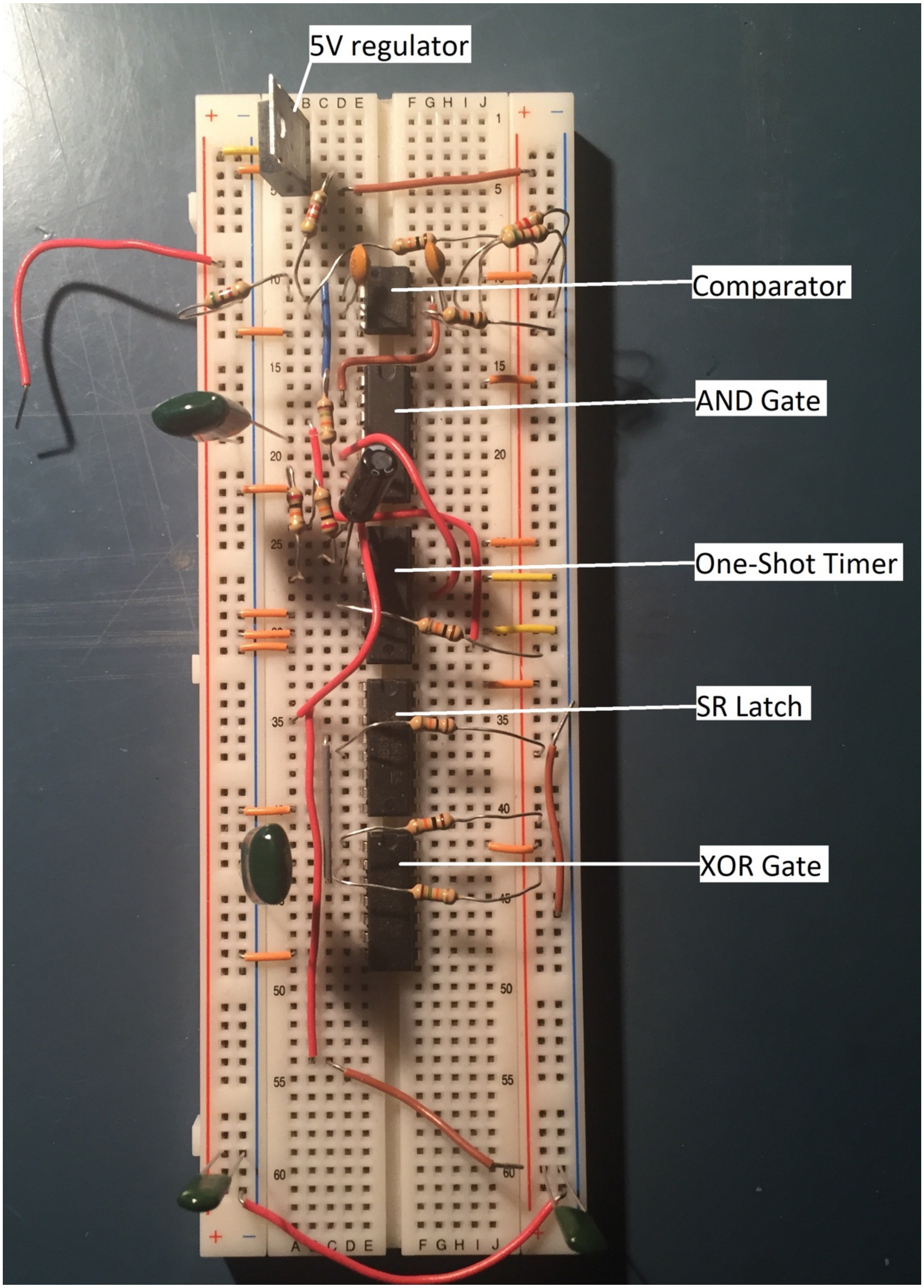


Figure 63: Brake plausibility device bread boarded prototype with pull-up and pull-down resistors simulating throttle and brake conditions

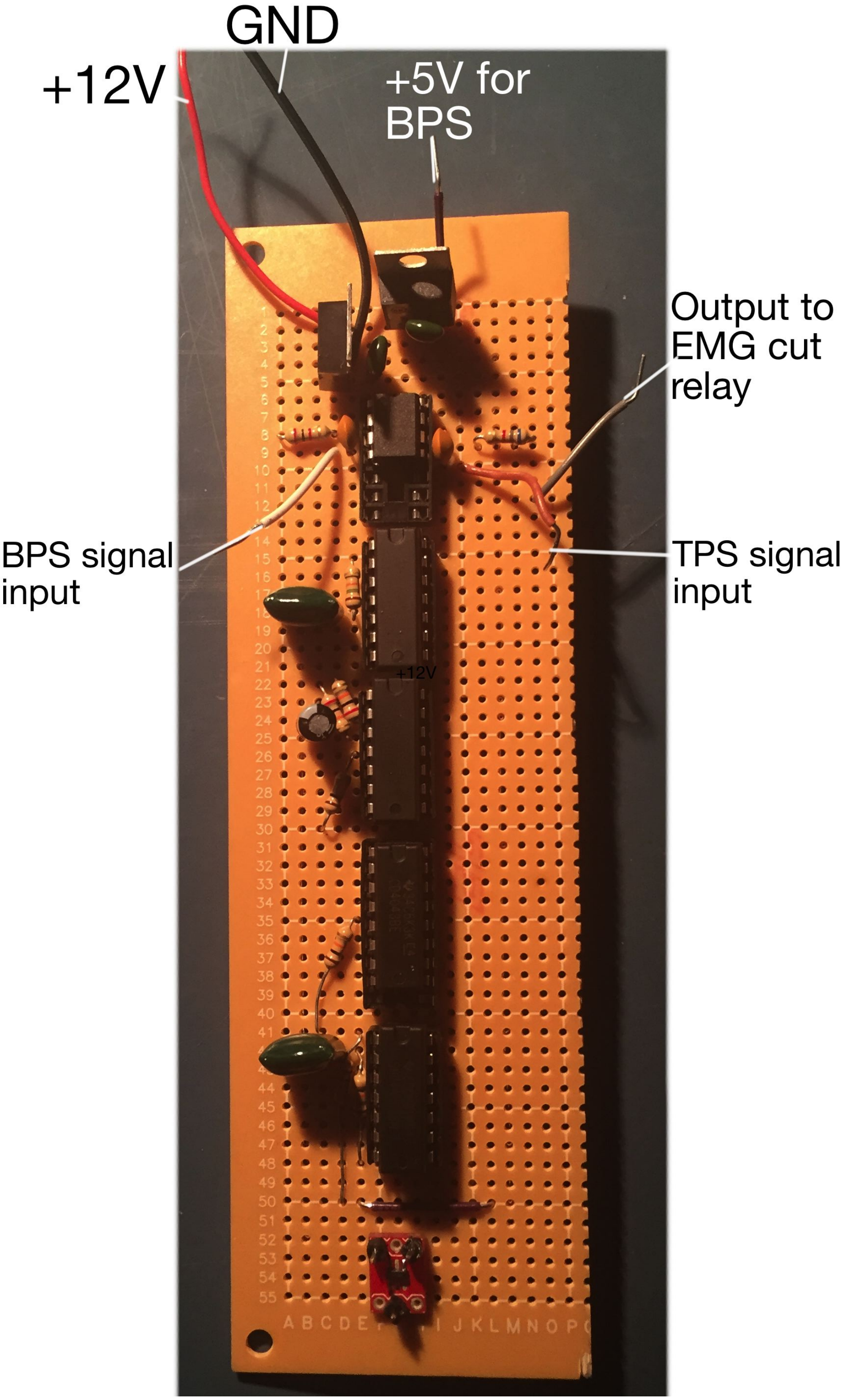


Figure 64: Final Brake Plausibility Device assembled on a perf-board.

Future MQP teams should consider making this into a PCB.

Additionally, a list of all connections for future reference can be found in Table 9 through Table 15 in Appendix C. The datasheets for each IC used are linked in each table. They are also attached as a .zip file in this MQP submission.

The FSAE rules specify a number of emergency switches which must disable the car in a predictable fashion [4]. The main emergency cut is a paddle switch between the battery and the rest of the wiring harness - this is a last resort for people outside the car in case of a major incident. The other two emergency cuts are inside the vehicle; one is the driver cutoff and the other is the brake over travel switch in case of brake system failure. In reading the rules carefully, we determined that the rules do not specify how the switches must cut power, only what systems the switches must cut power from. All the specified components are disabled by the Haltech when the "ignition" input voltage is low. Our implementation has the two emergency cut switches and the brake plausibility relay wired in series in between the Haltech ignition input and a 12V source. This means that if any of the three switches opens, the ignition line drops low and the Haltech turns off the engine along with the other components specified in the rules.

4.4 Additional Electrical Design

Although a one wire design was initially proposed for the gear indicator sensor, the final design included six wires; one for each metallic contact. The design is simple: when the ball contact touches any of the sensor contacts, the signal is grounded (pulled down) to the chassis ground and whichever wire is grounded indicates the current corresponding gear. The single-wire idea was discarded ultimately due to a shifting system design change. ADC functionality was eliminated so six individual signals were needed, rendering the single-wire design impractical and impossible. The Raspberry Pi is still able to process the information to be sent to a seven-segment display, however. Future revisions could include an ADC between the sensor and the Pi, but we did not think reducing the number of sensor wires represented a large enough improvement for the time required. Figure 65 shows the final implementation of the gear indicator sensor.

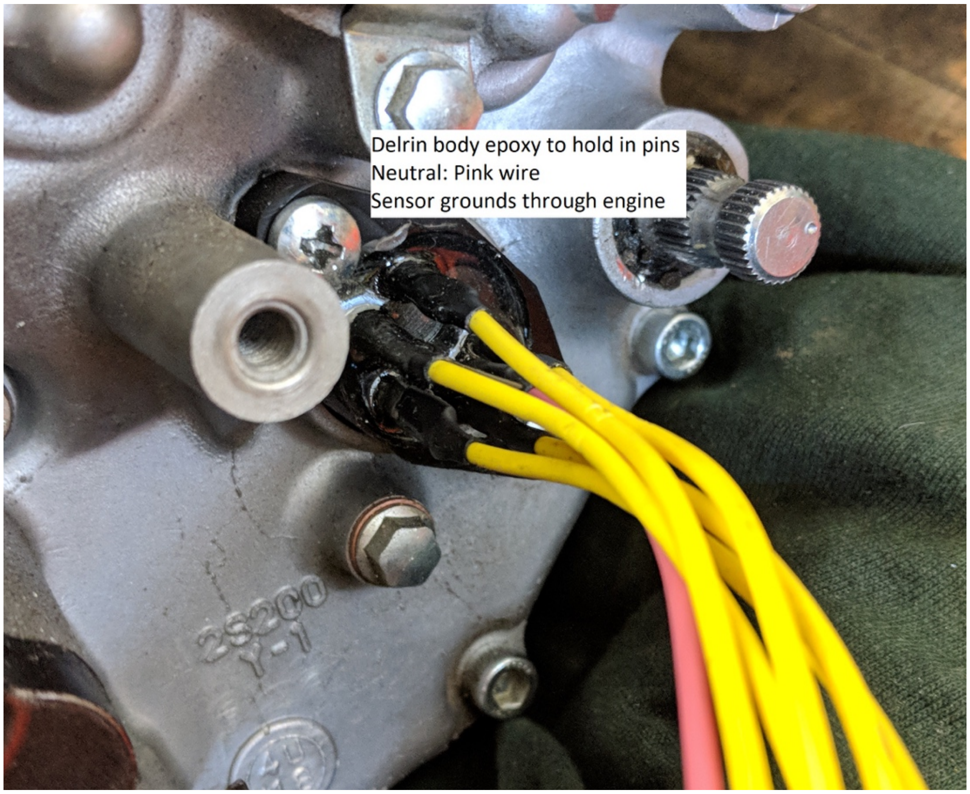


Figure 65: Gear indicator sensor installed

The main driver interface utilizes the gear indicator sensor information. A seven-segment display shows the current gear to assist the driver in keeping track of the gear with the sequential transmission. We placed it on the dashboard so that it would always be visible to the driver and did not rotate with the steering wheel.

The initial design of many non-critical engine systems called for the use of a standalone microcontroller that would handle all of the safety functionality ended with the implementation of the brake plausibility circuit as well as the Raspberry Pi 3B motherboard that is being used for the shifting system. The use of the MSP430F5529 microcontroller in a development board format has the potential of allowing an easy-to-use and small PCB board layout that was powerful enough to provide quick boot times on startup and handle all the functionality of an RTOS (Real Time Operating System). This would therefore provide quick priority driven responses to secondary vehicle function including shifting controls, brake plausibility, and various other functions that might be desirable.

To allow for this functionality, an RTOS was initially conceived and implementation began through the TI (Texas Instruments) CCS (Code Composer Studio) Graphical RTOS management system. This system is designed with the idea of providing easy user interfaces for development of an RTOS system. With limited reference material available and issues arising that resulted in no formal error codes, the code failed to enter as expected and it was decided that the added function of an RTOS was not possible with the limited resources available.

Fundamentally, the use of the MSP430F5529 was to input analog sensor inputs such as the gear indicator or brake pressure sensors and use those values to facilitate decision making for the vehicle as it interacts with the engine management system in the secondary wiring harness. In order to do so, the ADC of the microcontroller was critical. A multichannel, single sample interrupt driven ADC was therefore implemented on the MSP430F5529 in order to allow for up to 8 signals to be input for decision making purposes. The sample rate capable by the device allowed for 12-bit resolution on all channels. Due to the speed and low load of the microcontroller, this could be done with what was theorized to be no perceivable lag from the device in decision making. The ADC was designed and implemented on the board and is fully capable of taking in the required signals for a decision-making progress.

This design was not used in the vehicle for a number of reasons. Firstly through a rules inquiry, it was found that the brake plausibility circuit was required to be a fully analog decision process which therefore did not allow for the use of a microcontroller. In addition, it was decided that the MSP implementation was more complex than was necessary for the simple implementation of shifting circuitry and therefore the use of the Raspberry Pi would allow for a simpler and more understandable code for the average user in the future.

4.5 Vehicle Systems Testing

With any electrical design, it is important to check each connection before power is applied to the system. In this design, a single wire in an incorrect location could do thousands of dollars in damage and render the ECU as well as various engine sensors or actuators useless. Exercising great caution, the team designed a wiring verification procedure found in Appendix B. The procedure required each connection in the schematic to be verified before wiring began, then multiple verifications for each sensor, actuator, and ECU. The procedure required whichever team members that did not perform the wiring to check the wiring. This was done because many times, the person making the error will overlook the error even when double checking. The checks involved one team member going through each connection, and one team member witnessing this being done and checking it for themselves. The tests performed were simple continuity tests that worked for all aspects of the wiring harnesses, including the fuse and relay box.

When the engine was first being tested on the test stand, it was having a hard time starting consistently. Sometimes it would crank over just a few times and fire while other times it would continue cranking with little sign of starting. There was even an instance where the engine severely backfired, causing timing concerns. At cranking RPM, the Haltech was programmed to expect a +1V peak signal from the crankshaft position sensor - the sensor which provides the ECU with all vital timing information. The sensor was suspected to be the issue, so its output signal was probed over various engine speeds from cranking to nearly full throttle. It was quickly determined that the reluctor sensor delivers only a 300mV waveform at cranking speed. Table 6 displays peak output voltages for the crankshaft position sensor over engine speed.

Table 6: Crankshaft position sensor output over RPM

Waveform peak (V)	RPM
0.3	400
2.26	3200
2.8	4000
3.58	5200
3.92	6000
4.8	7450

This explained why the ECU was not receiving vital timing information, so the parameters for the sensor were changed in software and the issue was corrected.

Once designed and built, the brake plausibility circuit was bench tested before installation in the vehicle. A power supply was used in order to simulate the BPS and TPS sensor signals. For the first analysis, a failure condition signal was immediately sent to the plausibility device upon power up. The output of the SR latch is shown in Figure 66.

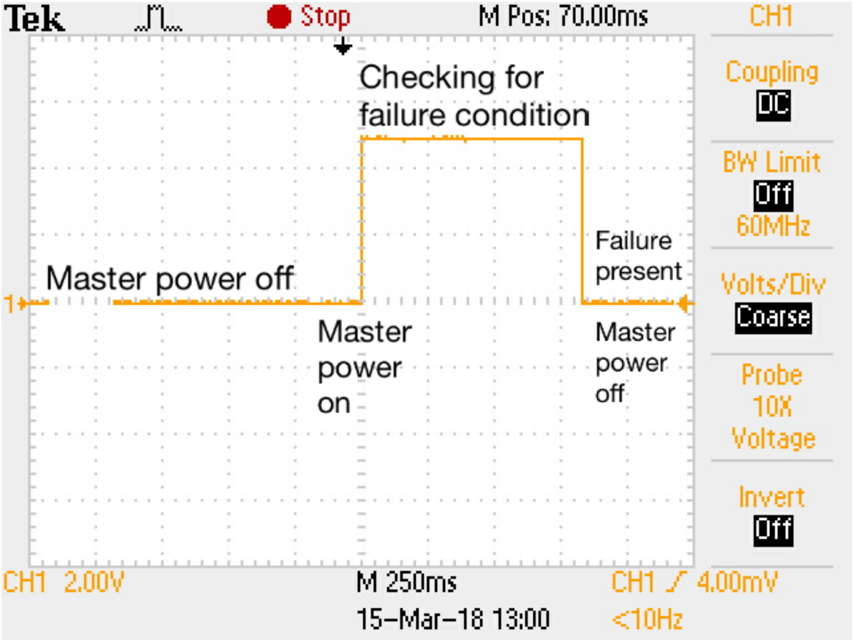


Figure 66: Brake plausibility output under failure condition. Turns on, stays on for ~0.84 seconds, turns vehicle off.

On power-on, the output goes high which holds the relay closed so the engine can operate. The plausibility device immediately checks if a failure condition is present. In this case, it was, so the signal goes low, opening the relay and turning off the engine. The rule specifies this must happen if the failure condition is present for 1 second or more, however it was measured to be 840ms due to the error tolerances of the resistors, as seen in Figure 67.

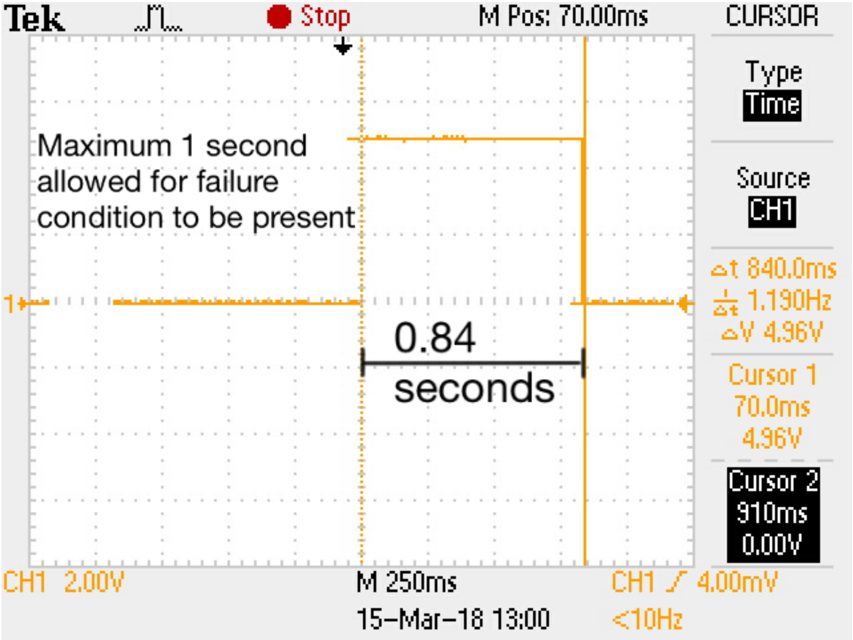


Figure 67: Time duration measurement. 1 second or less is acceptable.

It was determined that hard braking, as specified in the rules, is equivalent to a 1V output of the brake pressure sensor. Resistors were chosen to provide a 1V reference voltage at one of the comparator inputs. A simulated BPS signal was provided to the input of the comparator and gradually increased, simulating braking. When the simulated signal reached 1V on the test bench, as illustrated in blue on channel two in Figure 68, the SR latch output went low, shutting down the vehicle. The TPS signal was held high for this test, simulating more than ten percent throttle actuation.

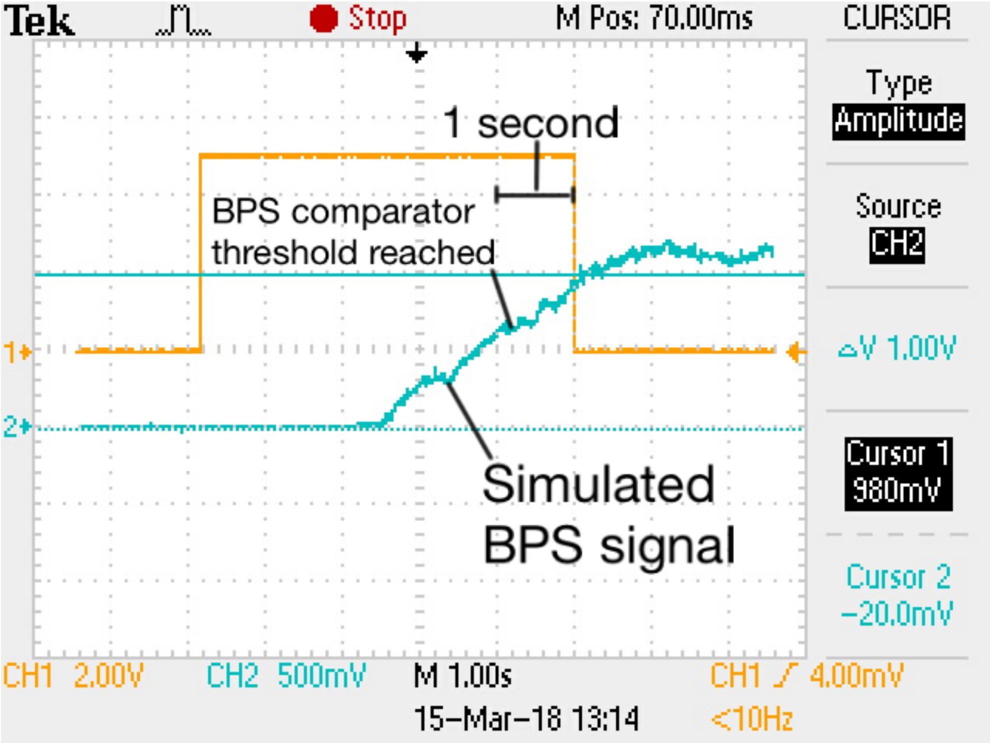


Figure 68: Device shutting down when brake sensor signal exceeded comparator threshold (with TPS held high)

The same test was performed on the TPS comparator threshold. Resistors were chosen to provide a reference voltage equivalent to ten percent of throttle actuation. The BPS was held high simulating hard braking, and the simulated TPS signal was increased in voltage, the plausibility device shut down the engine as intended, seen in Figure 69.

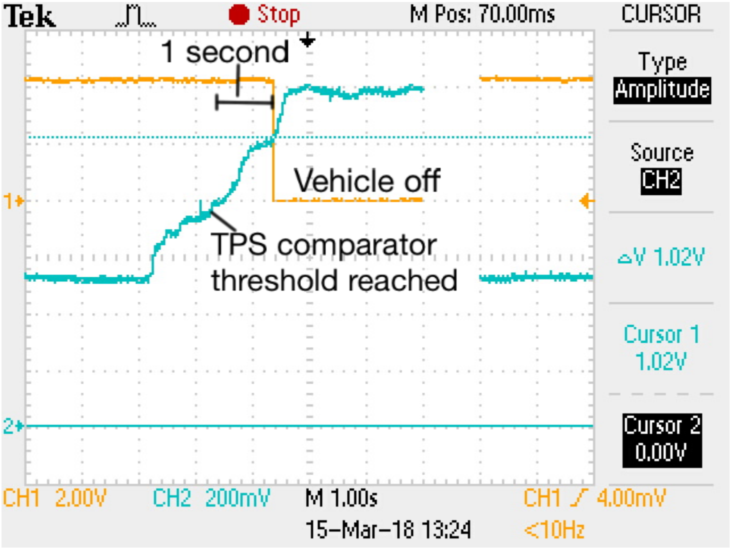


Figure 69: Device shutting down when TPS signal exceeded comparator threshold (with BPS held high)

The final part of the circuit investigated was the pulse sent to the 'set' input of the SR latch on power up. This pulse, along with the latching functionality, allows the vehicle to turn on only by master power reset as specified in the rules. This pulse is critical as the signal at the 'set' input of the latch must be low at all times other than initial power on, otherwise the failure handling of the circuit would be rendered useless. The pulse was created using a RC delay and XOR logic, where the output of the logic gate is high for all times the two inputs differ in voltage. This difference is temporary as the capacitor will eventually charge to be equivalent to 5V, which is what the other input is tied to. The pulse was measured to be 1.36ms, as seen in Figure 70.

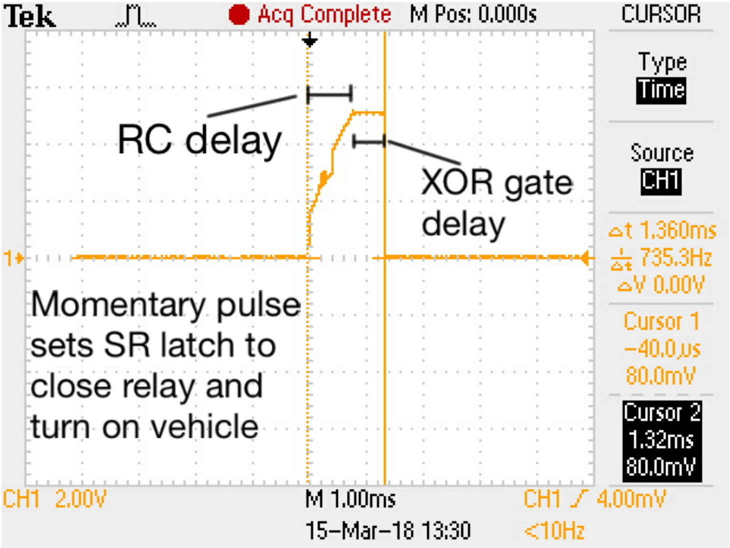


Figure 70: XOR RC pulse duration

4.6 Summary

Using this methodology, the entire vehicle wiring and subsystem design was created. In compliance with FSAE rules, all systems were developed in order to be easily demonstrated at competition. The testing reflected in this section is critical to the development of the resulting systems and should be used to prevent repeating research or repeating engineering practices that represent faults in our system. In the case of the design challenges of shifting and brake plausibility, testing manifested itself in various design changes that ended in the results following.

5. Results & Discussion

This MQP created multiple deliverables for use in both the 2018 FSAE competition and future years' design work. The first deliverable was the test stand wiring harness that connects all critical components required to run the engine in a standalone configuration. This can be used or easily adapted in the future for proof of concept. The next deliverable was the primary wiring harness custom-made for the 2018 FSAE vehicle. Furthermore, an electronic shifting system was installed on the vehicle complete with a driver interface. This MQP also delivered all required safety circuitry to be compliant with the FSAE rules. Finally, the team produced comprehensive documentation and kept all specification sheets for future reference.

5.1 Engine Test Harness - Primary Harness Prototype

The proof of concept, test stand wiring harness served its purpose in allowing the team to test engine performance before the frame was physically available for wiring of the primary vehicle harness. When attempting to wire the physical connectors of the harness, it occurred to the team that a standard must be created in order to ensure that all of the connections in the connector corresponded on both sides to one another. Therefore, a simple Excel document was created that determined how the connections from the component were being represented in each connector. This document, included in the .zip file submitted with this report, contained each side of the connector and was a rolling document to determine wiring progress as well as maintain a record of which pin on each connector contained which connections. A photo of the test stand wiring harness can be seen in Figure 71 on the test stand.

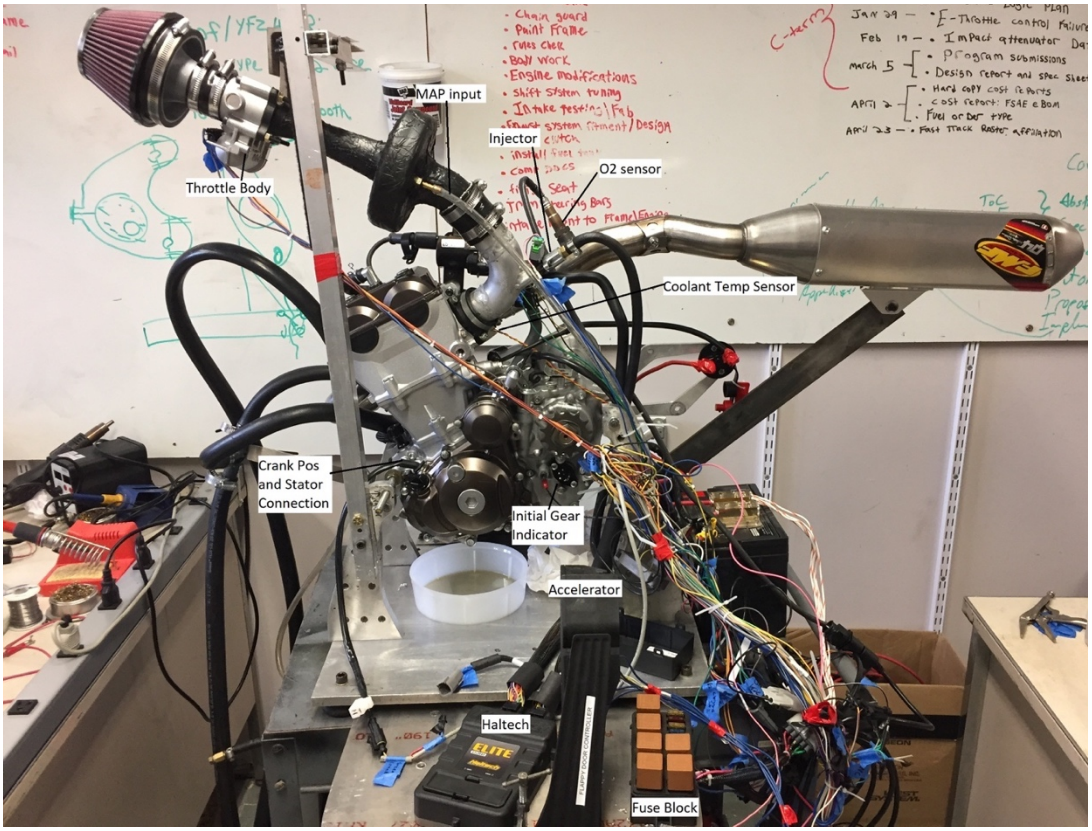


Figure 71: Test-stand wiring harness installed

The wiring harness contained all of the sensors required for the engine to be run but had some length requirement issues. At the time of construction, there were very few mechanical designs in place, such as the air intake design, that ideally should have first determined the length of various wires in the harness. Having to make an educated guess on physical wiring resulted in some of the wire runs being too short in the end product which constrained how components had to be placed for testing. Using the wiring procedure in Appendix B along with the wiring diagrams created for the vehicle in Cadence in Appendix E, only one wiring error was made throughout the entire process of wiring the vehicle which was determined to be unrelated to wiring procedure. It was determined that the ignition coil, which was believed to be a General Motors LS1 coil, was in fact an LS2 coil and has a different pinout in the same connector. This resulted in no spark and the connector simply had to be re-wired according to the LS2 pinout.

Except for the ignition coil wiring mistake, all harness and sensor function was determined to work through the test harness, all actuators and sensors were calibrated using the testing harness that were then transferred to the production harness on the vehicle. This harness used a pre-terminated Haltech connector that mitigated the need to terminate wires on the Haltech side.

5.2 Primary Wiring Harness - Engine Management System

The primary harness also resulted in the same exact wiring issue as with the prototype harness with the ignition coil. This error arose from a communication error that resulted in the wiring diagram being changed and the wiring being flipped twice in the physical car. The packaging concerns of the final harness were addressed and special care was taken in order to ensure that heat was avoid as much as possible. The primary wiring harness, removed from the vehicle, can be seen in Figure 72, Figure 73, and Figure 74.

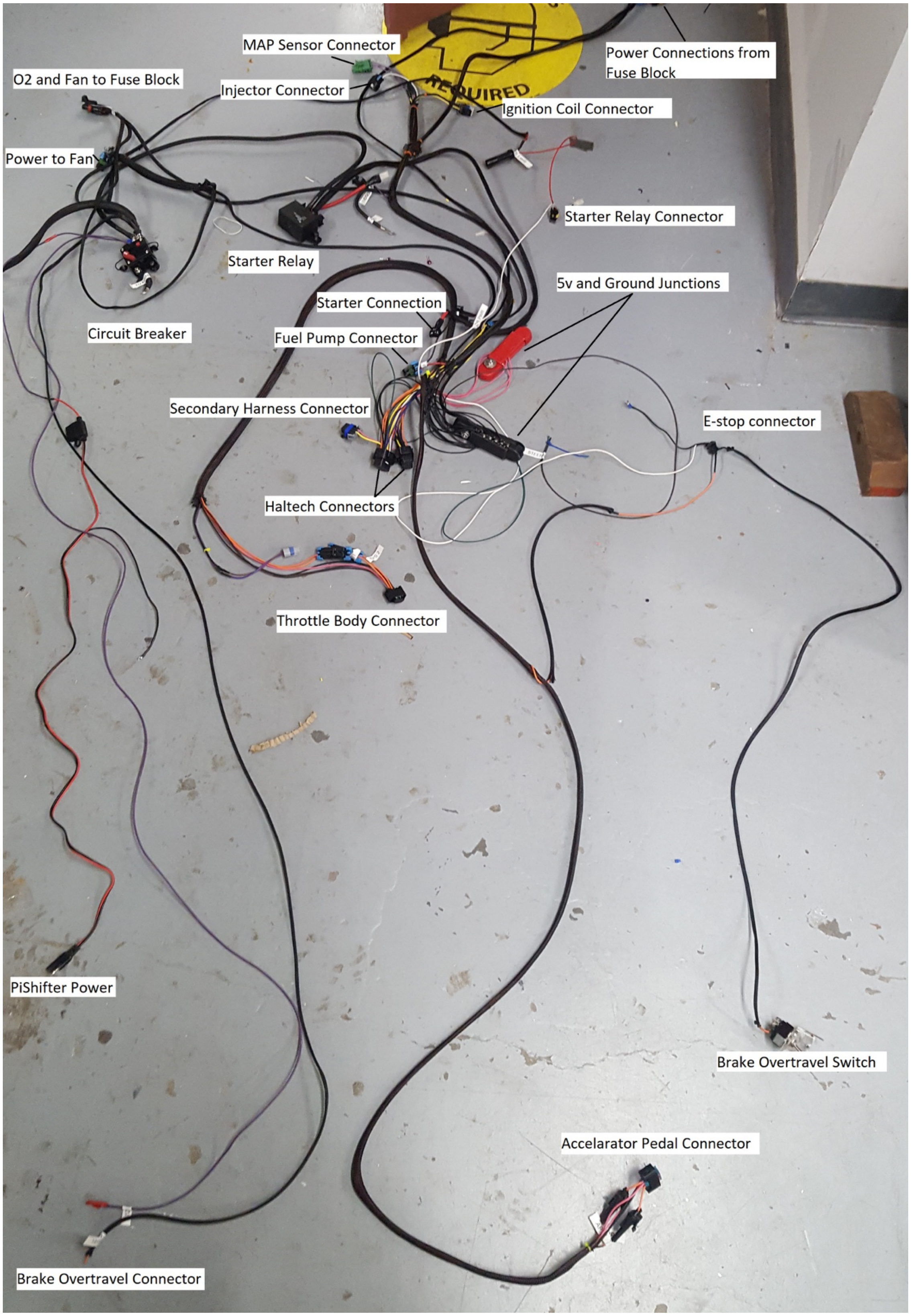


Figure 72: Primary vehicle wiring harness

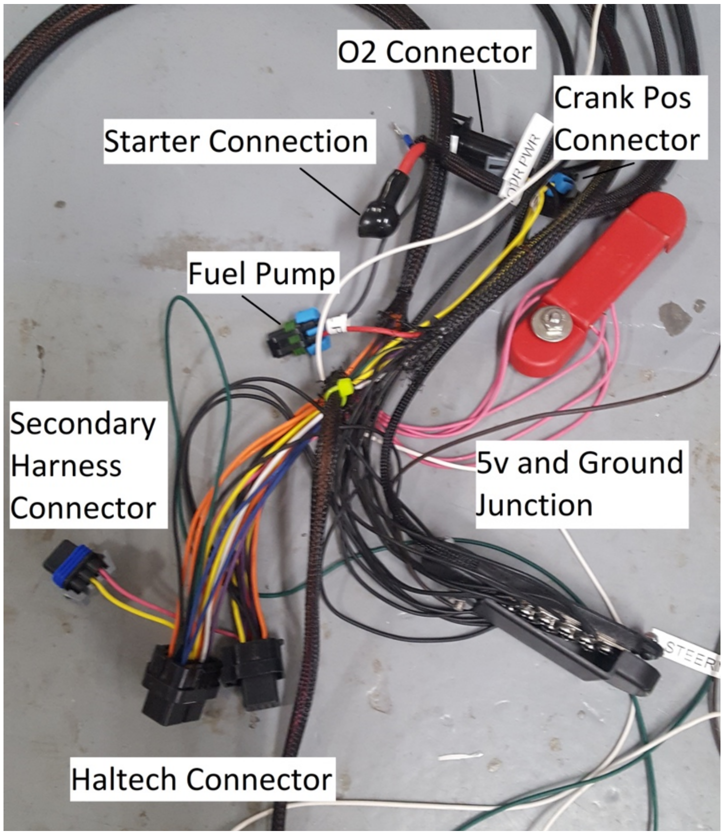


Figure 73: Primary wiring harness Haltech connectors and terminal blocks

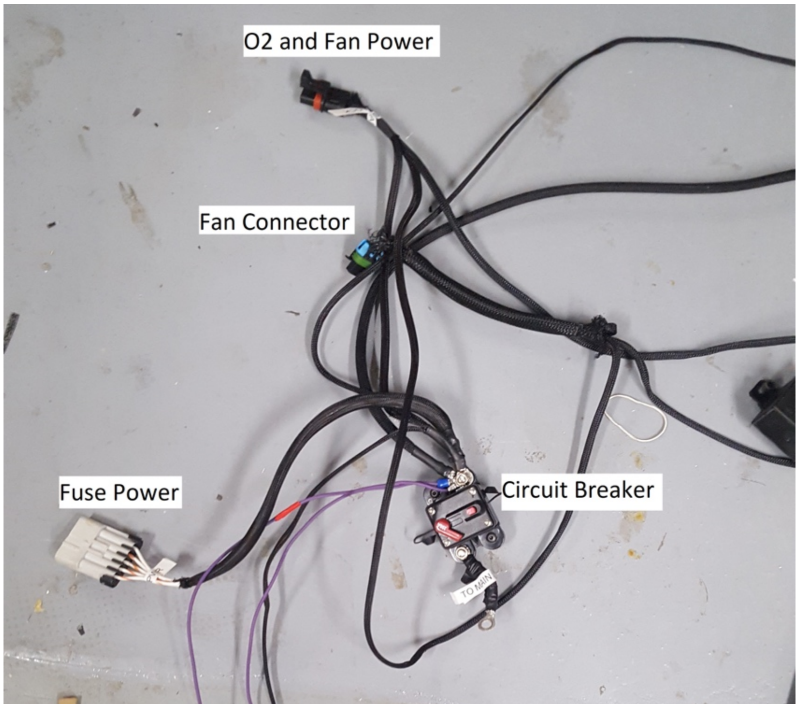


Figure 74: Primary wiring harness circuit breaker and fuse box connection

To date, no wiring harness failure has occurred due to heat or other environmental conditions to which the vehicle has been exposed in testing. No looming has melted, and cable routing has been kept far cleaner than in previous years, resulting in easier engine access and ventilation. We anticipate no issues with continued use of the current wiring harness in the foreseeable future.

5.3 Analog-to-Digital Converter

The analog-to-digital converter is currently unused in the vehicle for the reasons explained previously. There is no immediate need for the MSP430 in the design and unless a need arises for a microcontroller and an ADC, the MSP430 will not be integrated into the secondary or tertiary harnesses.

5.4 Shifting System

The proposed design of the shifting system was based on a motor, relays, and a custom tunable timing circuit as a controller. This design had the advantage of design simplicity and met the minimum requirements agreed upon by the electrical and mechanical teams. However, the prototype implementations were plagued with errors, such as not turning off properly or not triggering at all. This was not reliable enough for the harsh environment of the vehicle. We decided to base a new design on a microcontroller for greater reliability. This had the added advantage of implementing a number of extra features, since we were going to the trouble of redesigning the system.

The redesigned system is based on the same motor but uses a solid-state h-bridge motor driver and a Python control script running on a Raspberry Pi. The proof of concept system required a significant amount of debugging but ended up being reliable. We were able to implement additional features such as powered return to center for the motor, a shift indicator line to the Haltech, and a seven-segment display for the driver showing the current gear - which was not displayed in previous vehicles. The final design is significantly more complicated to implement than we originally intended, largely due to using a full Linux system as a controller. The added functionality of the system far outweighs the complexity and the system is much easier to upgrade in the future - only requiring updates to the Python script and interface expansion instead of a full circuit redesign.

5.5 Rules Compliance

Design work of the base wiring harness was completed before significant research went into the FSAE rules. The goal was to get the engine running as quickly as possible so that the Mechanical Engineers could begin tuning work. While this helped the greater competition team, it put the ECE team in a tough position as we then had to go back and adapt systems to be compliant. This was done much later than we would have preferred, also due to some schedule setbacks of vehicle frame welding. Though it was done later, the vehicle complies with FSAE rules to the best of our knowledge and is ready for competition in Michigan in May of 2018.

The Brake Plausibility Device was a key component of the electrical rules requirements. Much time went into first understanding the rule and then designing, specifying parts, and prototyping. The team learned a lot about the analog design process and reviewed the design multiple times before any parts were purchased. This paid off because when the parts arrived, the device worked the very first time it was tested on the bench. Once installed in the vehicle, however, there was a minor problem. The brake pressure sensors (Honeywell MLH03KPSB01A [50]) were determined to be less sensitive than expected, giving a lower voltage output at a hard brake pedal pressure than the circuit was originally designed for. The brake pressure sensors were characterized over a variety of pedal pressures and the voltage divider setting the comparator threshold was modified to be a lower value. Once a single resistor was switched out, the Brake Plausibility Device performed as designed.

5.6 Summary

Overall, our system meets project requirements and a number of optional project goals. The primary engine harness, secondary harness, and shifting system did encounter some errors in design or implementation, but none were impossible to fix. As a group, we also designed some systems potentially useful for future teams. The electrical system meets all rules requirements for FSAE competition in addition to reliably controlling the vehicle.

6. Conclusions

The electrical implementation of the 2017-2018 Formula SAE car is designed to be a baseline that allows the car to be easily wired and expanded upon in future years. This document provides critical information on rewiring each piece of the modular system. The primary wiring harness is labeled and prepared in order to provide a reusable harness that can be used as a baseline for other secondary and tertiary harnesses to be implemented. Future ECE Major Qualifying Projects will therefore be able to focus on adding and creating new secondary and tertiary wiring harnesses that are compatible with the primary harness in order to provide better telemetry capabilities and better support a racing environment for the driver.

All of the work accomplished in this project began with an analysis of previous vehicle electrical designs and how to most effectively design a system that allowed for vehicle reliability and potentially modularity. It occurred to the team through this analysis that the creation of a multi-harness system would render the designs created in this project most effective. Heading forward with this methodology, harnesses were isolated into sections in order to give the car certain functionality with each harness.

The design of the primary harness required the most forethought and time in order to wire it effectively. Research on electrical connectors was also critical as connectors had been a point of failure in previous years. All electrical connection decisions were documented and double checked. This methodical decision making and wiring process rendered a final product that was extremely neat and easy to implement both in the case of the test harness, primary harness and secondary harness.

From this point, the main focus shifted to secondary designs such as brake plausibility and shifting. Two designs were created for each. With delays in the shifting design process due to a lack of frame during an intended testing period, the initial design presented was not installed until late in February which created a great time constraint with testing. It was discovered that the overall concept of the shifting control was inadequate due to a lack of desire to implement driver training. Therefore, the microcontroller based PiShifting was implemented as a fool-proof primary shifting function while the relay system was utilized as a backup system.

Brake plausibility device design began in January and was bench tested through February, then was implemented without issue. Time constraints did not allow for the development of a PCB design, however this implementation would be ideal. The remainder of the year was spent verifying rules and ensuring Formula SAE compliance.

6.1 Future Work

Future work will entail shifting improvements as well as the addition of a variety of sensors that provide greater feedback for the driver and team while racing for an improved driver experience. Wheel speed sensors, accelerometers, GPS tracking, and wireless transmission of data are all areas that should be implemented in future work. The development of greater dashboard input that provides the driver with dynamic data as well as engine data and warning can easily be implemented into a future tertiary harness that allows for better support for the driver and team.

Data logging will provide the team with the ability to justify design results with more data and allow for improvements in the mechanical design. Suspension sensors, GPS tracking, wheel speed sensors, and accelerometers will allow the team to better test and tune and should be a critical part of any future work that attempted in the electrical design of the Formula SAE program.

With the materials delivered in this document and the deliverables provided, there is no need to reinstate the design of a baseline harness with a full redesign. Instead, work must be done to increase shifting reliability and performance as well as provide the team with the resources necessary to further the score of the team at competition. Any future work should be judged using the baseline done in this project and should represent an improvement in both the electrical and mechanical scoring of the team in the design events as well as an improvement of vehicle performance on the track without sacrificing reliability.

Overall, this project purposely represents a rollback of the 2016 design implementation. Considering the incomplete work of previous projects and the added benefits of electronic shifting, gear indication, and a modular design, the systems implemented provide the ideal foundation for adding this functionality in the future, exactly as we intended. No future work should sacrifice this reliability in order to achieve new goals in design. Competition is the benchmark by which future work should be judged.

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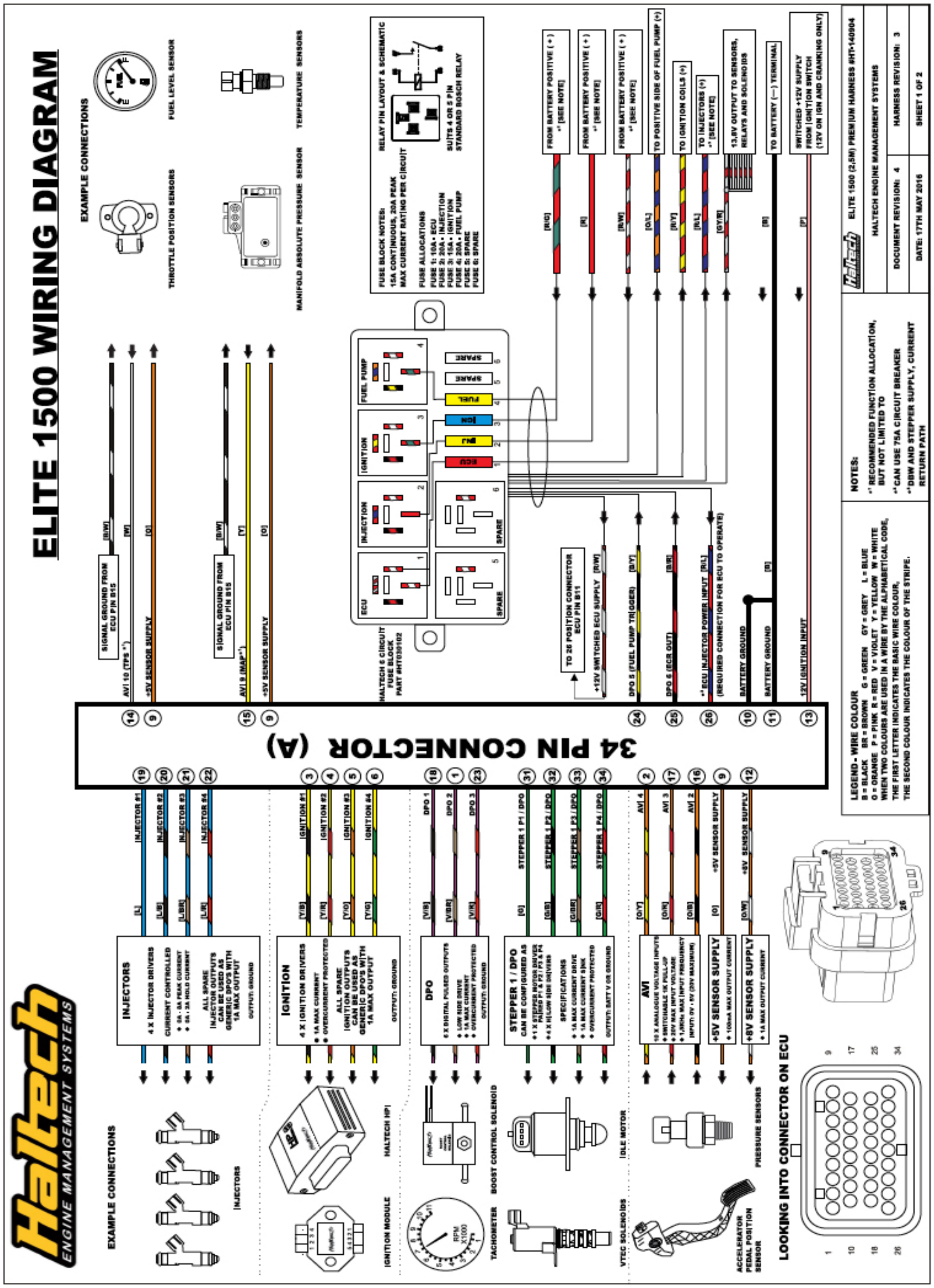
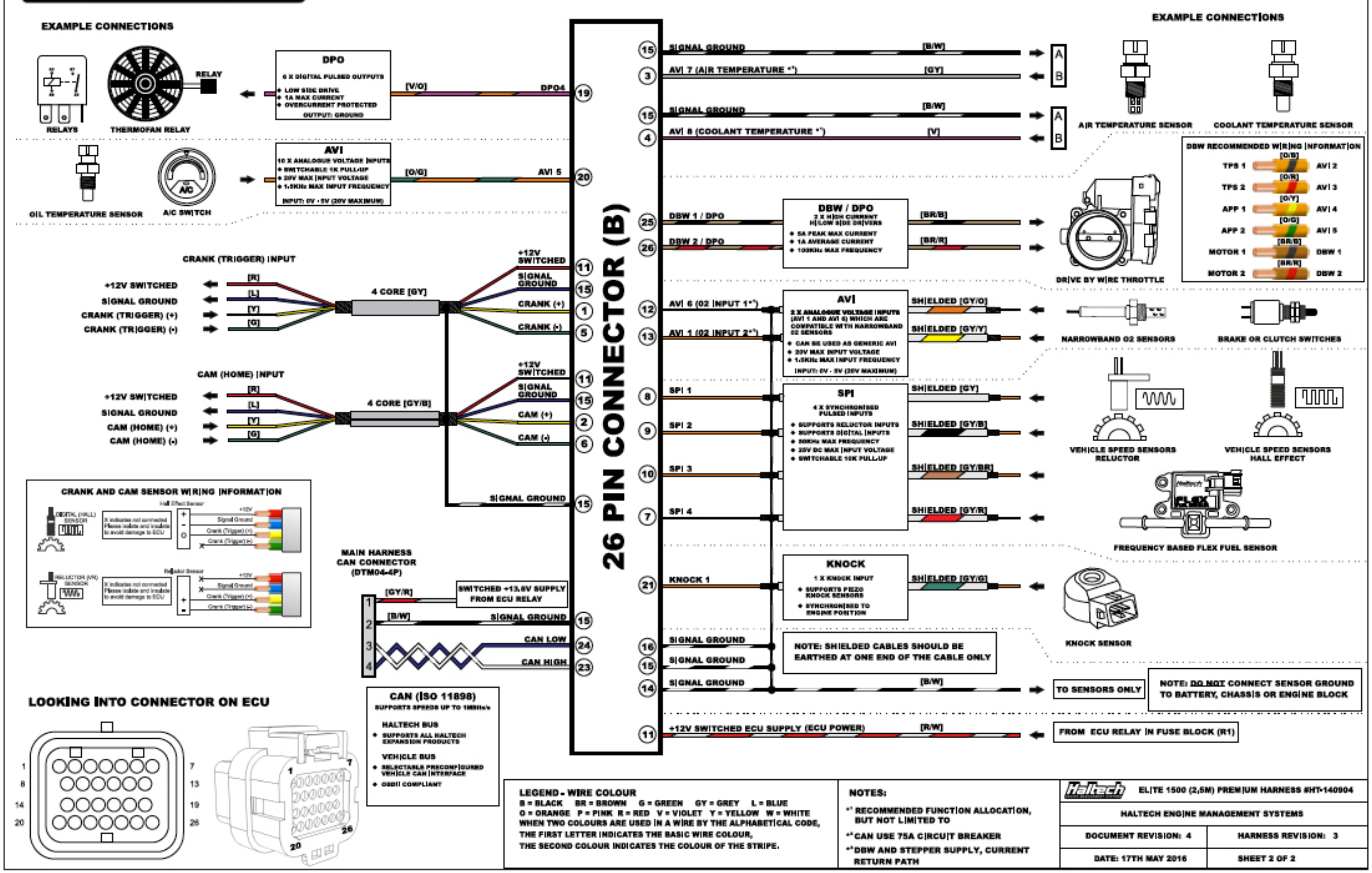
Appendices

Appendix A: Haltech Elite 1500 Schematic [51]



ELITE 1500 WIRING DIAGRAM



LEGEND - WIRE COLOUR

B = BLACK BR = BROWN G = GREEN GY = GREY L = BLUE
O = ORANGE P = PINK R = RED V = VIOLET Y = YELLOW W = WHITE
WHEN TWO COLOURS ARE USED IN A WIRE BY THE ALPHABETICAL CODE,
THE FIRST LETTER INDICATES THE BASIC WIRE COLOUR,
THE SECOND COLOUR INDICATES THE COLOUR OF THE STRIPE.

NOTES:

*1 RECOMMENDED FUNCTION ALLOCATION, BUT NOT LIMITED TO
*2 CAN USE 75A CIRCUIT BREAKER
*3 DBW AND STEPPER SUPPLY, CURRENT RETURN PATH

ELITE 1500 (2,5M) PREMIUM HARNESS #HT-140904	
HALTECH ENGINE MANAGEMENT SYSTEMS	
DOCUMENT REVISION: 4	HARNESS REVISION: 3
DATE: 17TH MAY 2016	SHEET 2 OF 2

Appendix B: Engine Wiring Harness Procedure

In order to minimize confusion, potential open or short connections, as well as signal matching, the following procedure will be utilized while wiring the engine test stand wiring.

Label all non-ECU terminations with proper Cadence labeling nomenclature _________________

Ensure Haltech connector both 34-pin 26-pin terminate in proper pinout
consulting Haltech Pinout diagram and continuity test _________________

Beginning with 34 pin connector moving from the pin 1 to the 34-pin in order, mark labels and bundle tested wires.

-unused leads and wrap for termination upon completion of wiring

____

Beginning with 26-pin connector moving from the pin 1 to the 26-pin in order, mark labels and bundle tested wires.

-unused leads and wrap for termination upon completion of wiring

____

Wire pigtails for each relay with individual connector for each relay, 14-gauge wire:
Certify and witness all relay connections:

Table 7: Relay connection sign-off sheet

Relay and Fuse	Certified By	Witnessed By
ECU		
Injection		
Ignition		
Fuel Pump		

_________________________ _________________________

Complete connector wiring individually for each component, certify each connection is complete with continuity check on each wire after crimp is made in connector, once all connections are made in each connector, re-check continuity on all wires in connection from Haltech connector to component connector end.

If circuit from component to Haltech has multiple connectors, continuity check should be repeated for each new connector until entire lead is complete, if relay is in line with electrical connection, connection should be bridged to form continuity without relay present. Certify and Witness for each full-length lead

Table 8: Continuity test sign-off sheet

Component	Certified	Witnessed
Fuel Pump		
Coil		
Crank Position		
Air Temp		
Coolant Temp		
O2 Sensor		
Accelerator Pedal		
Map Sensor		
DBW		
Injector		

Once all connections are made, recheck and certify all connections have continuity and are witnessed.

Appendix C: Brake Plausibility Device Components and Connections

Table 9: LM7805 connection table

Device: LM7805C	Description: 12V to 5V Voltage Regulator
Link	http://www.onsemi.com/pub/Collateral/MC7800-D.PDF [52]
Pin	Connection
1	+12V input
2	GND
3	+5V output

Table 10: MCP6542 connection table

Device: MCP6542	Description: Dual Comparator
Link	http://ww1.microchip.com/downloads/en/devicedoc/21696f.pdf [53]
Pin	Connection
1	SN74HCT08N pin 1
2	Brake Vref, input capacitor 1
3	Brake signal, input capacitor 1
4	GND
5	TPS signal, input capacitor 2
6	TPS Vref, input capacitor 2
7	SN74HCT08N pin 2
8	+5V

Table 11: SN74HCT08N connection table

Device: SN74HCT08N	Description: Quad AND-Gate
Link	http://www.ti.com/lit/ds/symlink/sn74hct08.pdf [54]
Pin	Connection
1	MCP6542 pin 1
2	MCP6542 pin 7
3	Resistor, CD4047BE pin 8
4	Resistor, capacitor
5	CD4047BE pin 11
6	CD4043BE pin 3
7	GND
8	NC
9	GND
10	GND
11	NC
12	GND
13	GND
14	+5V

Table 12: CD4047BE connection table

Device: CD4047BE	Description: One-shot
Link	http://www.ti.com/lit/ds/symlink/cd4047b.pdf [55]
Pin	Connection
1	Capacitor -
2	Resistor
3	Capacitor +, Resistor
4	Resistor to +5V
5	GND
6	GND
7	GND
8	SN74HCT08N pin 3
9	GND
10	NC
11	SN74HCT08N pin 5
12	GND
13	NC
14	+5V

Table 13: CD4043BE connection table

Device: CD4043BE	Description: SR Latch
Link	http://www.ti.com/lit/ds/symlink/cd4044b-mil.pdf [56]
Pin	Connection
1	NC
2	NUD3112 pin 1
3	SN74HCT08N pin 6
4	SN74AHC86N pin 3
5	Pull up resistor to +5V
6	NC
7	NC
8	GND
9	NC
10	NC
11	NC
12	NC
13	NC
14	NC
15	NC
16	+5V

Table 14: SN74AHC86N connection table

Device: SN74AHC86N	Description: Quad XOR Gate
Link	http://www.ti.com/lit/ds/symlink/sn54ahc86.pdf [57]
Pin	Connection
1	Pull up resistor to +5V
2	Pull up resistor to +5V, Capacitor to GND
3	CD4043BE pin 4
4	GND
5	GND
6	NC
7	GND
8	NC
9	GND
10	GND
11	NC
12	GND
13	GND
14	+5V

Table 15: NUD3112 connection table

Device: NUD3112	Description: Relay Driver
Link	http://www.onsemi.com/pub/Collateral/NUD3112-D.PDF [58]
Pin	Connection
1	CD4043BE pin 2
2	GND
3	Relay pin 85

Note: Connect any unused gate inputs low, leave output floating

Appendix D: ETC Notice of Intent

Notice of Intent - Teams planning to build an electronically controlled throttle complying with IC1.11-IC1.16 for entry into a North American competition must notify the Rules Committee of their intent by the date specified in the action deadlines for the competition. Submit the ETC Notice of Intent as instructed on the event website. For Michigan and Lincoln events submit through fsaeonline.com.

**Competitions may choose to apply limits to the number of ETC entries that they take and therefore the Notice of Intent may be used to screen which teams are accepted to build an ETC to the appropriate regulations.

University Name: Worcester Polytechnic Institute
Car # and Event(s): 084, FSAE Michigan 2018
Team Contact: Cote Taylor Email: ctaylor@wpi.edu
Faculty Advisor: David Planchard Email: planchard@wpi.edu

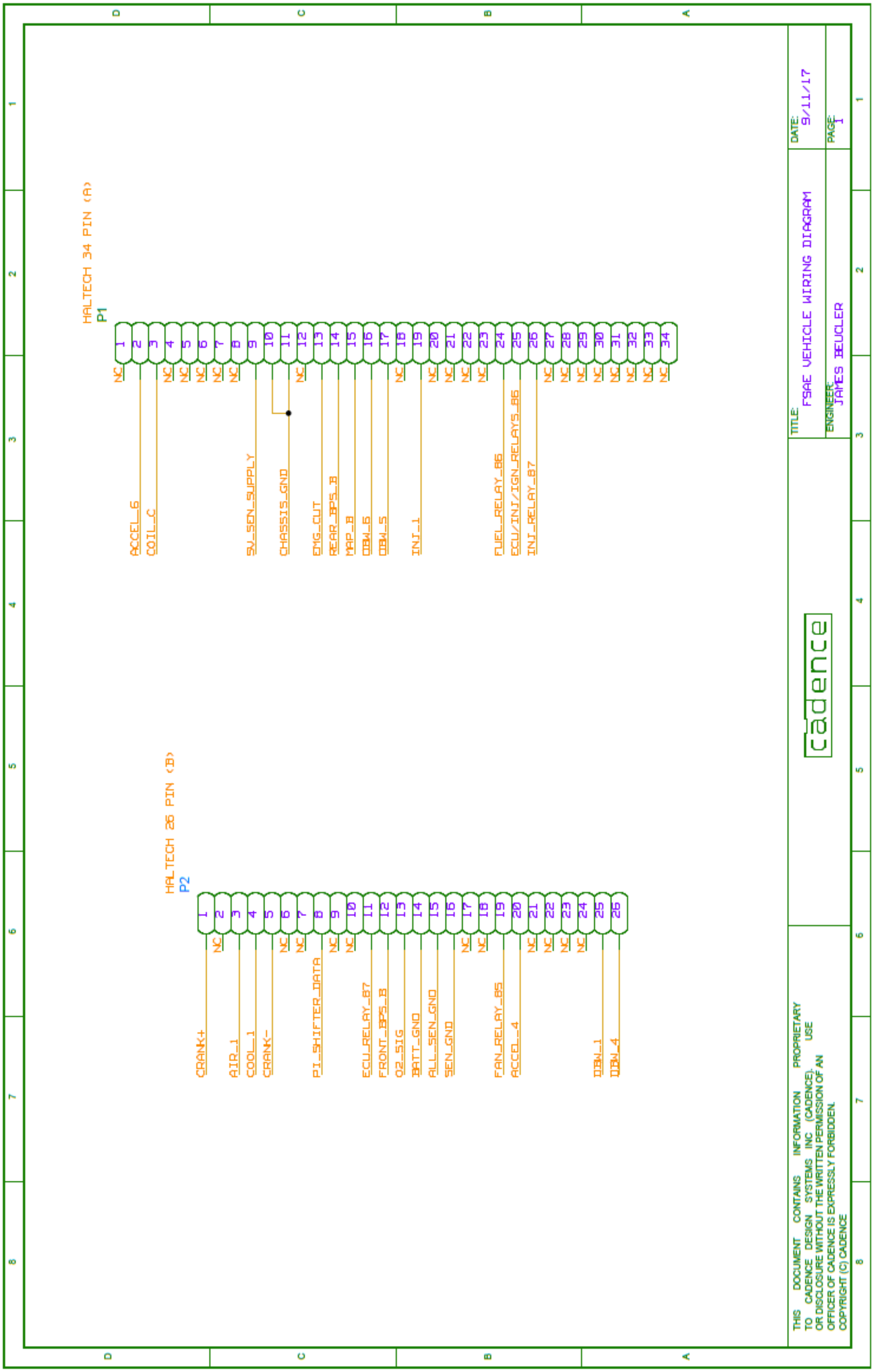
Include a short paragraph detailing your team's outline design and showing that you have the capability to design the electronic systems. Your "Notice of Intent" should include the email addresses and phones numbers of the team members who can answer any questions the Committee may have about your proposal.

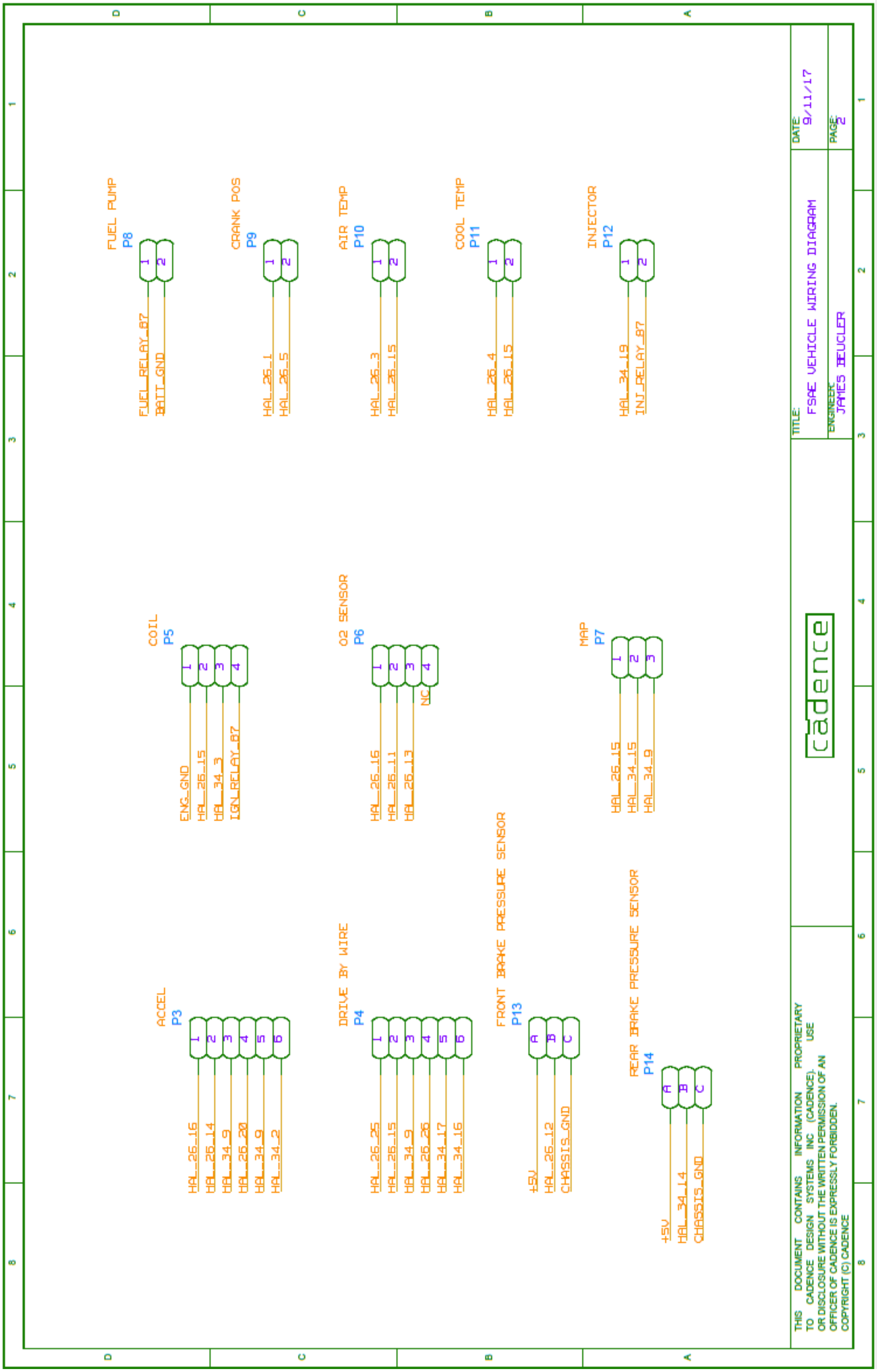
Our team will be using a BMW accelerator assembly consisting of the accelerator module and pedal, part number 35426786282. This accelerator pedal will be connected to a 40mm Bosch Automotive throttle body, part number 0280750149, controlled through the vehicle's Haltech ECU. Pins 1 and 2 of the accelerator pedal will be ground (0V), pins 3 and 5 will be +5V supply, and pins 4 and 6 will be reserved for accelerator pedal signal. On the electronic throttle body, pin 2 will be ground (0V), pin 3 will be +5V supply, and pins 1, 4, 5, and 6 will be reserved for the signal. Appropriate safety precautions will be taken in accordance to rules IC1.11- IC1.16, and all other applicable electronic safety regulations. Electrical design will utilize knowledge of courses such as ECE2019 (Sensors, Circuits, and Systems), ECE 2311 (Continuous-Time Signal & System Analysis), ECE2049 (Embedded Computing in Engineering Design), and ECE2799 (ECE Design). The team responsible for the vehicle's electrical system including the electronically controlled throttle includes two Senior Electrical & Computer Engineering (ECE) students and one Junior ECE student currently enrolled at Worcester Polytechnic Institute in Worcester, Massachusetts. James Beucler can be reached at username@wpi.edu or (xxx)xxx-xxxx, Gage Laskowski can be reached at username@wpi.edu or (xxx)xxx-xxxx, and Galahad Wernsing can be reached at username@wpi.edu or (xxx)xxx-xxxx for any questions.

Approved by____ Date_____________

NOTE: THIS FORM AND THE APPROVED COPY OF THE ETC FMEA SUBMISSION MUST BE PRESENTED AT TECHNICAL INSPECTION IF REQUESTED.

Appendix E: Cadence Schematic




FUEL PUMP
P8
1
2
FUEL_RELAY_87
BATT_GND
CRANK POS
P9
1
2
HAL_26_1
HAL_26_5
AIR TEMP
P10
1
2
HAL_26_3
HAL_26_15
COOL TEMP
P11
1
2
HAL_26_4
HAL_26_15
INJECTOR
P12
1
2
HAL_34_19
INJ_RELAY_87
COIL
P5
1
2
3
4
ENG_GND
HAL_26_15
HAL_34_3
IGN_RELAY_87
O2 SENSOR
P6
1
2
3
4
HAL_26_16
HAL_26_11
HAL_26_13
NC
MAP
P7
1
2
3
HAL_26_15
HAL_34_15
HAL_34_9
ACCEL
P3
1
2
3
4
5
6
HAL_26_16
HAL_26_14
HAL_34_9
HAL_26_20
HAL_34_9
HAL_34_2
DRIVE BY WIRE
P4
1
2
3
4
5
6
HAL_26_25
HAL_26_15
HAL_34_9
HAL_26_26
HAL_34_17
HAL_34_16
FRONT BRAKE PRESSURE SENSOR
P13
A
B
C
+5V
HAL_26_12
CHASSIS_GND
REAR BRAKE PRESSURE SENSOR
P14
A
B
C
+5V
HAL_34_14
CHASSIS_GND
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TITLE:
FSAE VEHICLE WIRING DIAGRAM
ENGINEER:
JAMES BEUCLER
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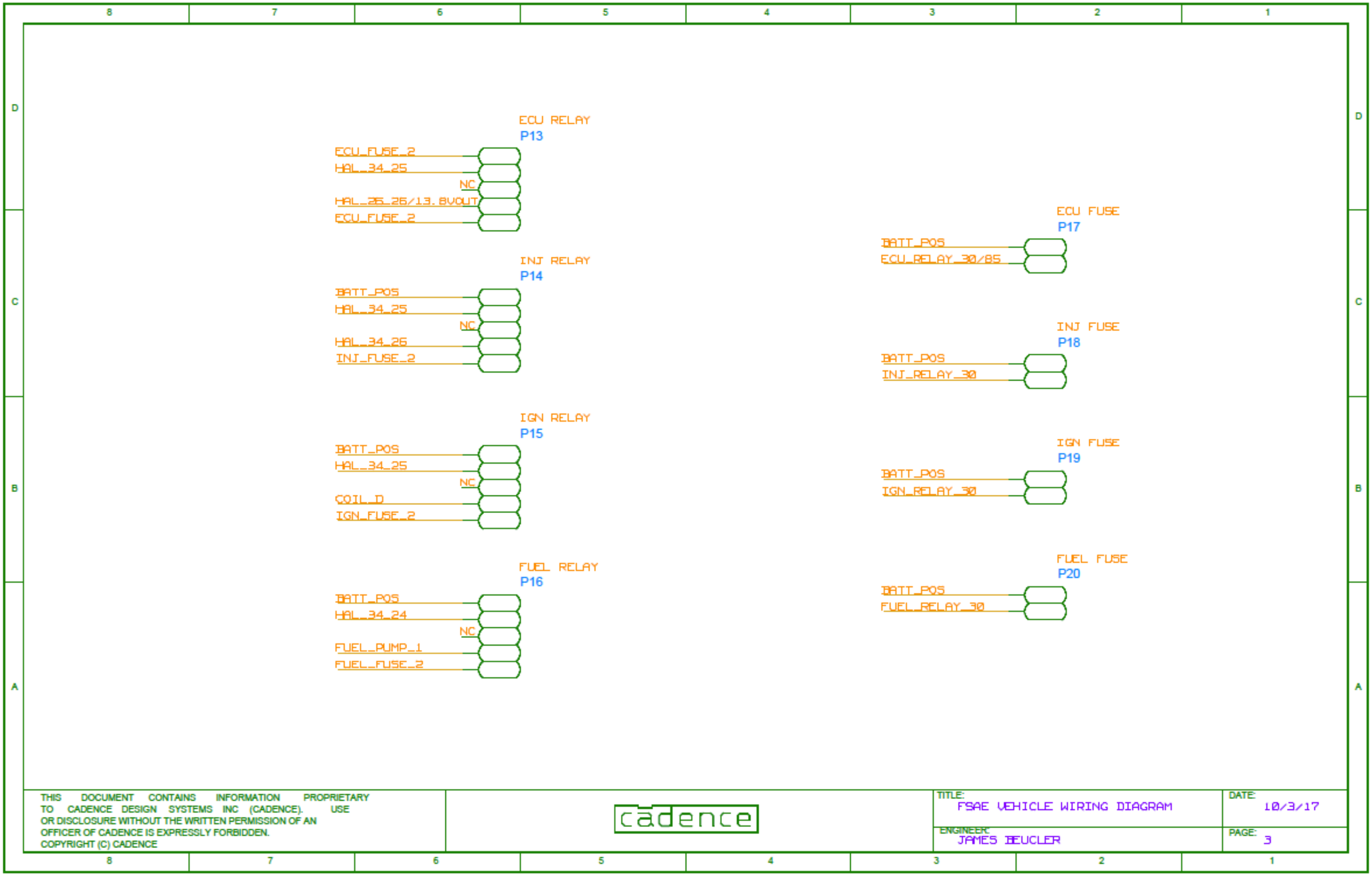
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P13
ECU_FUSE_2
HAL_34_25
NC
HAL_25_26/13.8VOUT
ECU_FUSE_2
INJ RELAY
P14
BATT_POS
HAL_34_25
NC
HAL_34_26
INJ_FUSE_2
IGN RELAY
P15
BATT_POS
HAL_34_25
NC
COIL_D
IGN_FUSE_2
FUEL RELAY
P16
BATT_POS
HAL_34_24
NC
FUEL_PUMP_1
FUEL_FUSE_2
ECU FUSE
P17
BATT_POS
ECU_RELAY_30/85
INJ FUSE
P18
BATT_POS
INJ_RELAY_30
IGN FUSE
P19
BATT_POS
IGN_RELAY_30
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BATT_POS
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cadence
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FSAE VEHICLE WIRING DIAGRAM
ENGINEER:
JAMES BEUCLER
DATE:
10/3/17
PAGE:
3
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D
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A

Appendix F: Shift Harness Wiring

Steering Wheel Pogo Pins

1	NO button 1
2	NO button 2
3	NO button 3
4	Buttons 1,2,3

Column Pogo Pins

1	Connector A 1
2	Connector A 2
3	Connector A 3
4	Ground

Relay Sockets

A 30	Motor
A 85	Connector A 1
A 86	12V
A 87	12V
A 87a	Ground
B 30	Motor
B 85	Connector A 3
B 86	12V
B 87	12V
B 87a	Ground

use TE 1432790-1 relays

Motor Controller

12V	A 87
Out 1	A 30
Out 2	B 30
Ground	B 87a

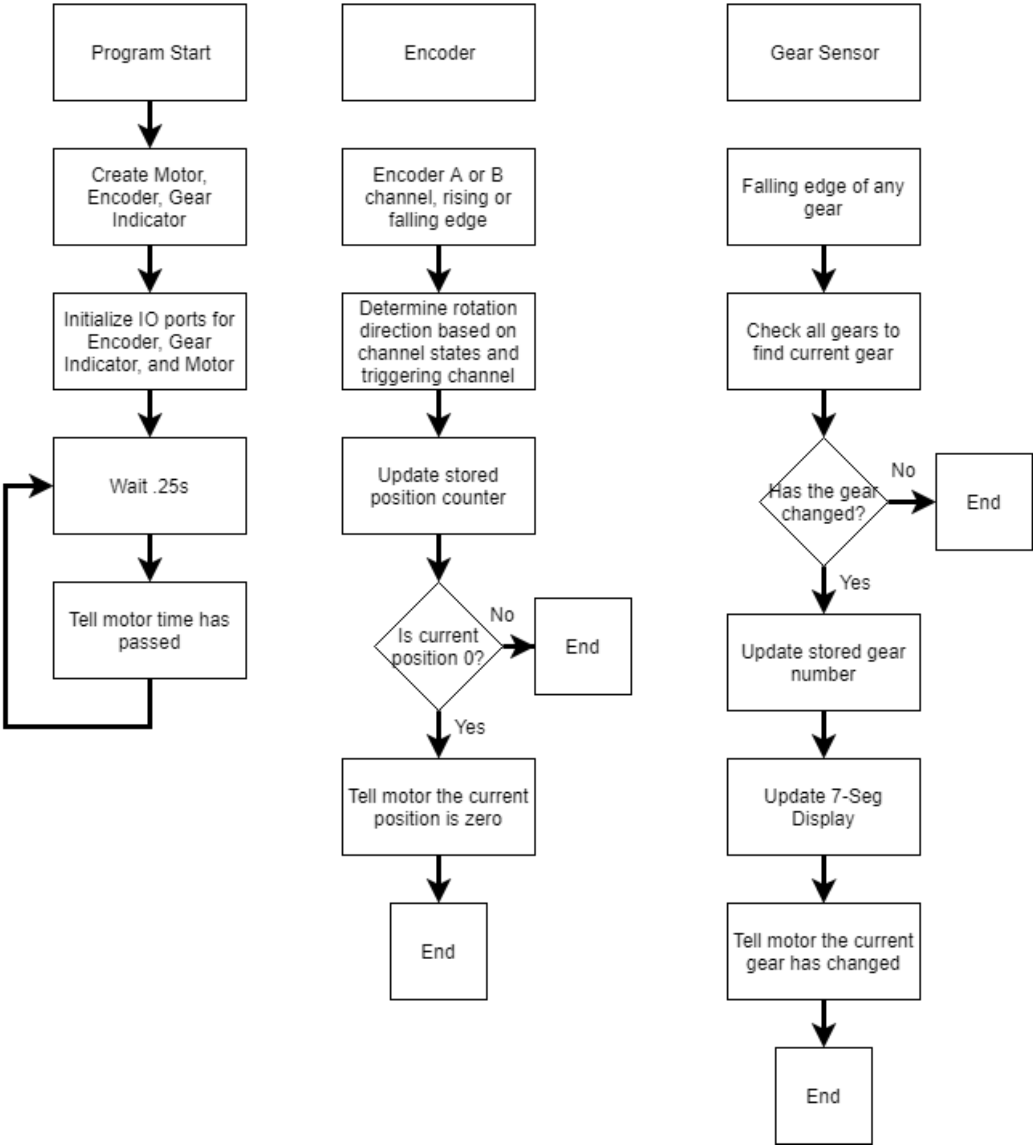
PiShifter (board numbering)

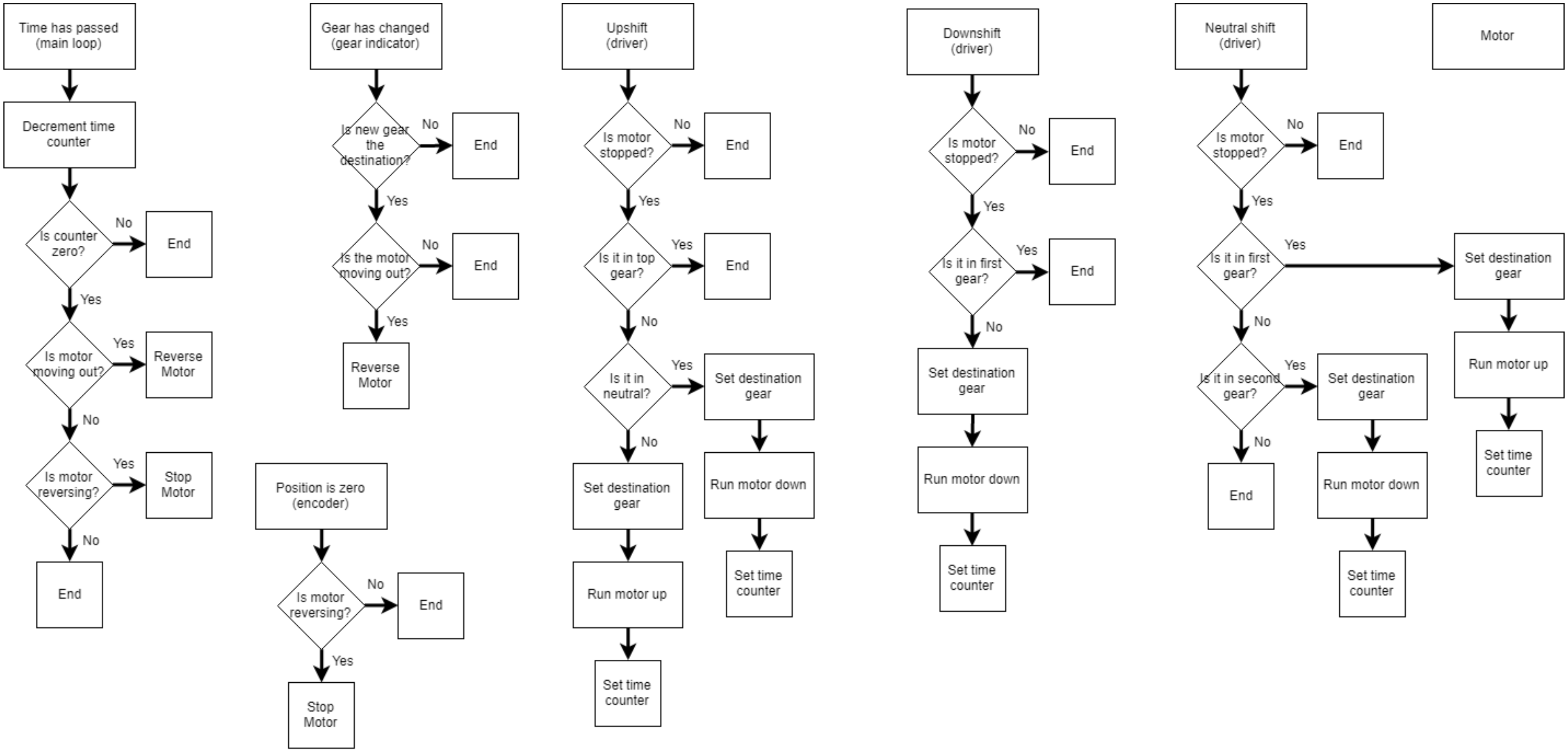
19	Gear sensor 1	
21	Gear sensor 2	
23	Gear sensor 3	
29	Gear sensor 4	
31	Gear sensor 5	
33	Gear sensor 6	
36	Motor controller DIR	
38	Motor controller PWM	
34	Motor controller ground	
8	Encoder A	diode, resistor protected
10	Encoder B	diode, resistor protected
4	Encoder 5V	
6	Encoder ground	
40	Status LED	resistor in series
11	Connector A 1	
13	Connector A 2	
15	Connector A 3	
32	Shift Indicator to Haltech	

Seven Segment Display requires 3 GPIO output lines

Numbers depend on Python script

Appendix G: PiShifter Code Flowchart




Time has passed (main loop)
Decrement time counter
Is counter zero?
No
End
Yes
Is motor moving out?
Yes
Reverse Motor
No
Is motor reversing?
Yes
Stop Motor
No
End
Gear has changed (gear indicator)
Is new gear the destination?
No
End
Yes
Is the motor moving out?
No
End
Yes
Reverse Motor
Position is zero (encoder)
Is motor reversing?
No
End
Yes
Stop Motor
Upshift (driver)
Is motor stopped?
No
End
Yes
Is it in top gear?
Yes
End
No
Is it in neutral?
Yes
Set destination gear
Run motor down
Set time counter
No
Set destination gear
Run motor up
Set time counter
Downshift (driver)
Is motor stopped?
No
End
Yes
Is it in first gear?
Yes
End
No
Set destination gear
Run motor down
Set time counter
Neutral shift (driver)
Is motor stopped?
No
End
Yes
Is it in first gear?
Yes
Set destination gear
Run motor up
Set time counter
No
Is it in second gear?
Yes
Set destination gear
Run motor down
Set time counter
No
End
Motor

Appendix H: PiShifter Python Script

```
import RPi.GPIO as GPIO
import time
import sys

GPIO.setmode(GPIO.BOARD)
GPIO.setwarnings(False)


motor = 0
encoder = 0
gear_indicator = 0

class EncoderClass:
    encoders = [8,10]

    position = 0

    def update_position(self, triggered_line):
        delta = 0
        if GPIO.input(self.encoders[0]) is GPIO.input(self.encoders[1]):
            delta = 1
        else:
            delta = -1
        if triggered_line is 'b': delta = -delta
        self.position = self.position + delta
        if self.position % 20 is 0: print self.position
        if self.position is 0: motor.enc_at_zero()

    def encoder_tick_a(self, event):
        self.update_position('a')

    def encoder_tick_b(self, event):
        self.update_position('b')

    def start_detectors(self):
      GPIO.add_event_detect(self.encoders[0], GPIO.BOTH, self.encoder_tick_a)
      GPIO.add_event_detect(self.encoders[1], GPIO.BOTH, self.encoder_tick_b)

    def __init__(self):
      GPIO.setup(self.encoders, GPIO.IN, GPIO.PUD_DOWN)
```

```
class GearIndicatorClass:
    current_gear = 0

    gears = [19, 21, 23, 29, 31, 33]
    #transmission goes 1 n 2 3 4 5
    #in the code, 19 is the pin for neutral (so referenced as 0)

    def read_current_gear(self):
      for gearnum, gear in enumerate(self.gears):
            if not GPIO.input(gear):
                  return gearnum
      else:
                return -2 #-2 makes sure it doesn't stop at neutral-
                #-if it doesn't know what gear it is in
            #this is a problem yo
            #hope for the best

    def update7seg(self):
        return
        #make this do shit later

    def set_gear(self, new_gear):
        self.current_gear = new_gear
        self.update7seg()
        print self.current_gear
        motor.new_gear(self.current_gear)

    def gear_trigger(self, event):
        new_gear = self.read_current_gear()
        if new_gear is self.current_gear:
            return
        self.set_gear(new_gear)

    def get_gear(self):
        return self.current_gear

    def start_detectors(self):
        for x in self.gears:
            GPIO.add_event_detect(x, GPIO.FALLING, self.gear_trigger, 100)

    def __init__(self):
      GPIO.setup(self.gears, GPIO.IN, GPIO.PUD_UP)
        self.current_gear = self.read_current_gear() #change to
gear_trigger(0)?
        print self.current_gear
```

```
class MotorClass:
    statusLED = 40
    errorLED = 37
    buttons = [11,13,15]
    motor_lines = [36,38,32] #[direction, PWM, Flat Foot Shift] ffs is rising
edge triggered

    next_gear = -57 #makes sure stuff doesn't go wrong during initialization

    timeout_ticks = 0
    state = ''

    def tick(self):
        self.timeout_ticks -= 1
        if self.timeout_ticks is 0 and self.state in ['up','down']:
self.run_motor('reverse') #this needs to get changed
        elif self.timeout_ticks is 0 and self.state is 'reverse':
self.run_motor('stop') #covers for encoder failure

    def enc_at_zero(self):
        if self.state is 'reverse': self.run_motor('stop')

    def new_gear(self, num):
        if num is self.next_gear and self.state in ['up','down']:
self.run_motor('reverse')
        elif num is 0 and self.next_gear in [1,2]: return
        else: return #this should throw an error

    def run_motor(self, direction):#self comes first
        self.state = direction
        # dir pwm ffs
        switch = {'up': [0,1,1], 'down': [1,1,0], 'reverse': [not
GPIO.input(self.motor_lines[0]),1,0]}
        new_output = switch.get(direction, [0,0,0]) #second argument is
default
        print new_output
        GPIO.output(self.motor_lines, new_output)

    def upshift(self, event):
        print "up"
        if self.state is not 'stop': return
        gear = gear_indicator.get_gear()
        if gear is 5: return
        self.next_gear = gear + 1
        if self.next_gear is 1: self.run_motor('down')
        else: self.run_motor('up')
        self.timeout_ticks = 6

    def downshift(self, event):
        print "down"
        if self.state is not 'stop': return
        gear = gear_indicator.get_gear()
        if gear is 1: return
        self.next_gear = gear - 1
        self.run_motor('down')
        self.timeout_ticks = 6
```

```
    def neutral(self, event):
        print "NNNNneutral"
        if self.state is not 'stop': return
        gear = gear_indicator.get_gear()
        if gear is 2:
            self.next_gear = 0
            self.run_motor('down')
            self.timeout_ticks = 6
        elif gear is 1:
            self.next_gear = 0
            self.run_motor('up')
            self.timeout_ticks = 6
        else:
            return

    def start_status_light(self):
        #run LED through 300ohm resistor or bad things happen
        GPIO.output(self.statusLED, GPIO.HIGH)

    def start_detectors(self):
      GPIO.add_event_detect(self.buttons[0], GPIO.FALLING, self.neutral, 500)
      GPIO.add_event_detect(self.buttons[1], GPIO.FALLING, self.upshift, 500)
      GPIO.add_event_detect(self.buttons[2], GPIO.FALLING, self.downshift,
500)

    def __init__(self):
      GPIO.setup(self.statusLED, GPIO.OUT, initial = 0)
      GPIO.setup(self.motor_lines, GPIO.OUT, initial = 0)
      GPIO.setup(self.buttons, GPIO.IN, GPIO.PUD_UP)
      self.run_motor('stop')




motor = MotorClass()
encoder = EncoderClass()
gear_indicator = GearIndicatorClass()

encoder.start_detectors()
gear_indicator.start_detectors()
motor.start_detectors()
motor.start_status_light()

'''
def error():
      #change current state, probably to return to center
      GPIO.output(errorLED, GPIO.HIGH)
'''

while True:
      time.sleep(.25)
      motor.tick()
      #gotta get stuck so the interrupts work


GPIO.cleanup() #this should never run
```