THE UNIVERSITY OF WESTERN AUSTRALIA

School of Electrical, Electronic and Computer Engineering

Final Year Project Thesis

Formula SAE Safety Interlock Circuit & Indicator Instrumentation

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Abstract

With ever increasing fuel prices and environmental impact becoming increasingly concerning, the REV Project continues to push the development of electric vehicles. The safety of such vehicles is paramount and must be addressed to ensure the viability of electric vehicles.

The aim of this project is to develop a comprehensive safety system for the 2012 Formula SAE race car. The primary objective is that it must help to protect the driver and crew from dangerous situations. In addition it must comply with the rules stipulated by the Society of Automotive Engineers Australia.

A highly integrated safety indicator system is also developed. Its purpose is to pinpoint faults in the safety system and effectively communicate this to the driver. A modular component of this system is the dashboard that forms the vital interface between the driver and the state of the car.

From the logical design of the electric system to the safety circuit implemented on a printed circuit board, this is a fully custom design to meet the exact requirements of the Formula SAE car. Due to the importance of safety, development of a robust and reliable safety system was critical and no shortcuts were made to obtain the best possible product.

Acknowledgments

I would like to extend my sincere thanks to Professor Thomas Bräunl for the opportunity to work with and be part of the REV Project. It has been a gratifying experience that will surely help ease my transition into the workforce next year. I wish you and all your future endeavours the best of luck.

The EAGLE community for maintaining and adding to the library of components.

Finally I would like to thank the REV team for all your help throughout the year. I'm sure you will all attest to the fact that we had a lot of fun.

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Nomenclature

SCB	Safety Circuit Box
CSMS	Control System Master Switch
TSMS	Tractive System Master Switch
RtD	Ready to Drive
LV	Low Voltage
HV	High Voltage
HSS	High Speed Steel
NO	Normally Open
NC	Normally Closed
LED	Light Emitting Diode
SPI	Serial Peripheral Interface
EUSART	Enhanced Universal Synchronous Asynchronous Receiver Transmitter
I2C	Inter Integrated Circuit
SAE	Society of Automotive Engineers
REV	Renewable Energy Vehicle Project
PCB	Printed Circuit Board
IO	Input Output
GND	Ground
BMS	Battery Management System
EVMS	Electric Vehicle Management System
uC	Microcontroller
ICSP	In Circuit Serial Programming
DC	Direct Current

1 Introduction

1.1 Electric Vehicle Motivation

The human civilization has heavily relied on the internal combustion engine since its inception some 200 years ago. The pivotal role that this remarkable technology has played in the advancement and industrialization of the human race cannot be overstated. This 19th century invention has persisted to this day and remains central to keeping the economies around the world ticking as well as maintaining the standard of living as we know it.

However, most prominently in the last decade there has been significant research and commercializing of new technologies with the electric vehicle being at the forefront. As the world's insatiable demand for fossil fuels continues to grow year by year, issues of finite resources and environmental consequences are suddenly becoming significant factors that warrant thoughtful consideration if we are to continue on a sustainable growth path into the future.

Electric motors are by no means a new concept however their use as the propulsion system in vehicles is. The general idea is that the internal combustion engine and the fuel which it relies on is replaced by an electric motor(s) and batteries respectively. The fundamental point to note is that by sourcing electricity generated using renewable methods results in a vehicle with significantly reduced emissions. As this technology is developed and prices come down, we may just find ourselves at the dawn of a new era of electric dominated vehicles.

1.2 The REV Project

1.2.1 Brief Overview

The UWA Renewable Energy Vehicle Project (REV) headed by Professor Thomas Braunl is a long-term initiative to develop solutions to secure the vision of a clean and sustainable energy future [1]. Some of the recent successfully completed REV projects have included the conversion of a Hyundai Getz in 2008 called the REV Eco and a Lotus Elise in 2009 called the REV Racer into electrically propelled vehicles. Currently the REV Formula SAE 2012 race car is under construction to be complete by end 2012 and is the focus of this thesis. This is not to be confused with the 'Formula SAE 2010' car [2] which was an electric conversion using an old UWA Motorsports chassis. The proactive and ambitious nature of REV is further demonstrated by a new and exciting project to begin in 2013. It will attempt the conversion of a jet ski, the first electrically powered marine vehicle to enter the REV line-up.

1.2.2 REV Formula SAE

The REV Formula SAE 2012 vehicle is the latest and current project being pursued by REV team 2012. The marked difference with past endeavours is that this is not a conversion; instead a combination of electrical and mechanical student engineers will collaboratively build this car from scratch. This off course brings new and exciting challenges but also gives students the chance to innovate and design every aspect of their respective components without the restriction of having to adapt to previous designs.

The ultimate goal besides having a fully functioning car is to participate in the Formula SAE-A 2012 competition [3] held at Victoria University Industrial Skills Campus. This will really enable us to put our designs through the strain of the myriad vigorous tests involved which will give us the best real world practical evaluation of our final product.

1.2.3 Personal Motivation

When choosing my thesis topic, I desired a project that would draw upon the skills and experience gained over my past 5 years at UWA. Setting a solid foundation prior to my entrance into the workforce was a top priority. Preferably it would involve circuit design and embedded systems, a deep interest of mine that would allow me to explore and gain proficiency in this field. Most importantly I didn't want to stop at the design phase, instead proceeding to physically implement and build my designs for a real practical purpose. This would immensely drive my motivation and ensure I remained enthusiastic, in important consideration for a project being performed over two semesters. I would also relish the opportunity to work in a team, requiring collaboration with other student engineers to strengthen by communicational skills. In other words, I wanted a project that epitomised what engineering is all about. These are the attributes that attracted me to the REV Project.

1.3 Objectives

The following sections outline conceptually the intended purpose and functionality of a safety system and fault indicator system.

1.3.1 Safety System

The Formula SAE car will operate entirely on electrical power. Electricity can be a lethal force if not respected. In fact under law you must hold an electricians license in order to work on voltages greater than 50VDC. Due to the fact that mainly students will actually work to build and maintain the car, it is clear that for the sake of cost and convenience, the tractive voltage of the SAE Formula car will need to be a maximum of 50V. The rules of the Formula SAE-A competition stipulate the requirement of a comprehensive safety shutdown system. A major proportion of this thesis will explore in detail the development of a comprehensive safety system. This includes the custom circuit and PCB design through to physical construction and implementation, all while overviewing the theory, calculations and good practise taken into consideration along the way. Ultimately, the safety shutdown system must both ensure the safety of the driver and compliance with all the required rules.

1.3.2 LED Fault Indicator System

There will be an assortment of safety elements that can trigger the Safety System. It would be of great convenience to have a fault indicator system that pinpoints the location of the problem. It will comprise not only of circuitry to sense the faults and drive the LED indicators, but also the important physical dashboard. The dashboard is an integral component of any car with instrumentation and forms the visual interface with the driver. It will be my responsibility to design and physically construct the dashboard that adheres to the rules and provides the necessary functionality to start or charge the car, indicate safety shutdown circuit faults and shutdown the car in an emergency. I will also liaise with the relevant team members to determine if additional instrumentation such as an energy meter and speedometer can be mounted.

1.3.3 Summary

The preceding text presents ambitious objectives that will underpin the rest of this thesis. The overarching aim of this thesis is to thoroughly document all my work such that is serves as a useful and precise reference in the future. As we will see there is a lot of detail in the designs, implementation and cabling that makes up the entire Safety System. By including a comprehensive examination of not only the theory but all implementation details, if any faults should occur in any part of my project in the future, successive REV teams will not be left in the dark. In particular, any changes, modifications or errors and corrections made while physically implementing this project in the car will be documented to ensure no inconsistencies exist between the designs and physical implementation. This process is in line with my principles of delivering a complete engineering package, a functioning robust product and precise, consistent and detailed documentation.

2 Low Voltage Electric System

2.1 Overview

The overall electrical system of the Formula SAE car can be separated into two distinctly separate areas of operation, the High Voltage (HV) Tractive System and Low Voltage Electric (LV) System. The HV Tractive System includes the accumulators, motor controllers, electric motors and all high current wiring. Broadly speaking, the LV Electric System includes all components running on the 12V power supply. The Safety Control System is contained within the LV Electric System and is currently the most substantial system contained within. Its primary purpose is to ascertain whether the current state of the car, or more precisely whether the state of various buttons, sensors and interlock modules implies a safe condition. If the current state of the car is safe, the Safety Control System will activate the tractive system by powering a series of contactors that in turn close the tractive circuit which physically allows current to flow between the accumulators and motors. So it is clear that the HV Tractive and LV Electric Systems are both logically and physically separate systems, with the contactors forming an interface between the two as illustrated in Figure 2.1.

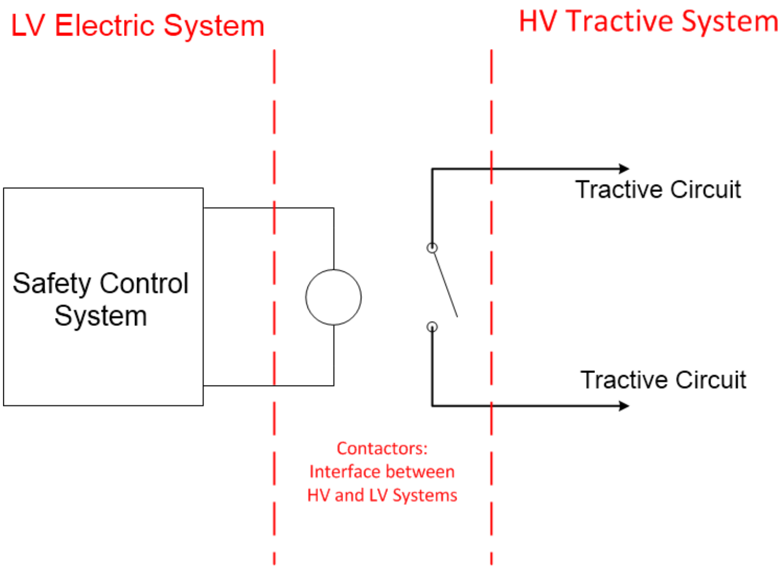


Figure 2.1 Separation of LV & HV Systems

The detailed operation of the high voltage tractive system is beyond the scope of this thesis and no further discussion on this topic will follow.

As the car currently stands, the Safety Control System differs little from the larger overall LV Electric System, containing only a few extra components such as the auxiliary battery. Electronics and componentry used for a variety of purposes other than safety may be added in the future. These would offcourse be part of the LV System but not relevant to the Safety Control System and for this reason we will keep this distinction.

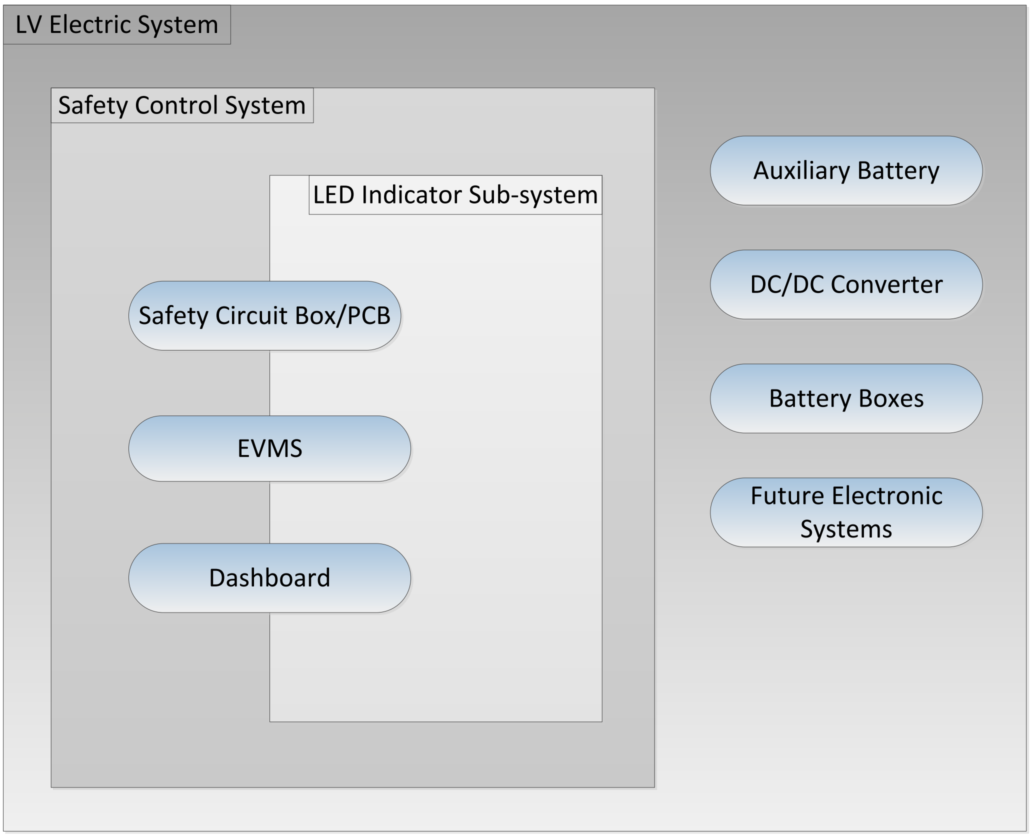


Figure 2.2 LV Electric System Breakdown

The LED Indicator system is a subsystem of the larger Safety Control System and is responsible for pinpointing the safety element at fault and notifying the driver or crew (Figure 2.2). The Safety Control System which includes the LED Indicator sub-system is physically implemented via the Safety Circuit Box (SCB), EVMS and dashboard (Figure 2.2).

At the heart of the Safety Control System is the custom designed and built Safety Circuit PCB contained within the Safety Circuit Box (SCB) which will be thoroughly examined Chapter 3. For now we begin our analysis by covering the basic operation of the other components that make up the LV Electric System, namely the EVMS and auxiliary components. Once this foundation is laid, we move onto a high level overview of the entire LV Electric System with an emphasis on the Safety Control System. This will aid in explaining its overall operation and how all the elements work together to put the car in the all-important DRIVE and CHARGE states. Even at this relatively high level view, there are plenty of interconnections and events occurring and hence it would be unwise to be distracted by low level details of the Safety Circuit PCB at this stage.

2.2 Electric Vehicle Management System

The electric vehicle management system (EVMS) device manufactured by Zero Emission Vehicles Australia (ZEVA) [4] was purchased for the Formula SAE car. The primary requirement of this device was that of a Battery Management System (BMS), however it also featured staged pre-charging, contactor control and a status light.

2.2.1 Functionality

The EVMS forms an important component of the Safety Control System. There is a heavy cause and effect relationships between the various terminals of this device. Therefore the operation of the EVMS is best described by examining various scenarios as a whole instead of individual terminals. Nevertheless a brief overview of the EVMS terminals is given in Table 2.1 and shown in Figure 2.3.

EVMS Terminal	Terminal Name	Terminal Description
+12VDC	EVMS_+12VDC	Positive power supply
Ground	EVMS_GROUND	Negative power supply
Key In	EVMS_KEY_IN	Signal to drive car. HIGH to drive. LOW otherwise
Chg Sense	EVMS_CHG_SENSE	Battery charging signal. LOW to charge, HIGH otherwise
BMS In	EVMS_BMS_IN	Battery Management System module signal input
Status R	EVMS_STATUS_R	Red EVMS status signal
Status G	EVMS_STATUS_G	Green EVMS status signal
Status B	EVMS_STATUS_B	Blue EVMS status signal
Buzzer	EVMS_BUZZER	Audible EVMS status
Ground	EVMS_GROUND_STATUS	Buzzer and status indicator

		ground
Prech A	EVMS_PRECH_A	Connect to main contactor terminal on the battery side
Prech B	EVMS_PRECH_B	Connect to main contactor terminal on the motor controller side
Drive	EVMS_DRIVE	Connections to the relay which closes when allowed to drive
Enable	EVMS_DRIVE_ENABLE	
Charge	EVMS_CHARGE	Connections to the relay which closes when allowed to charge
Enable	EVMS_CHARGE_ENABLE	
Main Ctr	EVMS_MAIN_CTR	Positive terminal of main contactor
Ground	EVMS_GROUND_MAIN	Negative terminals of main contactor
Aux Ctr	EVMS_AUX_CTR	Positive terminal of auxiliary contactor
Ground	EVMS_GROUND_AUX	Negative terminal of auxiliary contactor

Table 2.1 EVMS terminals and description

Note: The 'Terminal Name' column lists the name by which the EVMS terminals are referred to in the thesis.

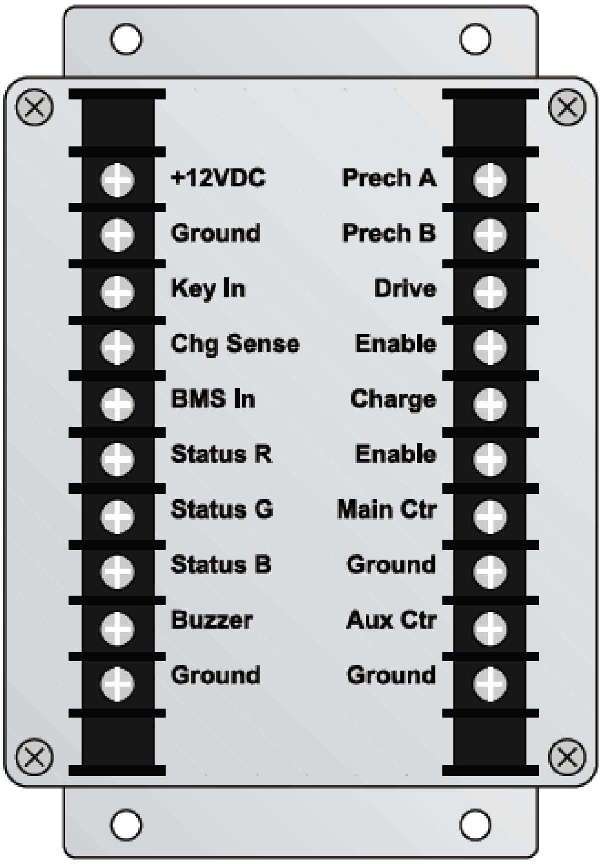


Figure 2.3 EVMS device and terminals

Scenario 1: Drive

Input:

KEY IN = HIGH

Preconditions:

1. BMS IN = LOW
2. CHG SENSE = HIGH

Effect:

1. DRIVE & ENABLE pins closed
2. AUX CTR = HIGH/ON
3. Pre-charge occurs over main contactor
4. MAIN CTR = HIGH/ON

Scenario 2: Charge

Input:

CHG SENSE = LOW

Preconditions:

1. BMS IN = LOW
2. KEY IN = LOW/FLOAT

Effect:

1. CHARGE & ENABLE pins closed
2. MAIN CTR = LOW/OFF
3. AUX CTR = HIGH/ON

Scenario 3: Battery Fault

Input:

BMS IN = HIGH/FLOAT

Preconditions:

1. N/A

Effect:

1. AUX CTR = LOW/OFF
2. MAIN CTR = LOW/OFF
3. DRIVE & ENABLE pins open
4. CHARGE & ENABLE pins open

Scenario 4: Standby

Input:

1. KEY IN = LOW/FLOAT
2. CHG SENSE = HIGH

Preconditions:

1. N/A

Effect:

1. AUX CTR = LOW/OFF
2. MAIN CTR = LOW/OFF
3. DRIVE & ENABLE pins open
4. CHARGE & ENABLE pins open

Notes:

1. An interlock acts between the charge and drive states. Its purpose is to ensure the car cannot transition from DRIVE to CHARGE or vice versa without first passing through the standby state. The idea is that the car contains a charge door which pulls CHG SENSE = LOW when opened for charging. When the car is connected for charging (having opened the charge door), the interlock will prevent the car from accidently being set into drive mode, even if KEY IN is pulled HIGH. Similarly, if driving and the charge door is accidently opened thereby pulling CHG SENSE = LOW, the interlock will prevent the car from entering the charge state which would open the main contactor and hence break the tractive circuit.
2. See [5] for full EVMS Manual

2.3 Auxiliary Components

2.3.1 Contactors

The contactors form the interface between the LV Electric System and the HV Tractive System. Contactors are electrically controlled switches, very much like a relay. The significant difference is that contactors are heavy duty and rated for much higher currents. In a car such as the Formula SAE where currents can peak 800A, contactors are not a choice but a necessity.

2.3.2 Battery Boxes

The battery boxes house the accumulator/batteries, contactors and BMS modules. The battery chemistry used is $LiFEPO_4$ having a nominal cell voltage of 3.3V [6]. There are two battery boxes each comprising of 8 sets of $LiFEPO_4$ cells in series resulting in an accumulator of 3.3 x 8 = 26.4V nominal. The two accumulators are wired in series to produce a total 52.8V nominal.

There is a BMS module for each set of parallel cells in the battery box. They provide over and under voltage protection. Essentially the signal line is daisy chained between each BMS module to ground. If the voltage is at a safe level, the MOSFETs inside each module are ON and conduct the signal path. The result is that the end of the daisy chain is LOW or grounded. If a fault occurs at any BMS module, the MOSFET is turned OFF, opening the signal path. The end of the line is now floating. This signal is used by the BMS interlock of the Safety Circuit PCB discussed in Section 3.3.3.2.

2.3.3 DC/DC Converter

The DC/DC converter takes the 52.8VDC nominal of the combined accumulators in series and reduces it to 13.8VDC for the LV Electric System. The choice of 13.8V for what is the 12V LV Electric System is explored next.

2.3.4 Auxiliary Battery

2.3.4.1 Specification

Figure 2.4 Chosen Auxiliary Battery Specifications [7]

2.3.4.2 Justification

The team was advised by Prof Bräunl to try and avoid using an auxiliary battery. In past REV projects such as the Hyundai Getz Eco Vehicle, the auxiliary would go flat and hence starting the car would be impossible. This caused great frustration and angst and therefore a robust solution was required for the new Formula SAE car. The DC/DC converter (Section 2.3.3) takes the 52.8VDC nominal of the tractive battery packs and steps down the voltage to 13.8VDC to power the control system. However connecting this idea with the following rule:

EV3.5.2 The accumulator isolation relays must cut both(!) poles of the accumulator. If these relays are open, no HV may be present outside of the accumulator container. [8]

results in an unfortunate and unavoidable circular condition. The contactors must be powered to close the poles of the battery boxes which in turn supply power to the DC/DC converter. However the contactors can't be ON in the first place because the DC/DC converter is OFF. The only solution to this problem is to utilize an auxiliary battery which will initially power the LV Electric System and hence contactors. Once the contactors close, the DC/DC converter will now have input power and hence can sustain the power requirements of the LV Electric System.

A significant flaw in the Getz auxiliary battery implementation is that there was no mechanism to keep it in a charged state. This was rectified in the Formula SAE design where in Figure 2.5 we can see that once the DC/DC converter is ON, it will charge the auxiliary battery in parallel. [9] states that for a sealed lead acid battery the ideal float charge is 2.25V - 2.27V per cell. A float charge is defined as a charger/voltage continuously applied to the terminals of the battery in order to keep it in an optimally charged state when ready to use [10]. Since a 12V lead acid battery is made of 6 cells and using the 2.27V value, the ideal float voltage for the lead acid auxiliary battery is 6 x 2.27 = 13.62V. From Section 2.3.3 the DC/DC converter outputs 13.8V which aligns closely with the correct float charge voltage for our lead acid battery. It is conceivable the auxiliary battery may be floated for long periods of time; however there is no chance of overcharging as the very definition of floating as given by [11] is the voltage that it is safe to apply indefinitely.

If for whatever reason the auxiliary goes flat, it will be a simple matter of connecting a 12V battery in parallel using jump leads than can supply the current to activate the contactors momentarily, at which point the DC/DC converter will kick in and take over supplying the power.

The last consideration was the capacity required for the auxiliary battery. The trade-off is between capacity and size and weight, with the latter being desirable to keep as low as possible for an electric race car. As we will see in Section 2.4.3, for car demonstration purposes the car will be in the STANDBY state where by definition the contactors are OFF implying the DC/DC is OFF as well. Therefore power to the entire LV Electric System including the EVMS, SCB and dashboard indictors is supplied by the auxiliary battery. A battery with sufficient capacity to drive these low power devices for a considerable time is desirable.

Item	Current
SCB (inc. indicator LEDs)	<50mA
EVMS	<50mA
TOTAL	100mA

Table 2.2 Current consumption by components of the Safety Control System

Assuming we want to be able to leave the car in this state for at least 48hours and taking 100mA from Table 2.2:

$$Battery\ Capacity\ (Ah) = .1 \times 48 = 4.8Ah \quad (2.1)$$

The auxiliary battery chosen has a capacity of 7.2Ah. This is well beyond the capacity of Equation 2.1 and should in fact last up to 72 hours on a full charge. It is highly recommended that when the car is not in use, the CSMS switch be turned OFF. This cuts power supplied by the auxiliary battery or DC/DC converter to the entire LV Electric System. The dimensions and weight of this battery (Figure 2.4) were also considered easily manageable for the Formula SAE car.

2.4 Safety System Operation

There are a number of states the safety system can be in. The easiest way to gain a full insight on the operation of the safety system is to follow the steps required to attain both the DRIVE and CHARGE states. The LV Electric System, largely comprising of the Safety Control System is presented in Figure 2.5. The numbers in the figures indicate where lines should connect.

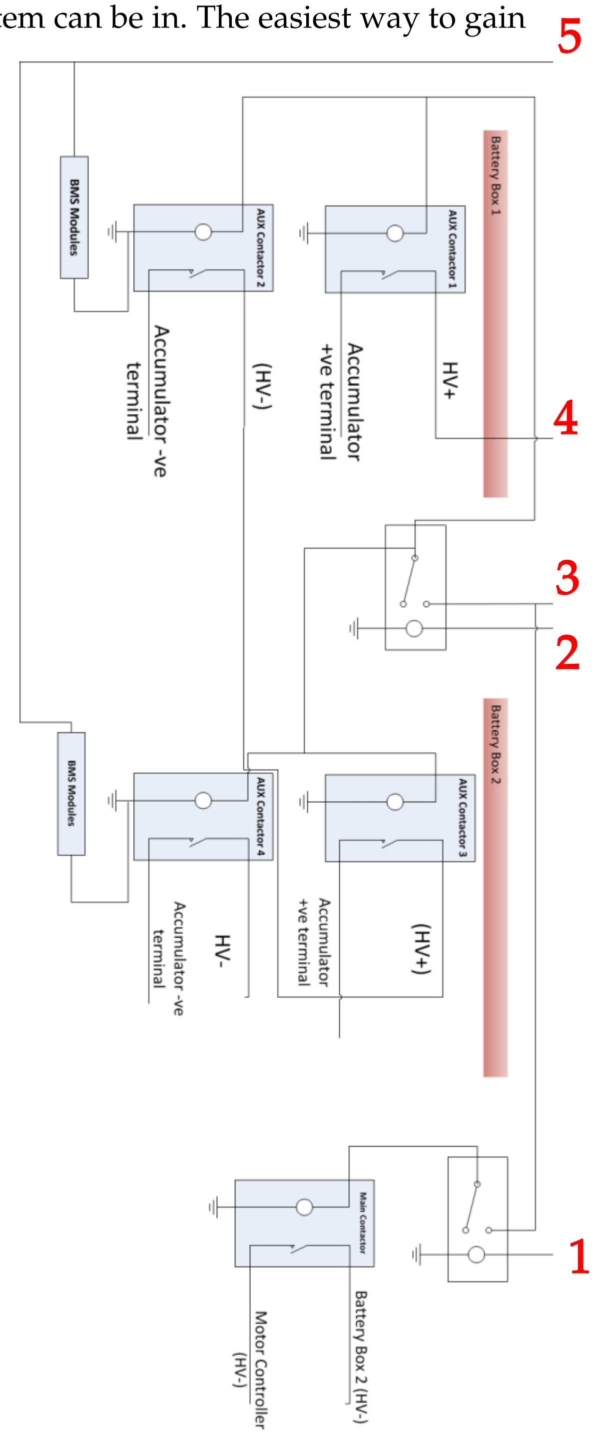
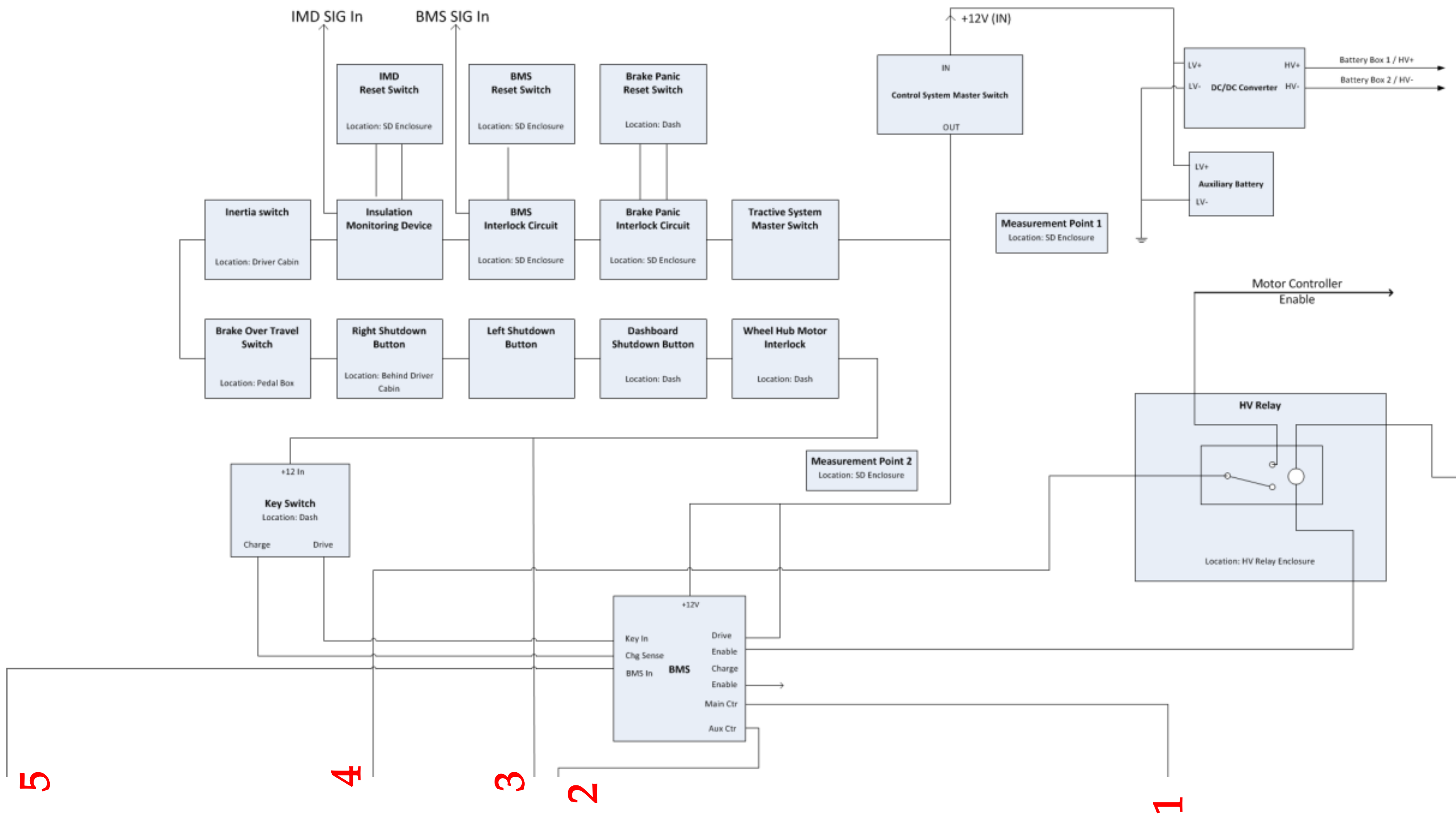


Figure 2.5-1 Bottom half - LV Electric System

Figure 2.5-2 Top half – LV Electric System



By following the current from the voltage source all the way through the system and considering the outcomes of the signals on various components, we will see exactly how the Safety Control System operates. In the process of covering the important DRIVE and Charge states, the other states will be covered as a matter of course. The proceeding section is heavily procedural with many cause and effect actions. To gain better insight it would be of great assistance to follow Figure 2.5 along with the explanatory text.

2.4.1 Drive the Car

We start off in the OFF/SAFETY_FAULT state where all contactors are open implying that the DC/DC converter is off. Therefore the only source of power possible to the safety system at this stage is the auxiliary battery. The CSMS is then closed which powers on the EVMS. In addition we can see a potential path through a multitude of various safety circuit interlocks, sensors and buttons. For simplicity each of these elements can be thought of as a switch, OPEN if it is in the FAULT state and CLOSED if the element is in the SAFE state. The detail and inner working of each element is thoroughly covered in Chapter 3.

Assuming each of these elements is CLOSED we have a closed path to the key switch. If the key switch is in the 'Standby' (middle) position then we are currently in the STANDBY state. To follow the remaining process, you may want to refresh your memory on the detailed functionality of the EVMS, see Section 2.2. By turning the key switch to 'Drive' (right) position, the key switch input is directed to the key switch drive output which in turn pulls the EVMS_KEY_IN terminal HIGH. Provided the EVMS_BMS_IN input is LOW and EVMS_CHG_SENSE is HIGH, the EVMS will output power on EVMS_AUX_CTR which turns ON (closes) the auxiliary contactors. Following immediately, the pre-charge occurs over the currently inactive main contactor. When the pre-charge is complete, power is output on EVMS_MAIN_CTR which turns ON the final main contactor.

At this stage all contactors are ON/CLOSED which implies that the tractive circuit is physically closed and that the DC/DC converter is now ON. However the car will still not respond to actuation of the torque encoder (accelerator pedal). When EVMS_KEY_IN was pulled HIGH, the EVMS also internally closed the EVMS_DRIVE and EVMS_DRIVE_ENABLE terminals. This allows current to flow through the HV Relay coil, and onto the Ready to Drive (RtD) Interlock Circuit. When the RtD button is pressed, the RtD circuit latches closed completing the circuit just described, which therefore turns the HV relay ON. This in turn connects the HV+ terminal to the motor controller enable terminals, pulling them HIGH. The car will now respond to the torque encoder. This completes the process of putting the car in the DRIVE state.

2.4.2 Charge the Car

Again let's assume we start in the OFF/SAFETY_FAULT state. Provided all the safety elements are ON/CLOSED, again we have a closed path to the key switch. When the key switch is turned to the 'Charge' position, current continues on to the EVMS_CHG_SENSE terminal, pulling it HIGH. In this case, provided the EVMS_BMS_IN input is LOW and EVMS_CHG _SENSE is HIGH, the EVMS will output power on EVMS_AUX_CTR which turns ON (closes) the auxiliary contactors. This closes the circuit between the charger and the batteries. It is worth mentioning that the DC/DC converter is now ON. The main contactor which connects the motor controllers to the batteries is specifically left OFF in the charge state to ensure the car cannot possibly move. The batteries will continue to charge until the charger's automatic end of charge detection mechanism activates.

2.4.3 Demonstrate the Car

It is inevitable that he Formula SAE car will be demonstrated at university events and various functions pushing the cause of electric vehicles. The LV safety control system has been designed with this in mind, resulting in the ability to safely leave the car unattended. In this state there is no chance that that the tractive system can be accidently activated even while the electronic instrumentation such as the indicator system is still functional and can be played with. To enable the car for demonstration, simply turn the key switch to the ‘Standby’ position and then remove the key for safe keeping. In this state, users can activate various safety elements, for example the ‘Dash Shutdown Button’ and watch the corresponding LEDs light up. All LV Electric System components will work because power is available. By removing the key, we are preventing the key switch from being placed in the ‘drive’ position which would send a HIGH signal to EVMS_KEY_IN and turn ON the contactors. Contactors OFF implies tractive system OPEN and hence no way for current from accumulators to reach the motors or motor controllers.

3 Safety Circuit

3.1 Circuit Theory

Here we will cover some circuit theory and design concepts that have been utilized in the Safety Circuit PCB design covered in Section 3.3.

3.1.1 Transistors

Transistors are a ubiquitous semiconductor device. A number of transistors are used in the safety circuit where they provide a convenient interface to control a relay as in the case of the BMS and IMD interlocks. They are a necessity to enable the limited current drive capacity of a microcontroller to drive the LEDs and buzzer.

3.1.1.1 Transistor as a switch

Transistor can be used as an amplifier device or an ON/OFF switch. Since its function as a switch is relevant to the safety circuit, we will cover it now. The key to using a transistor as a switch is to operate it in the SATURATION region. This ensures the transistor is in the fully ON state where the voltage across the transistor V_{ce} is almost zero. On the other hand, to turn the transistor fully OFF it is put in the CUTOFF region. The power developed across a switching transistor V_{ce} is [13]:

$$P = I_C \times V_{CE} \tag{3.1}$$

When CUTOFF (fully OFF) I_c is 0 so the power is 0.
When SATURATED (fully ON) V_{ce} ~ 0 so the power is very small.

When the transistor is in SATURATION, the voltage drop across it V_{ce} is as close to zero as it can get. This ensures the power consumed by the transistor is very small ensuring heat generation is kept to a minimum. Selecting the correct base resistor will ensure the transistor remains in SATURATION when ON. If however the resistance is too large limiting the required base current, the transistor will operate in the LINEAR region, where the voltage drop across the transistor V_{ce} is no longer zero. The full voltage is now split between the load and the transistor. The voltage drop across the transistor leads to increased generated heat and the load itself may no longer have the required voltage to work properly. Both of these are highly undesirable for switching transistor operation.

3.1.1.2 Selecting a base resistor

By selecting an appropriate base resistor, we can ensure the transistor remains in SATURATION. The important ratings of a switching transistor used in the calculation of a base resistor are [13]:

$HFE_{(\min)} - \ minimum\ current\ gain$
$I_{B(\min)} - \ minimum\ base\ current$
$I_{C(\max)} - \ maximum\ collector\ current$

To find the appropriate base resistor we first calculate:

$$I_{B(\min)} = \frac{I_{C(\max)}}{HFE_{min}} \qquad (3.2)$$

We use the minimum HFE and maximum collector current in our calculations to get the highest current value. This value is the minimum base current required to saturate the transistor.

[10] suggests the minimum base current is increased by 30% to guarantee the transistor is in SATURATION. This is incorporated in the follow equation:

$$R_B = \frac{Supply\ Voltage}{I_{B(\min)} \times 1.3} \tag{3.3}$$

Let's now follow these steps to find the appropriate base resistor for the transistors in the Safety Circuit PCB.

<u>For LEDS:</u>

$$I_{B(\min)} = \frac{I_{C(\max)}}{HFE_{min}} = \frac{0.02}{60} = 0.0003333 \tag{3.4}$$

$$R_B = \frac{Supply\ Voltage}{I_{B(\min)} \times 1.3} = \frac{5}{0.0003333 \times 1.3} = 11.54k\Omega \tag{3.5}$$

Based on this 10kΩ resistors have been used to drive LED transistors.

<u>For BMS/IMD relay:</u>

The maximum current through the relay coil $I_{C(\max)}$ has been experimentally derived to be at most 100mA.

$$I_{B(\min)} = \frac{I_{C(\max)}}{HFE_{min}} = \frac{0.1}{100} = 0.001666A \tag{3.6}$$

$$R_B = \frac{Supply\ Voltage}{I_{B(\min)} \times 1.3} = \frac{5}{0.001666 \times 1.3} = 2.3k\Omega \tag{3.7}$$

Based on this 1kΩ resistors have been used to drive BMS, IMD and buzzer transistors.

It is important to note that these calculations provide a good guideline to base resistor selection. They do not need to be adhered to exactly and it is safe to choose a lower value as this just further saturates the transistor.

3.1.2 Current limiting resistor for LED

Light Emitting diodes (LED) behave in accordance with the I-V characteristics exhibited by a diode. The I-V curve (an example of which is shown in Figure 3.1) is non-linear unlike that of a resistive component such as a resistor that complies with Ohms Law.

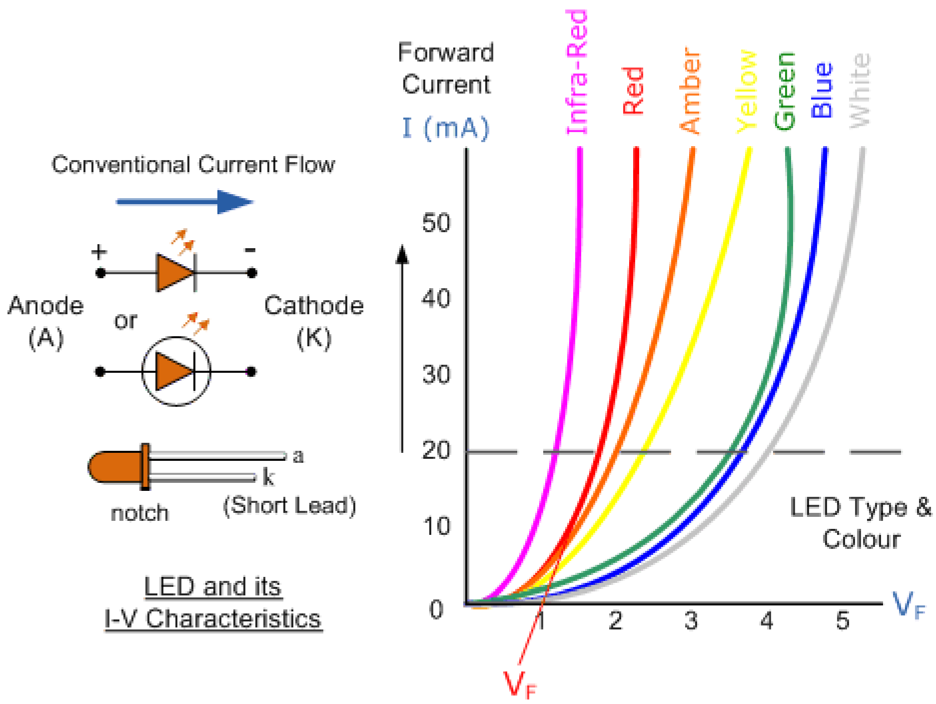


Figure 3.1 I-V curve for LED of various colour [12]

Without going into too much detail on the operation of a diode, one characteristic of a diode is the ON forward voltage. When a diode is forward biased in this way, it is ON an able to conduct a current. However, as the forward voltage is slowly exceeded, the resistance of the diode exponentially drops off. This will cause a larger current to flow that can very quickly burn out a diode. To prevent this, a resistor is used to limit the current to an appropriate level. Consider the simple circuit given in Figure 3.2.

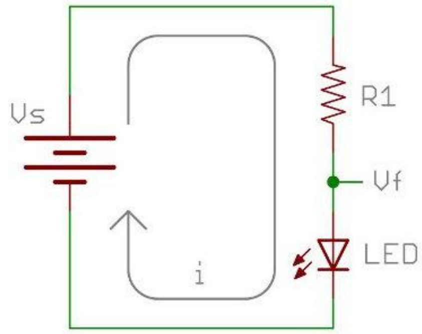


Figure 3.2 Simple LED circuit [13]

Where:

Vs = Supply voltage

i = LED forward current in Amps

Vf = LED forward voltage drop in Volts

The power supply Vs is known by the user and Vf is obtained from the LED datasheet. The value of 'i' depends on the type of LED being driven, but for a basic indicator LED a safe value is 5mA [12]. The resistor therefore needs a value of:

$$R1 = \frac{\mathrm{Vs} - \mathrm{Vf}}{i} \tag{3.8}$$

The values of the LED Driver Circuit (Figure 3.14), are Vs = 12V, i = 20mA and Vf = 2.6V. Hence we have:

$$R1 = \frac{12 - 2.6}{0.02} = 470\Omega \tag{3.9}$$

Therefore 470Ω resistors were used in the LED Driver Circuit.

3.1.3 LED multiplexing

Ordinarily each LED used would require its own dedicated pin on the microcontroller. However in many applications large numbers of LEDs may be necessary. Either a microcontroller with the required IO is utilized with the likely undesirable side effects of a larger physical footprint and higher cost, or a more efficient method to drive LEDs is employed.

The technique of LED multiplexing is one such method that can be used to significantly reduce the number of IO pins required to drive larger number of LEDs. The Safety Circuit PCB implements 11 LEDs as part of the LED Indicator Subsystem so we'll develop the theory based on this.

The idea of multiplexing is that a logical array of LEDs is developed as shown in Figure 3.3 below.

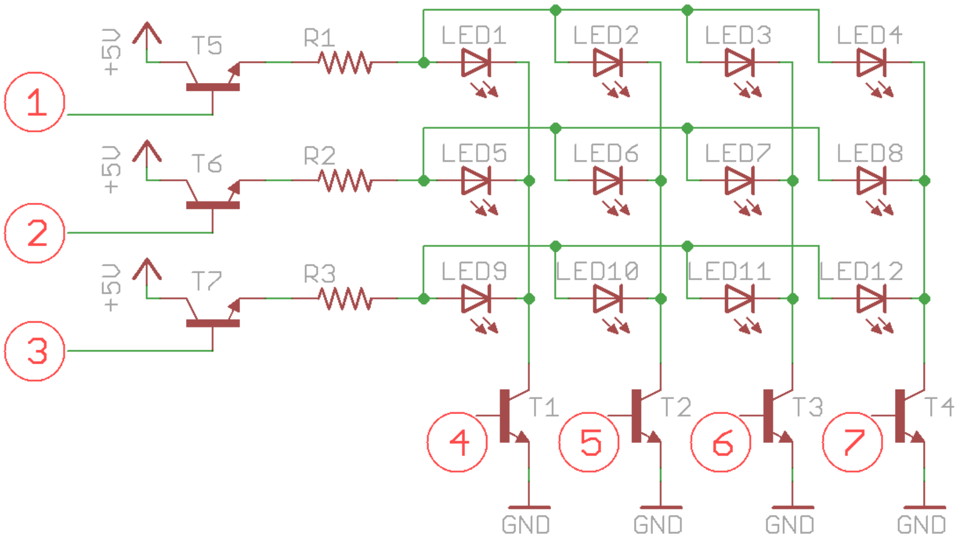


Figure 3.3 LED Multiplexing Circuit

Each row of LEDs has the anode connected to a µC pin. Similarly, each column has the cathode connected to a µC pin. To turn ON an LED the corresponding anode and cathode pins on the µC are pulled HIGH. In this schematic, the µC pins actually drive transistors which in turn drive the LEDs. This reduces current the microcontroller would otherwise have to supply to directly power the LEDs. Also it simplifies the logic of turning on a LED. Without transistors the anode pins would act as a voltage source but the cathode pins would be a ground. Hence to turn ON an LED the corresponding anode pin would be pulled HIGH but the cathode pin pulled LOW to ground.

So we can see that 7 pins are required to drive 12 LEDs which would have otherwise required 12 pins. This is a 42% saving. The pin savings become more pronounced as larger numbers of LEDs a used. For example if 100 LEDs are required, 20 µC pins are needed. This is a whopping 80% saving!

There is one potential downside to LED multiplexing. Although it does not apply to the Safety Circuit PCB, it should be mentioned for completeness. LED multiplexing is often used in displays to light multiple LEDs that form numbers or figures etc. [14]. When multiplexing it is evident that only individual or square groups of LED can be lit at once. For example referring to Figure 3.3, lighting LED 1 is a matter of driving inputs 1 and 4 HIGH. Now what if we want to light both LED 1 and 6, the type of activity we would want to perform to display a character consisting of multiple LEDs. Naively on first glance, one may say send inputs 1, 2, 4 and 5 HIGH. However this would actually light not only LEDs 1 and 4 but also LEDs 2 and 5 which is undesirable. This problem can be gotten around by quickly alternating between output HIGH on pins 1 & 4 to light LED 1 and pins 2 & 5 to light LED 6. If done fast enough, meaning 100Hz or more [15] the human eye sees both LEDs constantly lit. For small numbers of LEDs lit at once, it is not a problem to cycle each LED at 100Hz. However to keep the 100Hz rate for each LED, the clock of the µC goes up as a greater number of LEDs are lit at once. That is, for each cycle which is 10ms at 100hz, the processor must step through each LED required to be lit. So for example to give the effect of lighting 2 LEDs simultaneously a 2 x 100 = 200Hz processor is required and for 100 simultaneous LEDs a 10 x 100 = 1kHz processor is required. This off course is the bare minimum clock and does not take into account other tasks undertaken by the µC.

There is no doubt multiplexing should always be considered to drive LEDs. However large numbers of LEDs lit at once require more processor power in terms of clock speed to give that illusion.

3.1.4 Freewheeling diodes

Freewheeling diodes, also known as fly back diodes serve the purpose of protecting sensitive semiconductor devices or switch contacts when dealing with inductive loads. First let's review the basic operation of an inductor by considering the circuit of Figure 3.4.

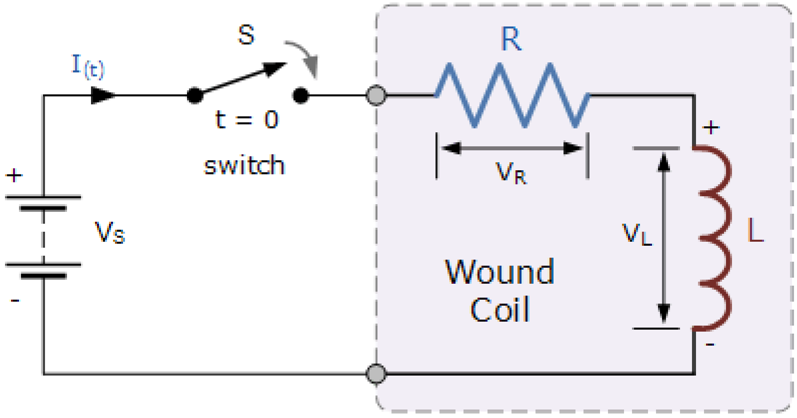


Figure 3.4 Basic inductor circuit

Keep in mind the fundamental characteristic of an inductor which is that it will always oppose or resist a change in current, whether it is increasing or decreasing. When the step voltage is initially applied (switch closed), the current essentially sees and open circuit. As the current begins to flow through the wire that is the inductor a circular magnetic field is established and begins to build. As this occurs the building magnetic field of each winding sweeps across every other winding inducing a voltage in those windings that opposes the voltage applied to the inductor [16]. This is confirmed by Faradays Law which states that a voltage will be induced in a conductor placed in a varying magnetic field. The reason the voltage is opposite comes from Lenz's Law which states 'an induced EMF gives rise to a current whose magnetic field opposes the original change in flux' [17]. The only way a current can oppose the change is flux is by flowing in the opposite direction and so in summary, an induced current will flow in the opposite direction to the current that induced it. The effective result of this expanding magnetic field is to hinder the rise of the current.

When the magnetic field reaches its maximum size (steady state), the inductor no longer impedes current flow as there is no long a varying magnetic field to induce an opposing EMF and hence current [18]. Therefore the inductor acts like a low resistive wire and current flows according to ohms Law.

Now assume the switch is abruptly opened. Since there is no longer a power supply, the built up magnetic field begins to collapse. As it does so, it again sweeps the windings of the inductor and induces a voltage which forces current to continue flowing in its current direction. This is similar to the previous case when the magnetic field was instead building. In effect the inductor has used the stored energy in its magnetic field to keep the current flowing after the disconnection of the power supply.

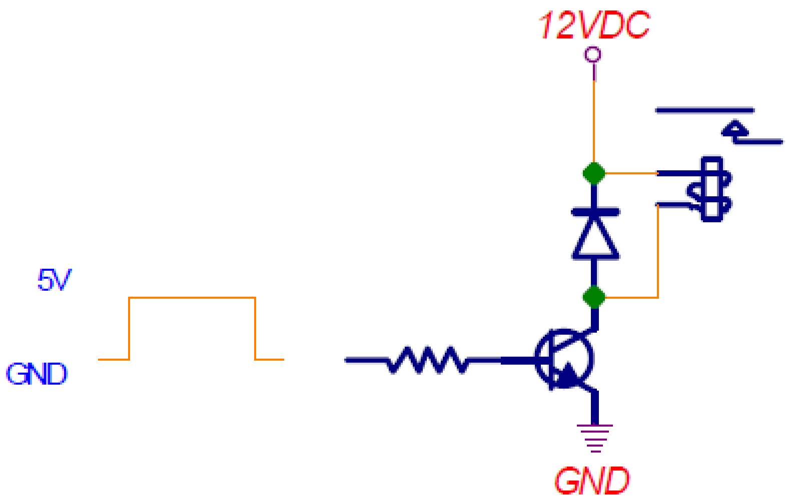


Figure 3.5 Freewheeling diode used in circuit

Consider the circuit in Figure 3.5 [19]. When the transistor is ON, the inductor reacts and behaves as previously described. However, when the transistor turns OFF there is no longer a closed path allowing current to flow through the inductor. The current is forced to 0 meaning almost instantaneously meaning di/dt is very large. Looking at the mathematical definition of an inductor:

$$V = L\frac{di}{dt} \tag{3.10}$$

we can conclude that a VERY large negative voltage will be induced across the inductor. This is likely to be detrimental to other components in the circuit, especially semiconductor devices such as the transistor in the circuit of Figure 3.5.

A relatively simple solution to this problem is the use of a 'freewheeling' or 'fly back' diode placed across inductive components. The diode is connected in reverse bias to the power supply as in Figure 3.5 so it is effectively invisible during normal operation of the circuit. When the transistor turns OFF, the diode clamps the voltage across the inductor to about 0.7V, protecting the transistor or other potential componentry.

3.2 Elements of the Safety Circuit

All safety circuit elements are part of the 'main safety circuit path' which is the electrical artery of the Safety Control System. The main safety circuit path is the one which travels from the power supply through all the safety elements. The current which flows via this path directly powers the contactors and is in line with rule:

EV5.1.1 The Shutdown Circuit directly carries the current driving the accumulator isolation relays (AIRs). [8]

The safety elements are placed in series with this path. An element is in the SAFE state when it has closed its portion of the main safety circuit path. This is referred to as the element being ON or CLOSED. If an element is in the FAIL state then it has opened its portion of the main safety circuit path. This is referred to as the element being OFF or OPEN. It follows that in order to have a closed main safety circuit path and hence ability to power the contactors, all elements must be in the safe state. If just one element switches to the FAIL state, then the main safety circuit path is electrically opened and the contactors cannot be powered.

The elements range from simple buttons to more complicated interlock circuits and are either external to or implemented inside the Safety Circuit Box. A list of all internal and external safety elements part of the Safety Control System is presented in Table 3.1. We'll begin this chapter by covering the external safety elements.

Safety Element	Location
Control System Master Switch (CSMS)	External
Tractive System Master Switch (TSMS)	External
Dash Shutdown Button	External
Left Shutdown Button	External
Right Shutdown Button	External
Brake Over Travel Switch	External
Inertia Sensor	External
BMS Interlock Circuit	Internal
IMD Interlock Circuit	Internal
Brake Panic Switch Interlock Circuit	Internal
Motor Loop Circuit	Internal

Table 3.1 Internal & External Safety Elements

The cable used for all external safety element wiring is summarised in Table

Name	Manufacturer	Conductor Cores	Conductor Diameter	Max Current
GEN_1	Generic	2	$1mm^2$	10A

Table 3.2 External safety element cable type

3.2.1 Control System Master Switch

The Control System Master Switch (CSMS) is the first element of the safety circuit. Its purpose is to control the power supply to the safety system. In Figure 2.5, we can see that when CSMS is OFF, power to the entire LV Electric System is cut. When the car is unused the CSMS should be kept OFF to prevent any power usage.

3.2.1.1 Requirements

EV5.2.2 *The CSMS must completely disable power to the Control System and must be direct acting, i.e. it cannot act through a relay or logic. [8]*

EV5.2.3 *The CSMS must be located on the right side of the vehicle, in proximity to the Main Hoop, at shoulder height and be easily actuated from outside the car. [8]*

3.2.1.2 Wiring

Termination of the cable at the CSMS is done by wrapping the stripped end of the wire around the terminal and tightening the nut. Table 3.2 below summaries the cabling involved for the CSMS.

TSMS I/O	Connector Termination	Wire length	Wire Type
Terminal 1	C1-P3	1.5m	GEN_1
Terminal 2	C1-P4	1.5m	

Table 3.3 Wiring details of CSMS

Note: For more detail on 'Connector Termination' please see Section 3.4.2

3.2.1.3 Physical Mounting

As per the rules the CSMS is located on the right side of the car. It is mounted on the 'Right Mount Plate' (see Figure 3.26).

3.2.2 Tractive System Master Switch

The Tractive System Master Switch (TSMS) is one element of the safety circuit. Its purpose is to simply open or close the main safety circuit path thereby directly controlling the contactors and state of the tractive circuit.

3.2.2.1 Requirements

EV5.2.4 *The TSMS must be located next to the CSMS and must open the Shutdown Circuit. The TSMS must be direct acting, i.e. it cannot act through a relay or logic. [8]*

3.2.2.2 Wiring

Termination of the cable at the TSMS is done by wrapping the stripped end of the wire around the terminal and tightening the nut. Table 3.3 below summaries the cabling involved for the TSMS.

TSMS I/O	Connector Termination	Wire length	Wire Type
Terminal 1	C1-P5	1.5m	GEN_1
Terminal 2	C1-P6	1.5m	

Table 3.4 Wiring details of TSMS

Note: For more detail on 'Connector Termination' please see Section 3.4.2

3.2.2.3 Physical Mounting

As per the rules the TSMS is located on the right side of the car next to the CSMS. It is mounted on the 'Right Mount Plate' (see Figure 3.26).

3.2.3 Shutdown Buttons

The safety circuit consists of three shutdown buttons:

1. Shutdown Button Dash – Located on the dashboard
2. Shutdown Button Left – Located on Left Mount Plate
3. Shutdown button Right – Located on Right Mount Plate

They can be regarded as panic or emergency buttons where if any fault occurs, they can be quickly pressed. As with all the safety elements the safety buttons are wired in series with the main safety circuit path. These buttons are normally closed allowing current to flow, however when the button is pressed the safety circuit is opened resulting in disconnection of the tractive system.

3.2.3.1 Requirements

EV5.3.1 *A system of three shut-down buttons must be installed on the vehicle. [8]*

EV5.3.2 *Pressing one of the shut-down buttons must separate the tractive system from the accumulator block by opening the Shutdown Circuit, see also EV5.1. [8]*

EV5.3.3 *Each shut-down button must be a push-pull or push-rotate emergency switch where pushing the button opens the Shutdown Circuit. The shut-down buttons must not act through logic, e.g. a micro-controller. [8]*

EV5.3.4 *One button must be located on each side of the vehicle behind the driver's compartment at approximately the level of the driver's head. The minimum allowed diameter of the shutdown buttons on both sides of the car is 40 mm. [8]*

3.2.3.2 Wiring

Termination of the cable at the Shutdown Buttons is done by inserting the stripped end of the wire into the terminal and tightening the screw. Table 3.4 below summarises the cabling involved for the Shutdown Buttons.

Shutdown Button I/O	Connector Termination	Wire length	Wire Type
Left Shutdown Button - Terminal 1	C2-P1	1.5m	GEN_1
Left Shutdown Button - Terminal 2	C2-P2	1.5m	
Right Shutdown Button - Terminal 1	C2-P3	1.5m	GEN_1
Right Shutdown Button - Terminal 2	C2-P4	1.5m	
Dash Shutdown Button - Terminal 1	C2-P5	3m	GEN_1
Dash Shutdown Button - Terminal 2	C2-P6	3m	

Table 3.5 Wiring details of Shutdown Buttons

Note: For more detail on 'Connector Termination' please see Section 3.4.2

3.2.3.3 Physical Mounting

As per the rules, there are three shutdown buttons mounted in the required locations on the car. They are summarised in Table 3.5 below:

Button	Mounting	Further Details
Left Shutdown Button	Left Mount Plate	Figure 3.25
Right Shutdown Button	Right Mount Plate	Figure 3.26
Dash Shutdown Button	Dashboard	Section 4.2.2.1 Figure 4.3

Table 3.6 Shutdown Button Mounting Details

3.2.4 Brake Over Travel Switch

The Brake Over Travel Switch (BOTS) is physically actuated by the brake pedal in the event a mechanical fault occurs, allowing the brake pedal to travel beyond its typical range. As with all the other safety elements, the BOTS is located in series with the main safety circuit path, so when it is actuated it opens this circuit.

The chosen BOTS is a SPST push-pull type button meaning once it has been actuated by the brake pedal, further contact cannot reset it to the CLOSED/ON position as per rule T7.3.2. A manual reset by hand is required.

3.2.4.1 Requirements

T7.3.1 *A brake pedal over-travel switch must be installed on the car as part of the shutdown system and wired in series with the shutdown buttons. This switch must be installed so that in the event of brake system failure such that the brake pedal over travels it will result in the shutdown system being activated and controlling the systems as defined in C4 (IC vehicles) or EV5.4 (electric vehicles). [8]*

T7.3.2 *Repeated actuation of the switch must not restore power to these components, and it must be designed so that the driver cannot reset it. [8]*

3.2.4.2 Wiring

Termination of the cable at the BOTS is done by inserting the stripped end of the wire into the terminal and tightening the screw. Table 3.6 below summarises the cabling involved for the Shutdown Buttons.

BOTS I/O	Connector Termination	Wire length	Wire Type
Terminal 1	C3-P1	1.5m	GEN_1
Terminal 2	C3-P2	1.5m	

Table 3.7 Wiring details of Brake Over Travel Switch

Note: For more detail on 'Connector Termination' please see Section 3.4.2

3.2.4.3 Physical Mounting

The BOTS is mounted on the pedal box assembly in line with the movement of the brake pedal. In this position the driver will not be physically able to reset the BOTS if it is actuated as per rule T7.3.2. The pedal assembly is currently in progress by another student and hence no further details are available at this time.

3.2.5 Inertia Sensor

An inertia sensor triggers when it experiences a predefined deceleration. They are widely used in conventional combustion engine vehicles where they stop the fuel pump in the event of an accident. With the advent of electric cars, inertia sensors remain a core requirement of the safety system. In an accident, just as you don't want fuel spraying around over a damaged car with potential sparks and hot engine parts, it is similarly dangerous to have live electric tractive wiring short circuiting over the chassis or in contact with the driver. In the Formula SAE car the inertia sensor will open the main safety circuit path, causing the contactors to isolate the voltage to within the battery boxes only.

3.2.5.1 Requirements

EV5.7.2 *The inertia switch must be part of the Shutdown Circuit and must be wired in series with the shutdown buttons such that an impact will result in the*

Shutdown Circuit being opened. The inertia switch must latch until manually reset. [8]

3.2.5.2 Wiring

Termination of the cable at the Inertia sensor is done via the accompanying crimp connector. This connector simply plugs into the inertia sensor socket. Table 3.7 below summaries the cabling involved for the inertia sensor.

Inertia Sensor I/O	Connector Termination	Wire length	Wire Type
Common (C)	C3-P3	1m	GEN_1
Normally Closed (NC) terminal	C3-P4	1m	
Normally Open (NO) terminal	Unused	N/A	N/A

Table 3.8 Wiring details of Inertia Sensor

Note: For more detail on 'Connector Termination' please see Section 3.4.2

3.2.5.3 Physical Mounting

The Inertia Sensor is located on the left side of the car. It is mounted on the 'Left Mount Plate' (see Figure 3.25).

3.3 Circuit Design

The Safety Circuit PCB comprises of the internal safety elements summarised in Table 3.1 and indicator circuitry, working together in harmony. Although the dashboard and mounted componentry are a physically separate component from the SCB, it is important to remember that the electronics of the LED Indicator Subsystem are actually integrated on the same Safety Circuit PCB. That is, the physical components on the dashboard are driven and controlled by the SCB.

This section will thoroughly cover the design detail, operation and purpose of the internal safety circuit elements and indicator circuitry.

3.3.1 Design Process

The development of electronics is an iterative process for all but the most basic of circuits. Once the design is complete, the next step is to fabricate the PCB and install componentry. The first fabricated board is normally referred to as a prototype. A prototype enables the design to be put to use and thoroughly tested. Any problems or design flaws encountered can be rectified. However, it is important to realise that the fabrication process can be costly and time consuming. Ideally, the prototype will have no flaws and can be used as the final product. This is off course not realistic and usually at least one prototype will be required. The aim is to tweak the design and sort out all the issues in the first prototype. Too many of these cycles will lead to cost and time blow outs. It just goes to show that thorough analysis and a systematic review of the circuit design and PCB layout will save time and money in the long run.

When comparing this with software development, it is evident that a very different approach and mindset is required in electronics design. In software development errors in the code can be corrected and the software recompiled with a few presses of a button. This cycle can occur continuously with virtually no time or monetary cost. Contrasting to electronics design, the analogy to compiling software is like manufacturing a PCB and we have seen this is something we do not want to repeat too many times.

3.3.2 Component Selection

This section will cover the specifications of all the components used in the Safety Circuit Box. The following table enumerates all components used in the SCB and their associated component ID as used in the circuit schematic (see Section 3.3.3) and Board Layout (Figure 3.19). It particularly aids in the placement of components on a blank PCB.

Component ID	Component Description	SCB Component ID
CNTR_M_IP67_P18	Connector plug male, rated IP67, 18 pin	C4, C5, C6
CNTR_M_IP67_P7	Connector plug male, rated IP67, 7 pin	C1, C2, C3
CNTR_F_IP67_P18	Connector socket female, rated IP67, 18 pin	S4, S5, S6
CNTR_F_IP67_P7	Connector socket female, rated IP67, 7 pin	S1, S2, S3
RLY_SPDT_12V	Relay 12V coil, SPDT, 16A/250VAC/110VDC rated contacts	K4, K5, K7, K8, K9, K10
RLY_DPDT_12V_1	Relay 12V coil, DPDT, 8A/250VAC/30VDC rated contacts	K2, K3, K11
RLY_SCKT_1	Relay socket base for RLY_SPDT_12V. This component is soldered in place of all RLY_SPDT_12V elements.	N/A
RLY_SCKT_2	Relay socket base for RLY_DPDT_12V_1 and RLY_DPDT_12V_2. This component is soldered in place of these two elements.	N/A
HDR_PCB_P4	PCB Header, 4 pin, 7A rated	H5, H6, H7
HDR_PLUG_P4	Plug for HDR_P4	N/A
HDR_PCB_P6	PCB Header, 6 pin, 7A rated	H3, H4, H8
HDR_PLUG_P6	Plug for HDR_P6	N/A
HDR_PCB_P10	PCB Header, 10 pin, 7A rated	H1-1, H1-2, H2-1, H2-2
HDR_PLUG_P10	Plug for HDR_P10	N/A
PIC16F887_uC	PIC16F887 microcontroller	U6
SCKT_PDIP40	40 PDIP socket. This component is soldered in place of PIC16F887_uC	N/A
REG_7805	7805Voltage Regulator	IC1
NPN337	NPN BC337 bipolar transistor	T1, T3, T4, T5, T6, T7, T8, T9
PNP338	PNP BC338 bipolar transistor	T2
CAP_100U	100µF Capacitor	C1, C2, C3
DIODE_1N4004	1N4004 diode	D1, D2

R10k	Resistor 10kΩ	R1, R2, R3, R4, R5, R6, R7, R8, R9, R10, R13, R14 R25, R26, R27, R28, R29, R30, R31, R32, R33
R15k	Resistor 15kΩ	R15, R16,R18, R19, R20, R21, R22, R23, R24, R34, R35
R470	Resistor 470Ω	R11, R12, R17
N/A	Copper PCB 1oz	N/A
LED1	LED Green low intensity 80mcd	LED1
BTN_SPST_IP67	SPST IP67 Dome momentary push button	IMD Reset Button, BMS Reset Button (see Figure 3.23)

Table 3.9 Components used in the Safety Circuit PCB

3.3.3 Circuit Schematic

The method being taken to explain the Safety Control System is a top down approach. Firstly a high level perspective on the operation of the LV Electric System was presented in Section 2.4. This gave us the ability to understand how the system works and how the various states of the car are achieved without getting bogged down low level circuit detail. It is now appropriate to delve into the Safety Circuit PCB details. Appendix A.3 contains the entire circuit schematic of the Safety System PCB. The following explanation will be broken up into individual logical sections of the circuit and analysed one at a time. Without breaking it down in this manner, the resulting explanation would be hard to follow and likely incoherent.

3.3.3.1 Header 1 (H1) – External Safety Elements

The Safety Control System consists of simple elements such as the 'Shutdown Dash button' and more involved interlocks that require implementation on the Safety Circuit PCB. The purpose of Header 1 is to provide an interface to the SCB from all the external elements which are essentially two terminal devices. The current flows through the header starting at +12V, deviating through the external safety elements and exiting at INTERTIA-T2 as seen in Figure 2.6.

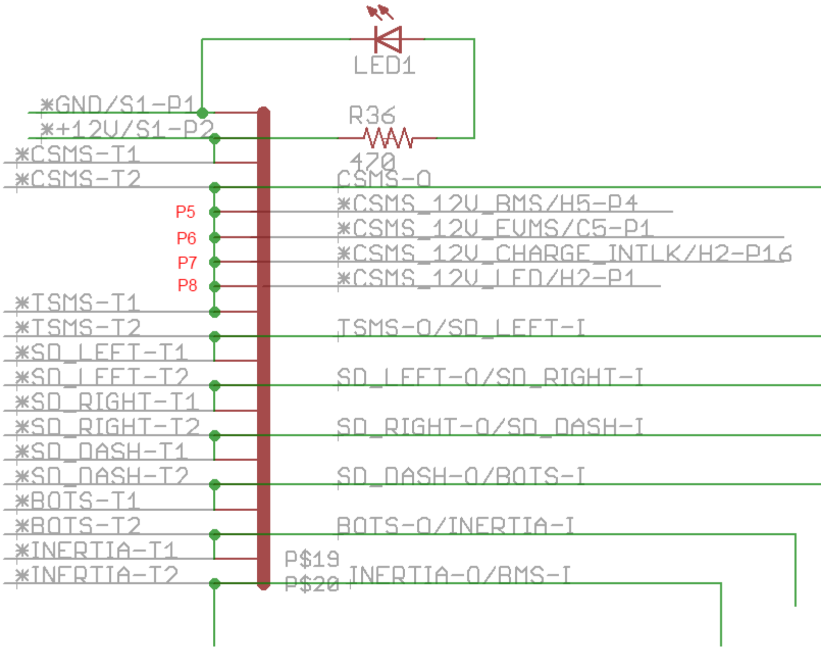


Figure 3.6 Header 1 schematic snippet

In addition points P5, P6, P7, P8 are jumper wires that supply power to various areas of the PCB and external EVMS unit. The resistor and LED are wired such that it will be lit when power is live at the box. This is a little diagnostic tool I like to incorporate in my circuits. When problems occur, one wants to eliminate as many variables as possible. This circuit aids in this endeavour by confirming availability of power at a glance.

3.3.3.2 BMS Interlock

After the current has passed through Header 1 and the associated safety elements, there are some on board interlocks it must then pass through before powering the contactors. The first of these is the BMS interlock. The following rules concerning battery safety must be satisfied.

EV5.1.4 *If the Shutdown Circuit is opened by the AMS or the IMD the tractive system must remain disabled until being manually reset by a person directly at the car which is not the driver. [3]*

Note: The AMS (Accumulator Management System) is what we refer to as the BMS (Battery Management System).

The current enters the BMS interlock (Figure 3.7) at IN-A and exits at OUT-B provided the circuit is in a safe state. IN-A and OUT-B are normally open complying with the fail safe principle.

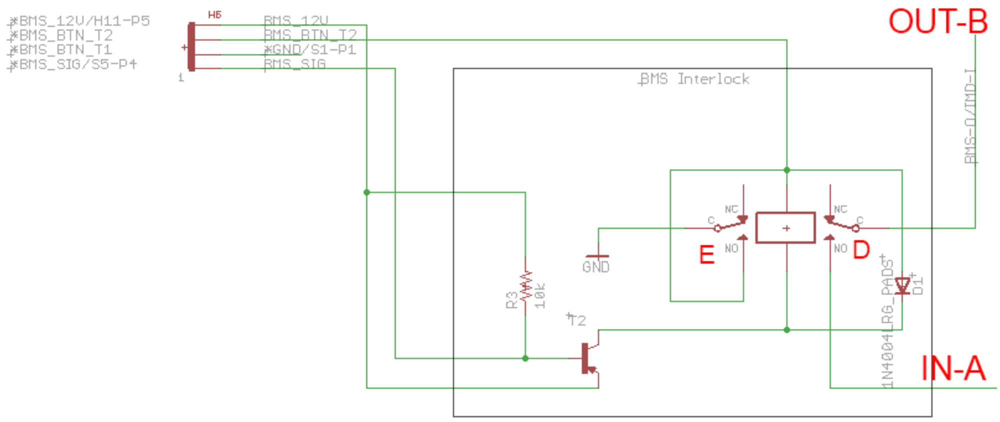


Figure 3.7 BMS Interlock circuit schematic

So the question is, how does the circuit close IN-A and OUT-B? Let's look at the PNP transistor T2. The base is driven by BMS_SIG from H5-P1. Remember that BMS_SIG is the signal from the BMS modules in the battery boxes that is LOW when there is no fault and floating otherwise. A floating signal is problematic and so a pull up resistor R3 is used to keep the base of T2 HIGH and hence OFF. Now a BMS Reset Button is connected to H5-P2 and H5-P3 (GND). Providing BMS_SIG is LOW and hence T2 is ON, if the button is pressed the circuit will be complete from BMS_12V to GND and hence current will flow through the relay coil turning it ON. When the button is released the circuit is opened i.e. there is no longer a ground point. However, the circuit is configured in such a way that the relay actually latches in the ON position. So how does the relay remain ON after the button is released? When the button is momentarily pressed energizing the relay, at point E, relay contacts C and NO are now closed creating a new path to ground thereby latching the relay permanently. Of course at D, contacts C and NO are also closed thereby closing IN-A and OUT-B. The circuit is in the 'ON' state.

What happens if a fault occurs at the batteries thereby pulling BMS_SIG HIGH? The transistor will turn OFF cutting power to the relay and so E and D revert to their original positions and IN-A and OUT-B open. The circuit is now in the OFF state. If BMS_SIG happens to go LOW again, the circuit will not turn ON until the reset button is again pressed. This is part of the interlock operation. In addition, to comply with Rule EV5.1.4 the reset button is placed on the SCB which is out of the reach of the driver.

3.3.3.3 IMD Interlock

After the BMS interlock is CLOSED, the next safety element the current must pass is the IMD interlock circuit. Similarly to the BMS interlock, the current enters the IMD interlock (see Figure 3.8) at IN-A and exits at OUT-B provided the circuit is in a safe state. IN-A and OUT-B are normally open complying with the fail safe principle.

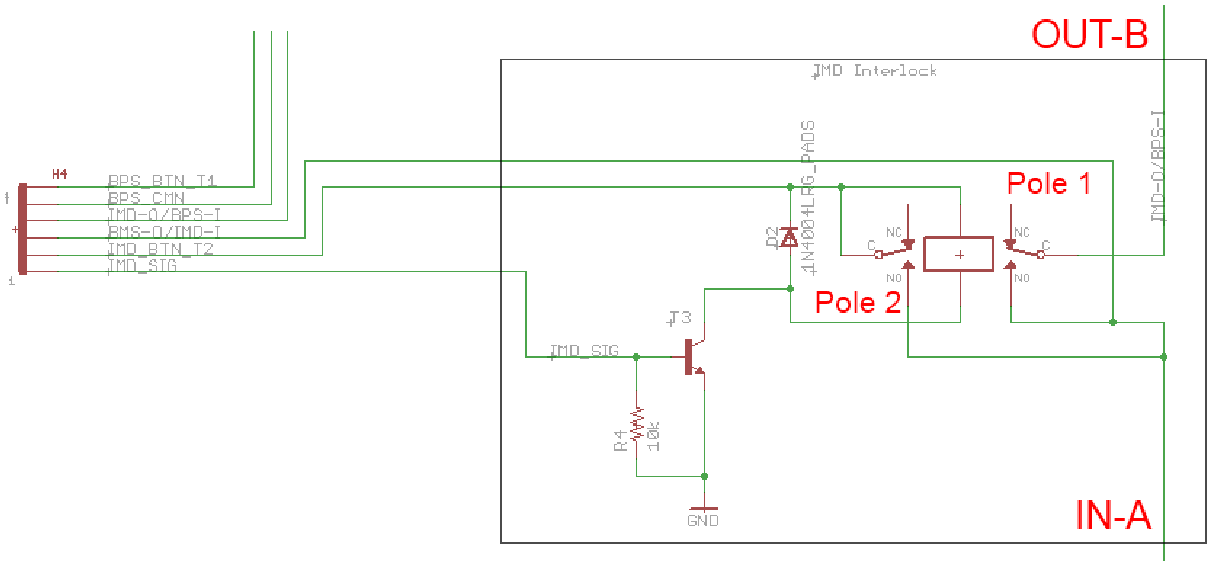


Figure 3.8 IMD Interlock circuit schematic

The operation of the IMD interlock is similar to the BMS interlock but will be covered now for completeness. Firstly let's look at the NPN transistor. Its base terminal is driven by IMD_SIG which is the signal from the IMD device. If it is HIGH, the IMD has determined that the insulation condition of the car is in a safe state and hence the transistor is ON. However, if IMD_SIG is LOW or

FLOATING there is an insulation fault in the car and the transistor is OFF. The pull down resistor ensures the transistor is OFF when IMD_SIG is not HIGH.

Now assuming the transistor is ON, the last obstacle to allowing the current to flow through the relay is the BMS Reset button. When it is pressed, current flows from IN-A, through the BMS Reset button via header H5-P2 and H5-P3, through the relay coil, through the transistor and to ground. The relay is turned ON. This offcourse connects the contacts C and NO of both poles. A new path to IN-A is created which actually provides a new voltage source via pole 2. This latches the relay in the powered state. That is, when the BMS Reset button is released, the newly created path keeps the relay powered/latched. Pole 1 also allows current to flow through it and onto the next safety element that is the BPS interlock. The IMD interlock is in the ON/CLOSED state.

If IMD_SIG now goes LOW or FLOATING in which case the pull down resistor will pull it LOW anyway, the transistor will turn OFF. This opens the current path for powering the relay and therefore it turns OFF, reverting the poles to the original position. The IMD interlock is now in the OFF/OPEN state. If IMD_SIG goes back to HIGH, the circuit will not automatically turn on again. The IMD reset button will need to be pressed again. This is part of the interlock operation of the circuit. It is also in line with rule EV 5.1.4 that states a manual action is required if the safety circuit has been triggered by the IMD.

A freewheeling diode has been incorporated in this circuit as we have the relay of the coil in series with a semiconductor device, namely the transistor. As covered in Section 3.1.4, the inductive voltage spike of the relay coil when it is abruptly turned off by the transistor will likely damage the transistor. The diode clamps the voltage across the relay coil to its turn on voltage and allows current to dissipate in the diode/relay loop.

3.3.3.4 BPS Interlock

The Brake Panic Switch interlock circuit ensures the main safety circuit path is opened when the brake panic switch is actuated. The details of the switch and its placement are being managed by the student designing the pedal box. The related rule is:

T7.4.1 *All vehicles must be equipped with a brake panic switch as part of the shutdown system such that in the event of a panic braking incident, the brake panic switch will be activated. This switch must kill the engine and cut the power to any electrical fuel pumps and for electric vehicles it must open the Accumulator Isolation Relays. [3]*

The assumption in this circuit design is that the brake panic switch will be of normally closed type. To comply with fail safe practise, due to R1 configured as NC, R2 had to be added to ensure the BPS interlock was open when not powered (see Figure 3.9).

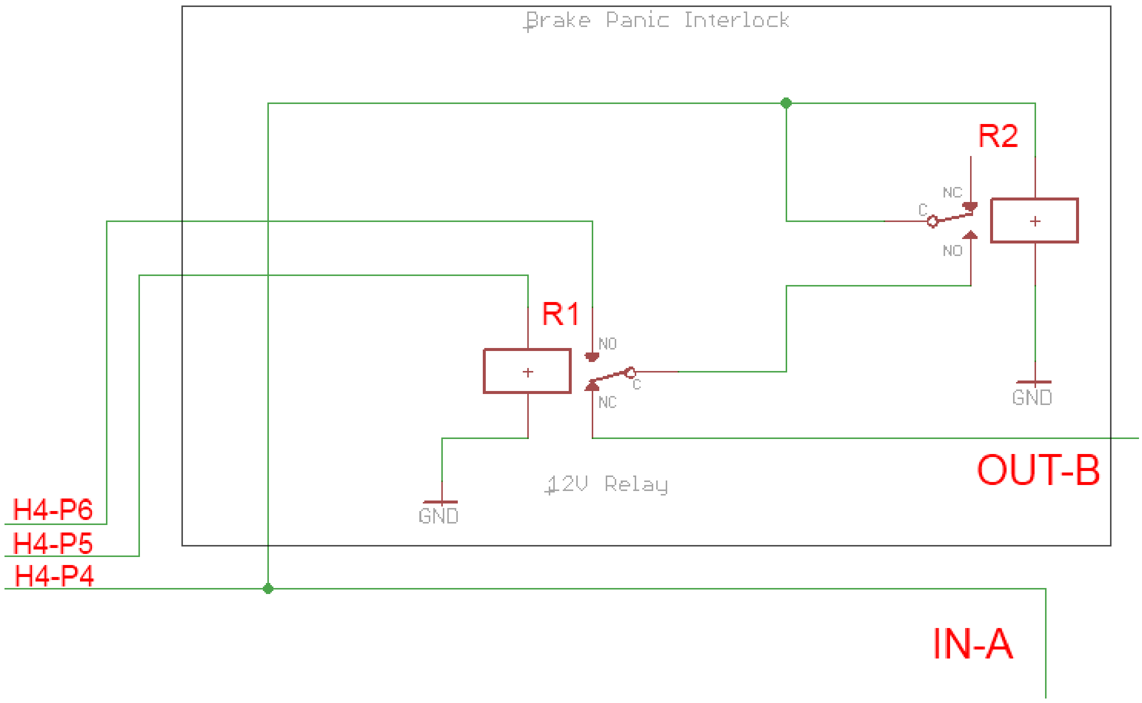


Figure 3.9 BPS Interlock circuit schematic

As soon as the two previous BMS and IMD interlocks turn ON, it is clear current can flow through the coil of R2 and the BPS interlock becomes ON.

As soon as the BPS is actuated its corresponding pins of H4-P4 and H4-P5 are closed allowing current to flow and power relay coil R1. However the BPS is only a momentary switch because we don't want to have to manually reset the BPS every time it is actuated. In addition the BPS will be in a difficult to access position near the pedal box. This means the relay would normally de-energize once the BPS was released. However what actually happens is that once the BPS is pressed, contacts NO and C of R1 become closed allowing current to bypass the BPS, flow through the normally closed BPS reset button via H4-P5 and H4-P6 and then through the relay coil and ground. When the BPS is released, R1 is now powered via an alternate path (via BPS reset button) and remains ON, meaning the BPS interlock stays OFF.

To reset the BPS interlock back to the ON state is simply a matter of pressing the BPS reset button. This will interrupt the current to the coil of relay R1, closing contacts C and NC which puts the BPS interlock back ON.

3.3.3.5 Motor Loop Module

The purpose Motor Loop Module is to open the main safety circuit path in the event of an accident where the mechanical integrity of a wheel hub motor is compromised. The rule for this is stated below:

EV4.2.3 Outboard wheel motors are allowed where the motor is outside of the frame but only if an interlock is added such that the Shutdown Circuit, EV5.1, is opened if the wheel assembly is damaged or knocked off the car. [3]

A long length of cable will run the perimeter of the car with particular attention paid to how it is attached to the wishbones and motor of each wheel. Crimped spade connectors are strategically placed in series with this cable on both sides of the wishbone. The idea is that in an accident the connectors will rip apart causing the circuit and hence the main safety circuit path to open.

The main safety circuit path passing through the Motor Loop Module (see Figure 3.10) between IN-A and OUT-B is OPEN fulfilling failsafe requirements.

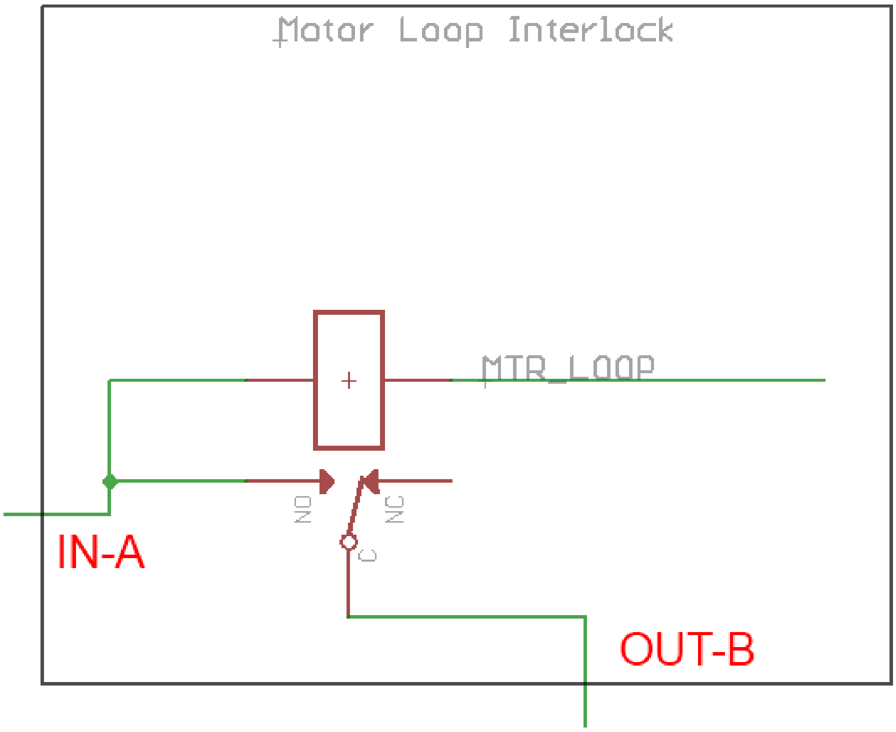


Figure 3.10 Motor Loop Module circuit schematic

The current can only reach the Motor Loop Module if the previous Brake Panic, IMD and BMS interlocks are all in the ON state. Once it reaches the Motor Loop Module, it will flow through the relay coil and then through the long motor loop cable. If the cable is in order it will conduct the current to the ground which it is terminated at. This keeps the relay energized so long as the motor loop cable is not severed meaning IN-A and OUT-B are closed allowing the current to continue to the next module.

3.3.3.6 AUX & Main Relay Module

As covered in the Section 2.2, the EVMS controls powering the auxiliary and main contactors. The EVMS was not a custom design for the Formula SAE car unlike the Safety Circuit Box this thesis covers. Consequently it does not fit in with all the requirements of the Safety Control System. In particular the inability of the EVMS to drive more than one contactor, as required by the Safety Control System was found out the hard way. The EVMS documentation is fairly poor especially regarding to specifying electrical ratings. After contacting the manufacturer, it was made clear that driving four contactors would be acceptable. However an experiment to power two contactors in parallel damaged the EVMS, which then had to be repaired.

The solution to this problem is the AUX/MAIN Relay module as shown in Figure 3.11

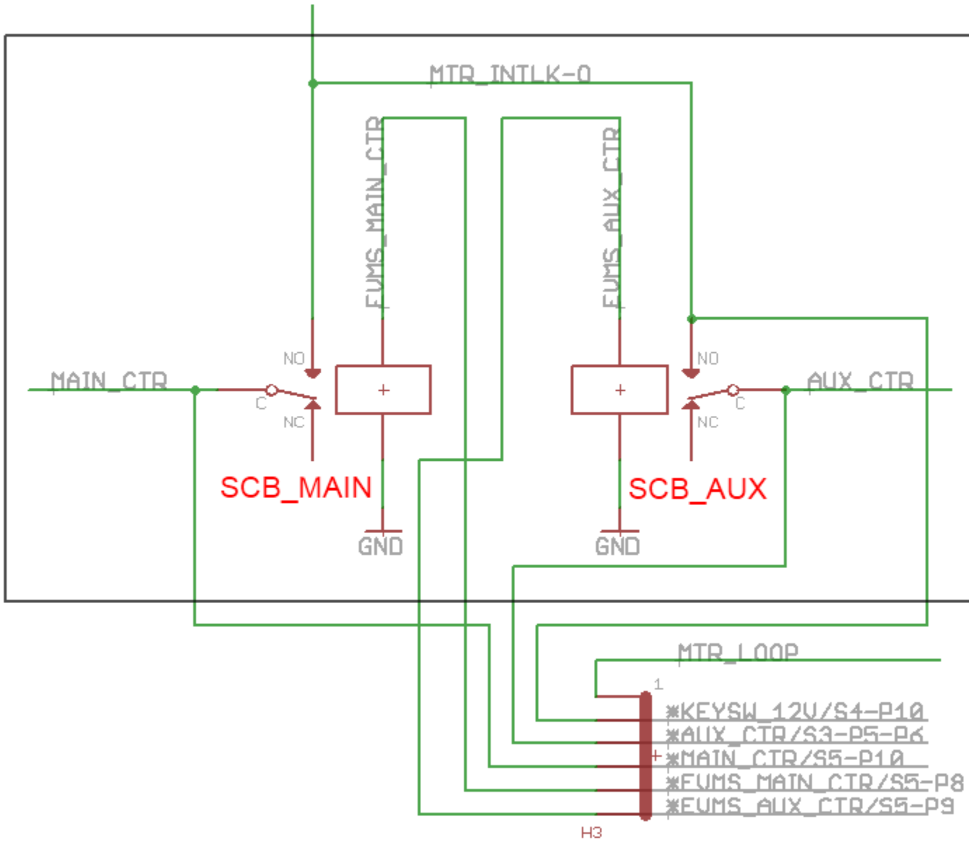


Figure 3.11 Aux & Main Relay Module Schematic

Instead of the EVMS directly driving the contactors, it instead drives relays internal to the SCB. Specifically, the EVMS_MAIN_CTR output drives the SCB_MAIN relay and the EVMS_AUX_CTR output drives the SCB_AUX relay. I am no longer subject to the limitations of the EVMS. Subject to limitations of the chosen relays and current capacity of the SCB, any number of contactors can potentially be driven.

3.3.3.7 Ready to Drive Interlock & HV relay

Once the main safety circuit path is closed allowing current to close the contactors the car should not yet respond to the accelerator pedal. The rule is:

EV4.11.3 Only closing the Shutdown Circuit must not set the car to ready-to-drive mode. The car is ready to drive as soon as the motor(s) will respond to the input of the torque encoder / acceleration pedal. Therefore additional actions are required by the driver to set the car to ready-to-drive-mode e.g. pressing a dedicated start button, after the tractive system has been activated. [3]

The ready to drive interlock controls the activation of the motor controller enable line via an external HV relay. The additional action required by the rules is performed by the driver pressing the Ready to Drive (RtD) button. This will enable the motor controllers and hence the car will respond to the torque encoder.

The functionality of this circuit (see Figure 3.12) depends on the EVMS and also the external HV Relay box. Firstly when the RtD button is pressed, RTD_BTN_T2 goes HIGH powering the relay. Contacts C and NO are now connected meaning the relay has a new power source RTD_12V that does not flow through the button. So when the button is released (it is a momentary button), the relay remains latched in the ON position.

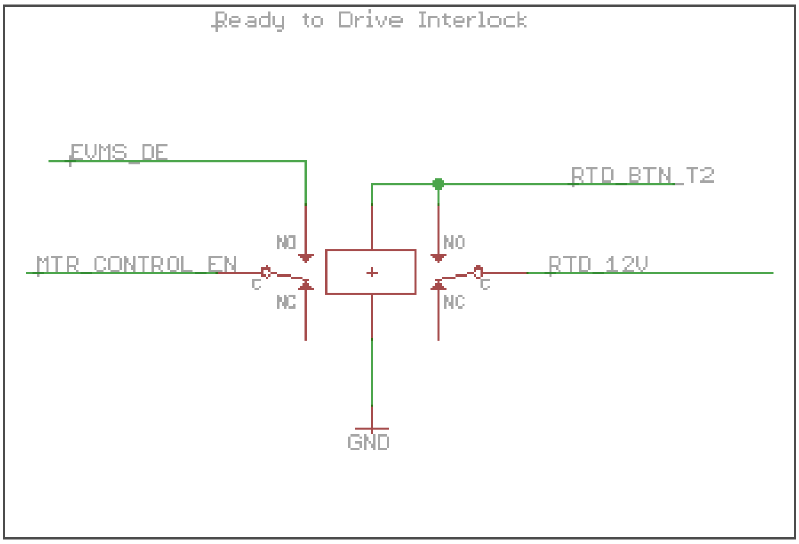


Figure 3.12 Ready to Drive Interlock circuit schematic

Since the contactors are ON, the EVMS_DRIVE and EVMS_DRIVE_ENABLE terminals are already closed. Hence from the Safety System Figure 2.5, we can see the current can now flow through these EVMS terminals to the HV relay coil, through the closed contacts of the RtD interlock circuit relay and then to ground. This turns on the HV relay. The current from the HV tractive supply can now flow through the HV relay and to the motor controller enable terminals, turning them ON.

At first it may seem that the external HV relay is redundant. Why not directly control the motor controller enable line with the RtD interlock circuit relay? There is a good reason why it has been designed and implemented this way. The HV relay is named so because it passes the tractive HV through its contacts. If there was no external HV relay, the relay from the RtD interlock would have to pass this HV. This implies that HV cabling would enter the SCB. The problem with this approach is that the rules are very strict when dealing with HV. Specially rated insulating barriers must be used between HV and LV areas in an enclosure and the specified spacing has to be maintained on the PCB. The safety circuit design purposely ignored these spacing requirements so that the circuit could be better compacted. This off course meant no HV would be allowed inside SCB. Overall the chosen implementation is better because it avoids mixing HV and LV which minimises risk of contact, a more compact safety circuit and sourcing specific insulating material is difficult.

3.3.3.8 Ready to Drive Sound

Rule EV4.14 stipulates the requirement of a 'Ready to Drive' sound. The READY TO DRIVE (RtD) state is defined in the rule below:

EV4.14.2 The car is ready to drive as soon as the motor(s) will respond to the input of the torque encoder/accelerator pedal. [3]

This function will be performed by the microcontroller utilizing a piezo electric buzzer. The circuit shown in Figure 3.13 relates to the RtD Sound portion of the Safety Circuit PCB.

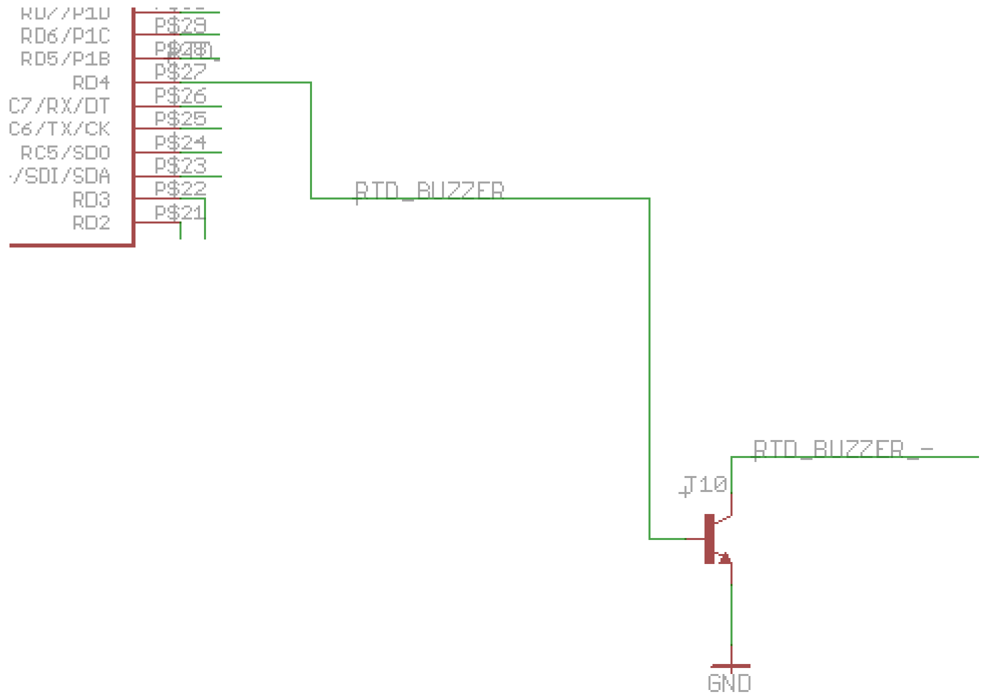


Figure 3.13 Ready to Drive Sound circuit schematic

An NPN transistor is simply driven by a digital output of the microcontroller. When the signal is HIGH the transistor is ON, current supplied from CHG_INTLK/MICROC_12V/BUZ+ of H 22 flows through the buzzer via the header, through the transistor to ground.

The sound should be easily recognisable for the benefit of car identification. In addition the rule below must be complied with:

EV4.14.1 The car has to make a characteristic sound, once not continuous for at least 1 second and a maximum of 3 seconds, when it is ready to drive. [8]

Some thought has been given to the desired sound and the final result will be continuous momentary bursts of noise gradually speeding up until almost continuous. The program code implementation can be seen in Appendix B

The buzzer itself is terminated to C5, utilizing P12 and P13. Using C5 in this way means the buzzer cannot then be mounted to the SCB because that would hinder removal of C5 if required and hence hangs freely with the plug connector. The buzzer is extremely light and does not require securing. Ideally the buzzer would be mounted on the chassis with a direct connection to inside the SCB but this would require another hole, compromising the waterproof integrity of the SCB enclosure. On balance, it did not make sense to do this when free pins were available on the C5 connector. In this configuration the buzzer can also be quickly replaced if it becomes faulty.

3.3.3.9 Charge Interlock

The Charge Interlock (Figure 3.14) controls the input to the EVMS_CHG_SENSE terminal and hence whether the car is in a charge mode or not.

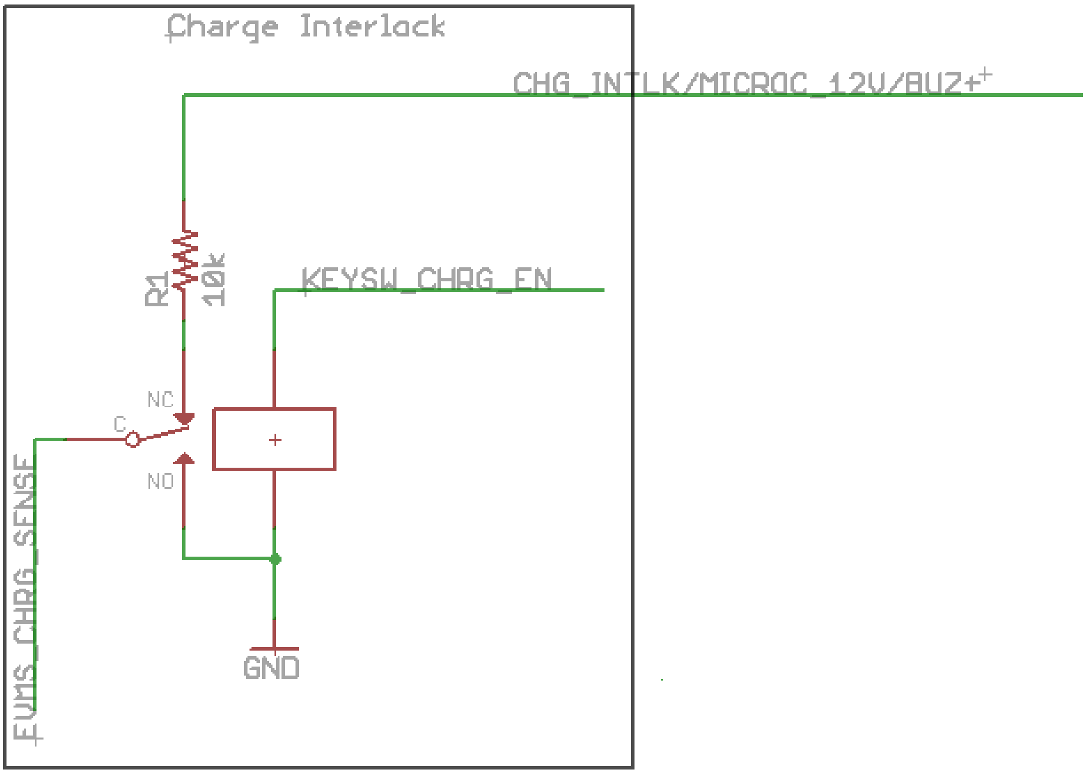


Figure 3.14 Charge Interlock circuit schematic

CHG_INTLK/MICROC_12V/BUZ+ supplies the HIGH signal for EVMS_CHG_SENSE which puts the EVMS in a non-charge state. When the key switch is flicked to charge, KEYSW_CHRG_EN is HIGH, powering the relay coil .This in turn creates a path from EVMS_CHG_SENSE to GND which puts the EVMS in the charge mode.

3.3.3.10 LED Indicator Subsystem

Although the end user experiences the LED Indicator subsystem via the dashboard, the heart of the LED Indicator Subsystem is implemented on the same Safety Circuit PCB as the rest of the modules covered in this section. Not only does this centralise the circuitry and hence alleviate the need for further PCBs, enclosures, mounting and space requirements, the Safety Circuit PCB has all the required signals from each safety element in one convenient location. The circuitry of the LED Indicator Subsystem consists of the microcontroller and LED drive transistors which will be covered next.

3.3.3.10.1 Microcontroller Inputs

All microcontroller inputs utilized are part of the LED Indicator Subsystem. In Section 3.2 the idea of the main safety circuit path was introduced. The LED Indicator Subsystem works by connecting the output of each safety element to the input of the microcontroller. When all elements are ON, the signal on each input pin will be HIGH. If any element turns OFF, then that element and all proceeding element input pins will read LOW. By knowing the order of the safety elements, it is possible to identify which safety element was triggered. See Appendix B for code implementation.

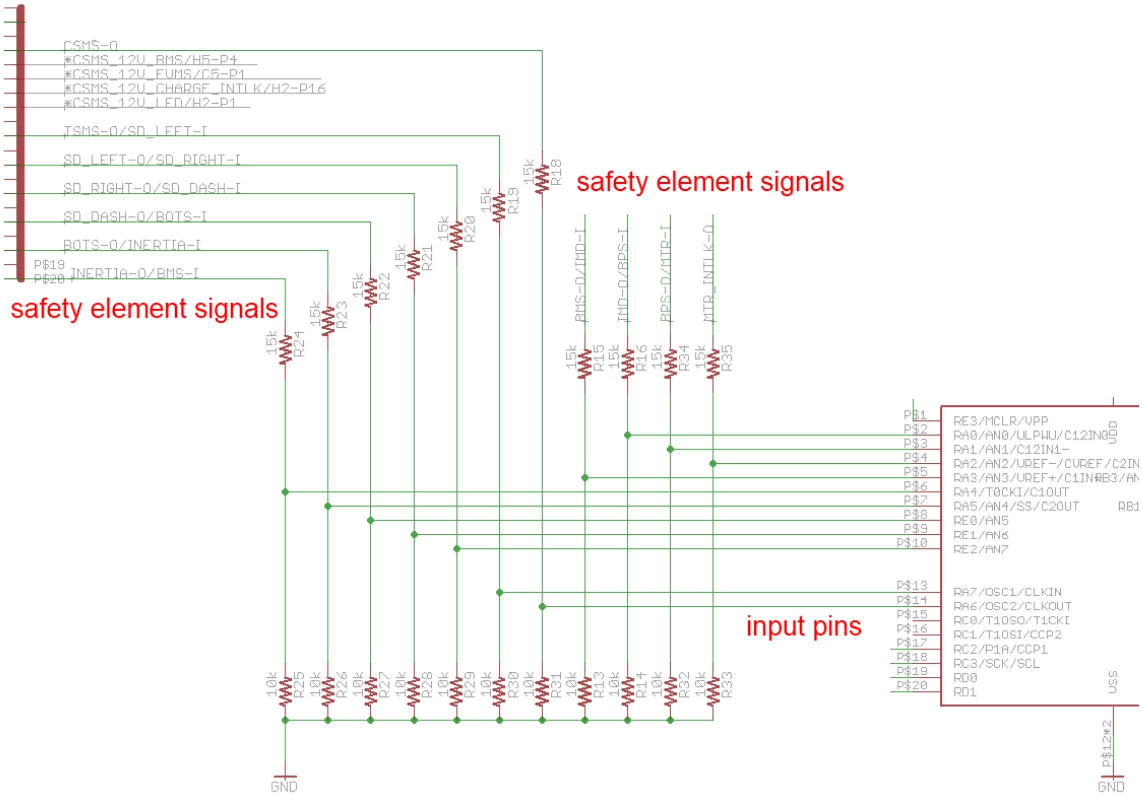


Figure 3.15 Voltage Divider inputs to Microcontroller

In actual fact the inputs to the microcontroller IO pins cannot be directly connected, rather they must be fed through a voltage divider. This is because the microcontroller is a 5V device whereas the safety circuit including the main safety circuit path runs off 12V. Inputting 12V into the microcontroller would certainly damage it. The nature of the voltage divider implies there will be a continuous loss of power to ground. This can be minimised by a judicious selection of resistors. We first need to find the ratio of the resistors to achieve 5V

$$\left(\frac{R}{R+x}\right)12 = 5$$

$$\left(\frac{R}{R+x}\right) = \frac{5}{12}$$

$$R = R\left(\frac{5}{12}\right) + x\left(\frac{5}{12}\right)$$

$$R\left(\frac{7}{5}\right) = x$$

Assume R = 10k. Then x = 14k. The closest resistance to this from the E12 standard without going lower is 15k. This ensures the voltage to the microcontroller is slightly under 5V or more precisely:

$$\left(\frac{10k}{10k + 15k}\right) 12 = 4.8V$$

4.8V is well above the minimum input voltage of 2V of the PIC16f887 microcontroller (data sheet p251) [20] to register as a HIGH input.

The amount of current leaking to ground with 10k and 15k resistors is:

$$\frac{12}{25k} = 480\mu A$$

Using resistors of 1k and 1.5 k would achieve the same result in terms of voltage division but if we check the current flow now we have:

$$\frac{12}{2.5k} = 4.80mA$$

This is a 10 times increase of wasted current per voltage divider used of which there are 10. This is essentially completely wasted power which can be avoided by just simply making correct design decisions.

3.3.3.10.2 Microcontroller Outputs

The microcontroller outputs are used to drive transistors which in turn power the LED indicators and also the buzzer covered in Section 3.3.8. The PIC16F887 has a maximum source or sink current of 25mA per pin and a maximum of 75mA for all ports combined (datasheet p245) [20]. Even though only one fault LED is ever on at once, meaning the current is kept within those limits, it is best to minimise microcontroller loading.

3.3.3.10.3 LED Driver Circuit

As described in Section 3.3.3.10.2 above, the microcontroller does not power or drive the LEDs directly. Instead it does so via bipolar transistors (see Figure 3.16).

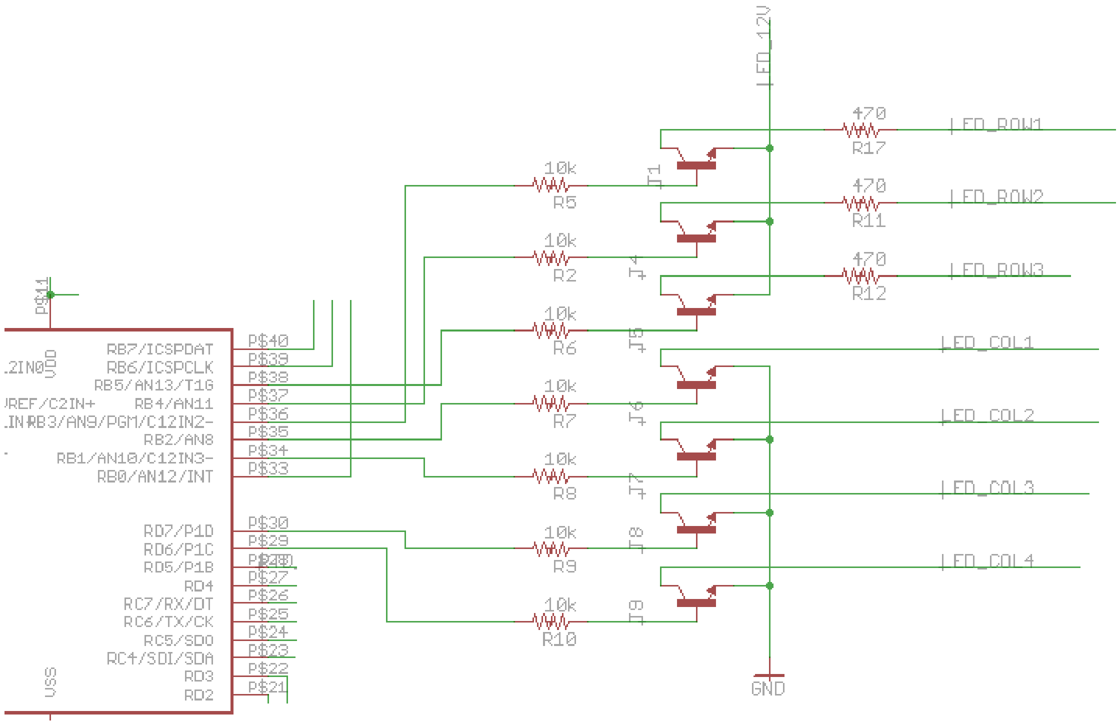


Figure 3.16 LED Driver circuit schematic

Further a technique of LED multiplexing discussing Section 3.1.3 is implemented to significantly reduce the number of microcontroller output pins required. Table 3.9 summaries the connection details for the LED multiplexing implemented on the Safety Circuit PCB

Logical LED Row, Column	Connector Pin C4 Anode, Cathode	uC pin	LED Indicator
1, 1	1,4	RB3, RB2	TSMS
1, 2	1,5	RB3, RB1	SD Left
1,3	1/6	RB3, RD7	SD Right
1,4	1/7	RB3, RD6	SD Dash
2,1	2/4	RB4, RB2	BMS
2,2	2/5	RB4, RB1	Inertia
2,3	2/6	RB4, RD7	BOT
2,4	2/7	RB4, RD6	IMD
3,1	3/4	RB5, RB2	Motors
3,2	3/5	RB5, RB1	BPS

3,3	3/6	RB5, RD7	RTD
3,4	3/7	RB5, RD6	unused

Table 3.10 LED Multiplexing implementation summary

3.3.3.11 5V Power Supply

The Safety Control System is mostly a 12V system. However the microcontroller is a 5V device. In section 3.3.3.10 we saw the use of voltage dividers to ensure a maximum 5V input. However the microcontroller itself must be powered from a 5V source. The safety circuit utilises a 5V linear regulator to attain the required voltage input (see Figure 3.17).

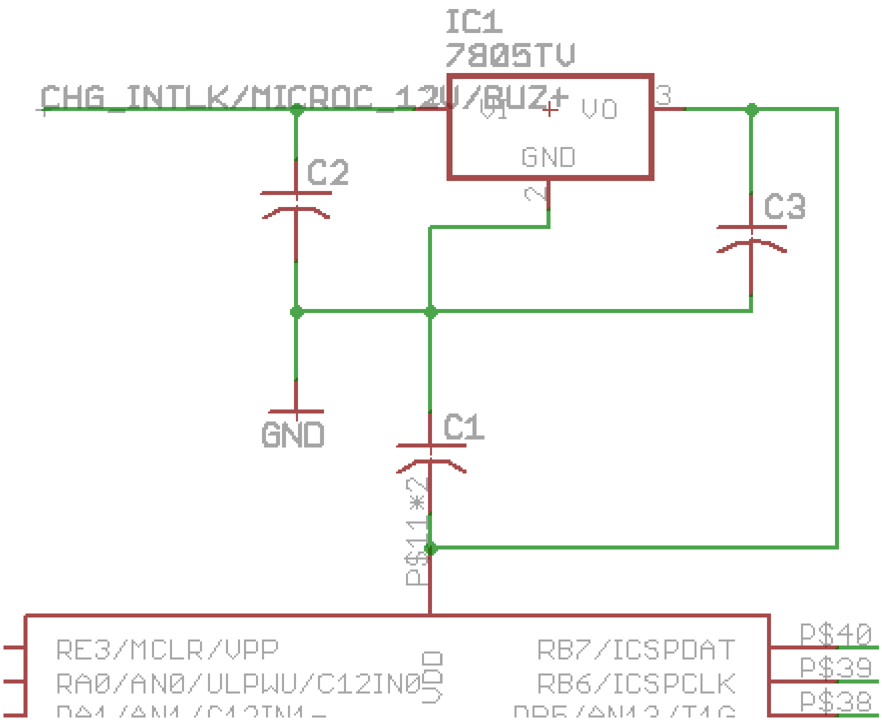


Figure 3.17 5V Power Supply circuit schematic

Bypass ceramic capacitors are used at the input and output of the regulator as well as close to the microcontroller input. This minimises the noise and provides a clean and stable 5V power supply to the microcontroller.

3.3.3.12 Programming Header

The inclusion of a programming header adds immeasurable convenience to the programming process of an embedded system. As discussed in Section 3.3.1, programming is an iterative cyclic process where the program can be updated and uploaded to the microcontroller numerous times over the lifetime of a project. Thousands of times is likely for a complex project. By using an integrated PCB programming header H7, the vast number of potential updates that will occur during the testing and debugging phase will not be a worry because of the simplicity of the process. The programmer is simply connected straight to the programming header, and the new programs uploaded. The programming is done completely on board using the In Circuit Serial Programming (ICSP) Microchip protocol.

The alternative is to use an external programmer, prevalent in the past. The microcontroller would have to be physically removed from the circuit and placed in a standalone programmer where the programming function was performed. Then the microcontroller had to be placed back into the main circuit. At first this may not seem like a heavy burden, but the nature of programming alluded to above would quickly convince anyone that in circuit programming is the way to go.

There are pins on the microcontroller related to the ICSP protocol but they multiplexed with other functionality. Microchip [21] recommends the clock (PGC) and data (PGD) pins should be kept free from other passive circuits to ensure trouble free programming, highlighting the vulnerability of these critical signals to capacitive loading [22]. Since the chosen microcontroller the PIC16F887 is a 40pin device with plenty of IO to meet the requirements of the Safety Circuit PCB, there is no need to utilise the programming pins for anything other but that purpose. This will ensure another variable that could cause a problem is eliminated, resulting in one less issue to think about during troubleshooting.

3.3.3.13 Spare Headers

As part of a robust design, provisions for possible future additions or expansions should be provided. This practise is demonstrated in the Safety Circuit PCB. The microcontroller is large and not fully utilised. A number of spare pins have been broken out to PCB header pins. A summary is listed in Table 3.10.

Header & Pin	Microcontroller Pin	Pin Functions	Suggested Use
H6-P1	20	RD1	Digital IO
H6-P2	19	RD0	Digital IO
H6-P3	18	RC3/SCK/SCL	I^2C, SPI
H6-P4	17	RC2/P1A/CCP1	Digital IO
H7-P1	40	RB7/ICSPDAT	Programming
H7-P2	39	RB6/ICSPCLK	Programming
H7-P3	33	RB0/AN12/INT	Digital IO
H7-P4	1	RE3/MCLR/VPP	Programming
H8-P1	26	RC7/RX/DT	EUSART
H8-P2	25	RC6/TX/CK	EUSART
H8-P3	21	RD2	Digital IO
H8-P4	22	RD3	Digital IO
H8-P5	23	RC4/SDI/SDA	I^2C, SPI
H8-P6	24	RC5/SD0	SPI

Table 3.11 PCB Spare Header Pins to Microcontroller Functions

The 'Pin Functions' column describes the functionality or uses for each pin. Most pins have multiple functions referred to as multiplexing functionality on a pin. The 'Suggested Use' Column groups pins used for important communication peripherals.

Overall these headers make it extraordinarily simple to interface with the microcontroller, whether that be additional safety elements, sensors or even communication with a whole new subsystem. See Section 6.1 for ideas on future work. It is important to note such breaking out of spare pins is not an afterthought. In particular the communication peripherals of the microcontroller including Serial Peripheral Interface (SPI), I^2C and EUSART will be useful or even necessary to communicate with external systems. Care was taken not to use pins related to these peripherals for the purpose of the Safety Circuit PCB. In the end, it is up to the future designer to choose what each pin will ultimately be used for. For example, P24 of the µC is one of three pins required for SPI but can also be used as a simple digital IO. It cannot be used for digital IO (RC5) if SPI is required and should be left free for this purpose. If digital IO is required for instance, it would be sensible to first use up P21 and P22 because they can only perform digital IO and are not part of any other peripheral that may be used in the future.

3.3.4 Board Layout

When designing a circuit and drawing up the schematic diagram, the primary objective is the correct application of electronics theory and meeting application requirements so that the final product works as intended. Once this is complete the important step of PCB trace routing must be performed. This is the transformation from a circuit design schematic to a trace layout which will be the basis on which the PCB is manufactured. PCB trace routing is an artistic process. Those who have used the auto router in various CAD packages often exclaim how poor the results are. This is because the auto router function is an inherently algorithmic process, it cannot think artistically as humans can.

The trace layout for the Safety Circuit PCB is presented in Figure 3.18.

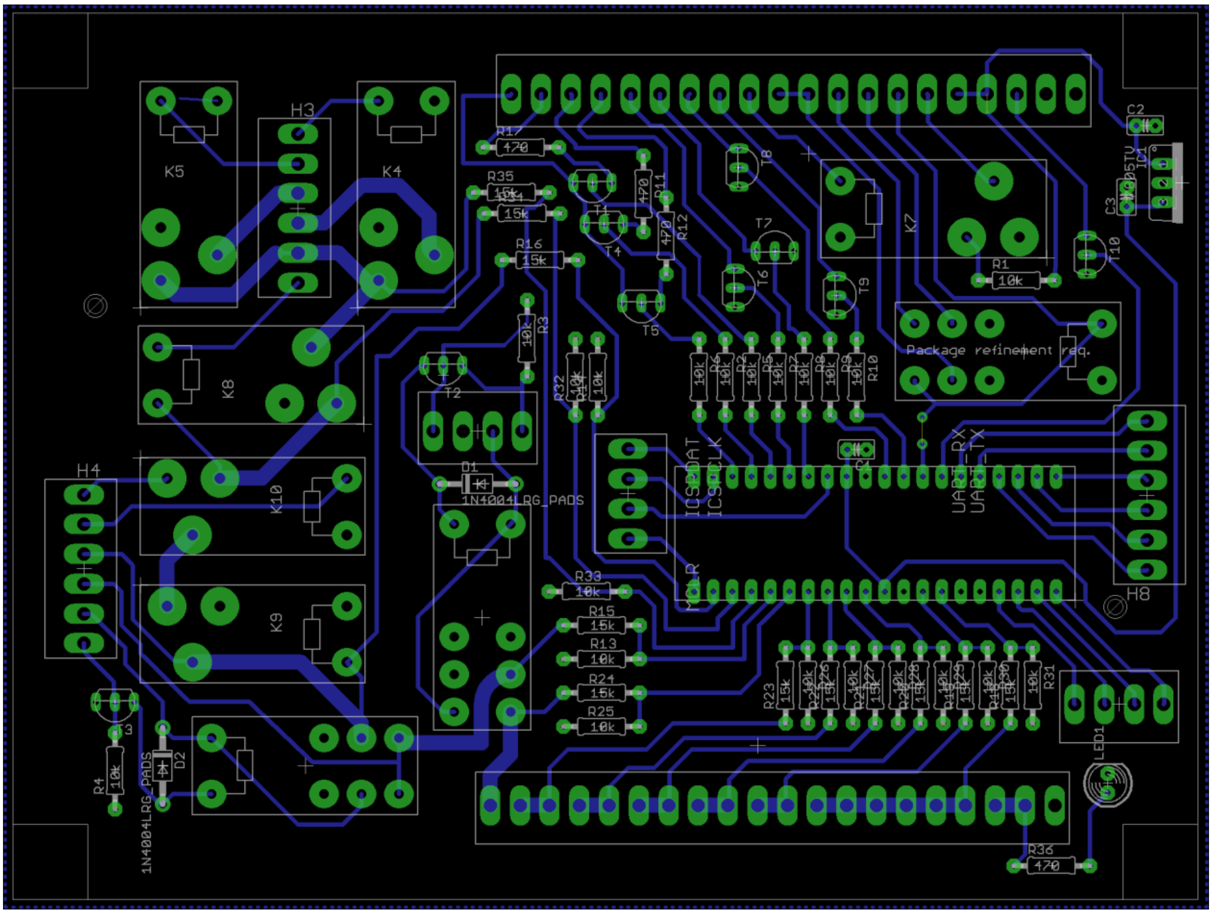


Figure 3.18 Safety Circuit PCB route layout

Other than achieving a nice clean and consistent route layout, the other consideration is the width of the actual traces. The safety circuit deals with current in the range of 6 – 8A which flows in the main safety circuit path but also with small currents of <100mA. Clearly a trace suitable for the latter will not be so for the former. [23] presents formulas to calculate PCB trace widths based on the IPC-2221 [24] current vs. conductor cross section graph. The formulas have been generated by curve fitting to empirical data.

The main safety circuit path must be rated for at least 8 A. Using [23] to calculate the required trace width for 8A gives 5.29mm. This is quite a large trace for a PCB making it very difficult to route and may require a larger PCB. I decided to make a compromise by choosing a trace width of 2mm. The additional required cross section for the trace is obtained by applying a liberal amount of solder along the main safety circuit path as shown in Figure 3.19.

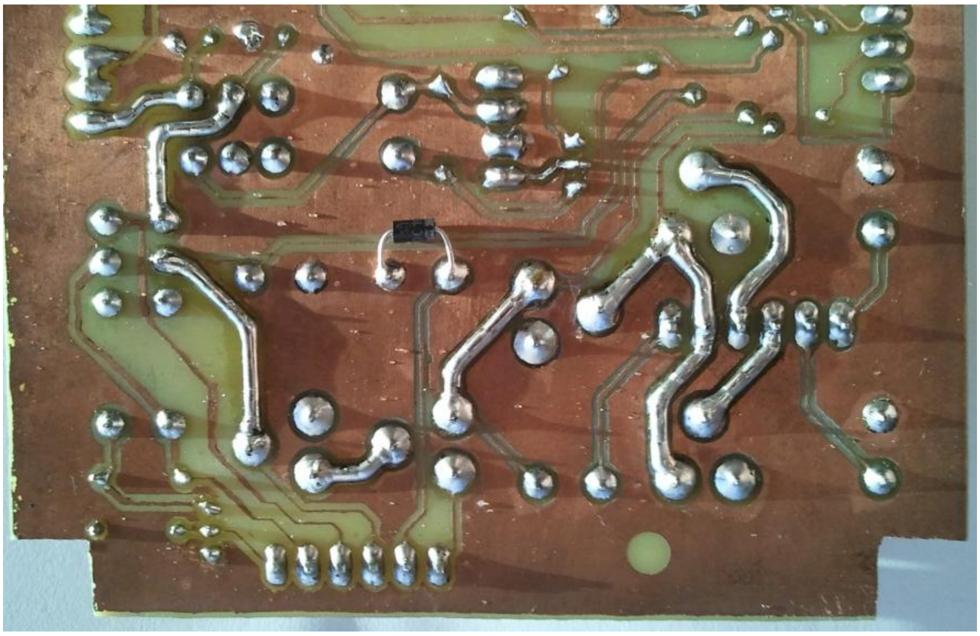


Figure 3.19 Safety Circuit PCB – Main safety circuit path trace thickening

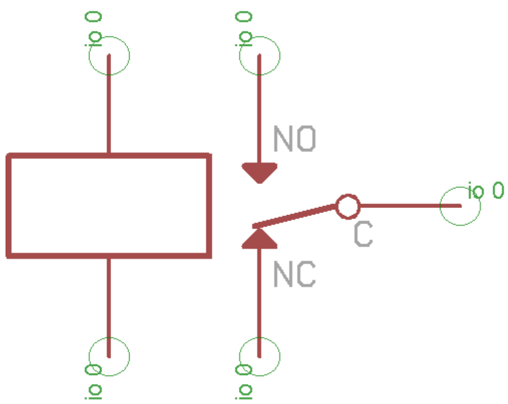
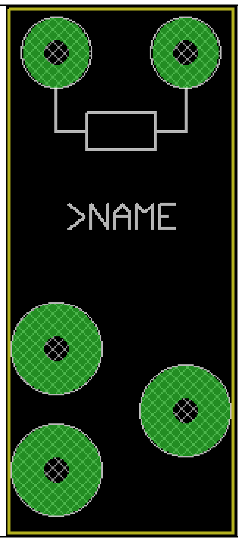
Mcgyvr [9] exclaims that 'adding solder to a trace is not a good reliable way to increase the current carrying ability'. Further they suggest to use a wider trace or use thicker copper cladding. I agree this is the professional method to use for a commercial mass produced product. They then go onto say 'Having said that, will it work? Sure for a home/one off project'. This is precisely the situation I find myself, constructing a one of project, on a limited budget and limited selection of components from Altronics (from whom we are encouraged to buy due to a sponsorship).

For the rest of the traces, calculating the required trace width for 1A gives 0.300mm width. Using a value of 1A far exceeds the current that any other trace in the circuit will conduct. The actual trace chosen is again compromised, this time up to 0.508mm. Off course using a large width is always acceptable in terms of current capacity. However the reason a larger trace was chosen was because I planned to manufacture this board myself. Clearly my capacity to make a PCB and tolerances involved in my process will be markedly worse than a professional fab house. However a width of 0.508mm small enough to effectively route with but at the same time ensuring they are wide enough to result in solid traces in my PCB manufacturing process.

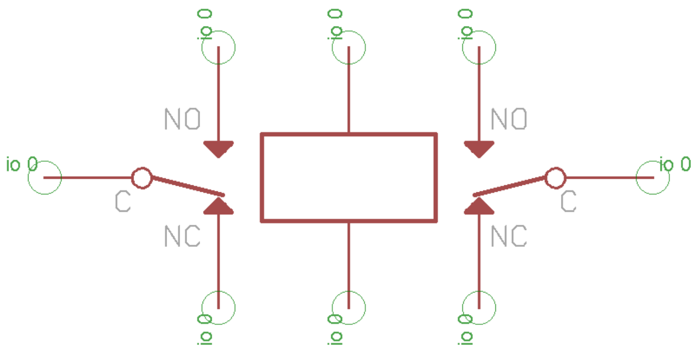
3.3.4.1 Custom Component Footprints

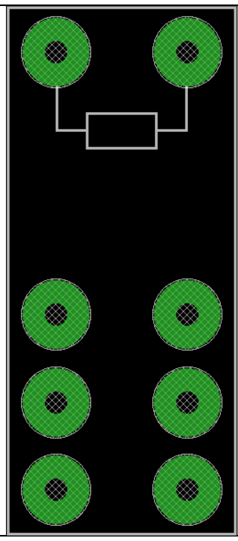
The library of components available in EAGLE [25] is extensive but lacks consistent nomenclature and organisation. Due to the countless number of electronics componentry available today, CADSOFT chose to use an open community type paradigm for the building of the library. This off course allows the electronics community at large to add their own footprints and symbols of various components. While this leads to an extensive database of components, unfortunately the quality of the designs cannot be guaranteed. Therefore my principle is that you either check the footprint dimensions of each component you use from the library or implement them yourself.

Each library component is known as a package and consists of a symbol used in the schematic and a footprint used in the PCB layout. In the case of the safety shutdown circuit the standard components such as the resistors, BJT transistors and diodes have matching packages. Packages for others such as the relay bases, PCB headers and PIC16F887 microcontroller don't exist. The implementation of these components is displayed in Table 3.11 below.

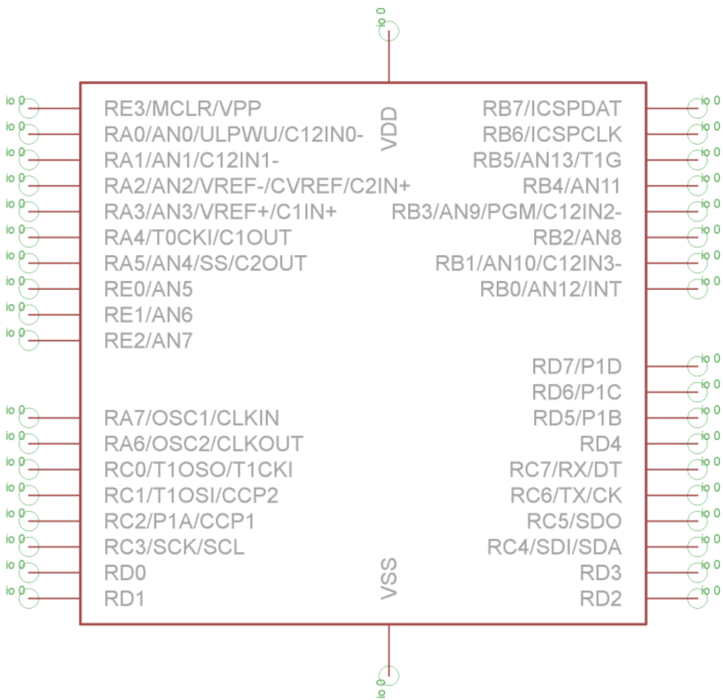
Schematic Symbol	Layout Footprint
RLY_SPDT_12V	
	

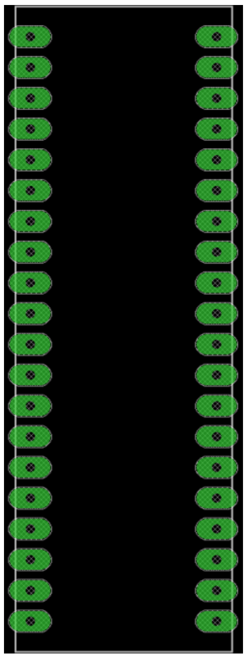
RLY_DPDT_12V_1





PIC16F887_uC





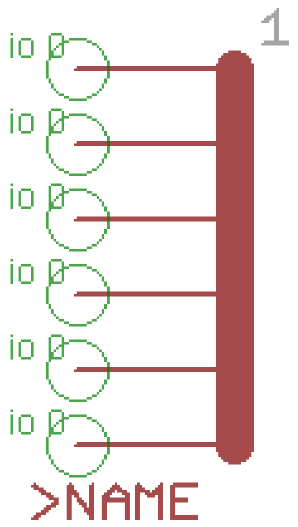
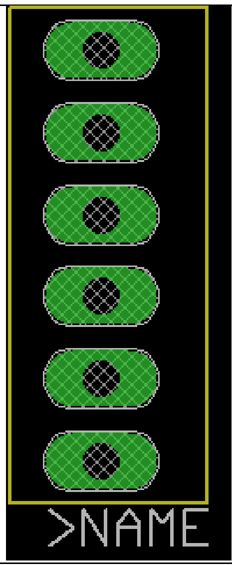
HDR_PCB_P6	
	

Table 3.12 Custom designed Footprints and circuit symbols

3.4 Physical Design & Implementation

At this stage we have covered a great deal on the Safety Circuit PCB on a design level. The external safety elements have been covered in depth and a thorough analysis of the design and operation of the Safety Circuit PCB has followed. However this is really just the first step of the product development cycle. Next the designs and decisions related to the physical implementation of the safety system are considered.

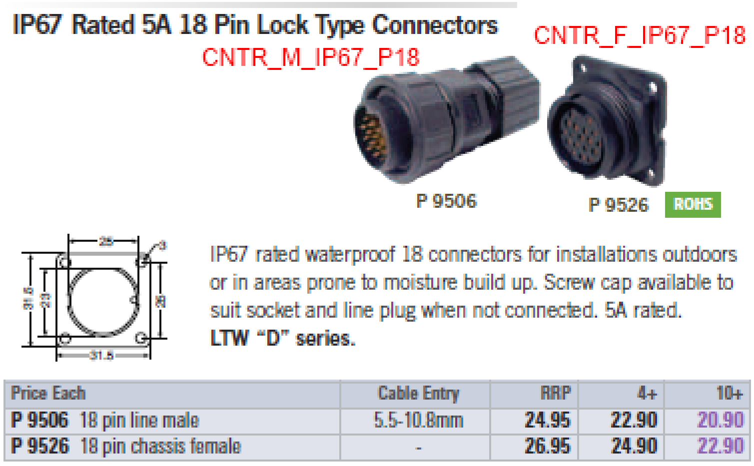
3.4.1 PCB Manufacture

The PCB manufacturing process was conducted using the photo resist method. This method can achieve excellent results, having both a better success rate and producing a better quality product than using the Laser Transfer Method [26]. This is because it is based on photolithography, the extremely accurate process used in microfabrication usually on a silicon substrate [27]. Photos from the fabrication process can be seen in Appendix A.2.

3.4.2 I/O Connections

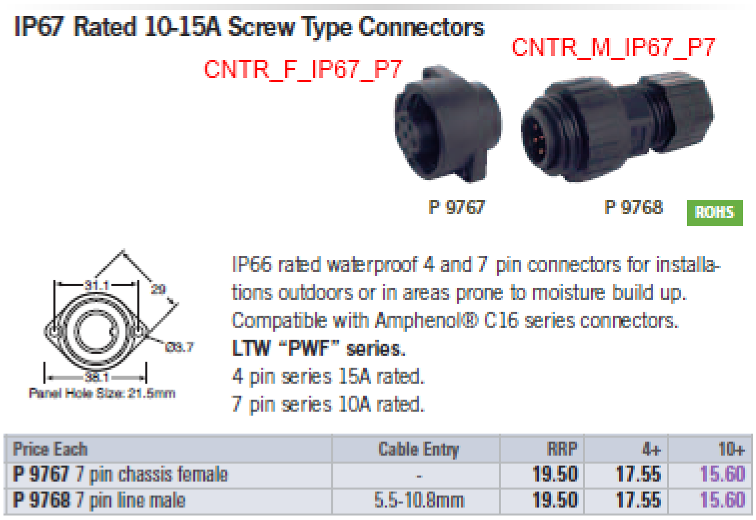
3.4.2.1 Connector Specification

The connectors in Figures 3.20 & 3.21 have been sourced from Altronics and used extensively for the SCB IO. They are IP67 rated, ensuring longevity of the connectors and minimising the probability of water ingress into the SCB itself.



Price Each	Cable Entry	RRP	4+	10+
P 9506 18 pin line male	5.5-10.8mm	24.95	22.90	20.90
P 9526 18 pin chassis female	-	26.95	24.90	22.90

Figure 3.20 CNTR_M_IP67_P18 and CNTR_M_IP67_P18 connector specification [7]



Price Each	Cable Entry	RRP	4+	10+
P 9767 7 pin chassis female	-	19.50	17.55	15.60
P 9768 7 pin line male	5.5-10.8mm	19.50	17.55	15.60

Figure 3.21 CNTR_M_IP67_P7 and CNTR_M_IP67_P7 connector specification [7]

3.4.2.2 Connector Placement and Wiring

There are a number of connectors used in the safety system, in particular for IO of the Safety Circuit Box. The following list describes all connectors used in the

Safety Control System and associated abbreviated names used throughout the text.

Connector Socket	Location	Name	Mates with . . .	Connector Plug	Name
CNTR_F_IP67_P7	SCB	S1		CNTR_M_IP67_P7	C1
CNTR_F_IP67_P7	SCB	S2		CNTR_M_IP67_P7	C2
CNTR_F_IP67_P7	SCB	S3		CNTR_M_IP67_P7	C3
CNTR_F_IP67_P18	SCB	S4		CNTR_M_IP67_P18	C4
CNTR_F_IP67_P18	SCB	S5		CNTR_M_IP67_P18	C5
CNTR_F_IP67_P18	Dashboard	S6		CNTR_M_IP67_P18	C6
HDR_PCB_P10	SCB	H1-1		HDR_PLUG_P10	HP1-1
HDR_PCB_P10	SCB	H1-2		HDR_PLUG_P10	HP1-2
HDR_PCB_P10	SCB	H2-1		HDR_PLUG_P10	HP2-1
HDR_PCB_P10	SCB	H2-2		HDR_PLUG_P10	HP2-2
HDR_PCB_P6	SCB	H3		HDR_PLUG_P6	HP3
HDR_PCB_P6	SCB	H4		HDR_PLUG_P6	HP4
HDR_PCB_P4	SCB	H5		HDR_PLUG_P4	HP5
HDR_PCB_P4	SCB	H6		HDR_PLUG_P4	N/A
HDR_PCB_P4	SCB	H7		HDR_PLUG_P4	N/A
HDR_PCB_P6	SCB	H8		HDR_PLUG_P4	N/A

Table 3.13 Connectors used in SCB and Dashboard

Note:

1. This thesis will refer to connectors given by the Name in Table 3.12.
2. Individual pins of connectors are referenced by appending –PX to the connector name where X is the pin number.
3. Use of 'N/A' indicates spare PCB headers that currently are not utilised.

The internal wiring of SCB is very dense. All wiring lengths between the PCB and lid connectors is such that it does not hinder the removal of the lid. It can be taken off it can be easily placed to the side of the SCB. However the wiring is also kept as short as possible to ease congestion in the enclosure once the lid is on.

The following figures show the placement of external connectors listed in Table 3.12.

Figure 3.22 Placement of connectors S1, S2, S3, S4, S5 on the SCB lid.

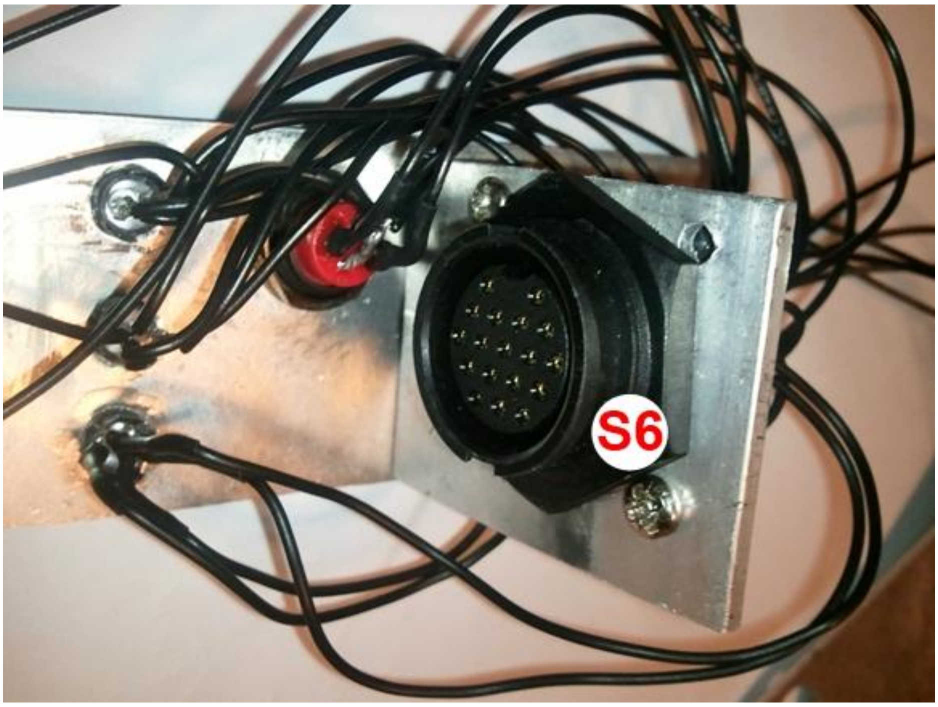


Figure 3.23 Placement of connector S6 mounted behind the dashboard.

3.4.2.3 Connector Pin Allocation

Connector Type	Pin Allocation
CNTR_F_IP67_P7	
CNTR_F_IP67_P18	

3.4.3 Safety Circuit Box Final Product & Mounting

Figure 3.24 shows the Safety Circuit PCB mounted in the SCB enclosure. The relays and PCB header plugs have been omitted for clarity.

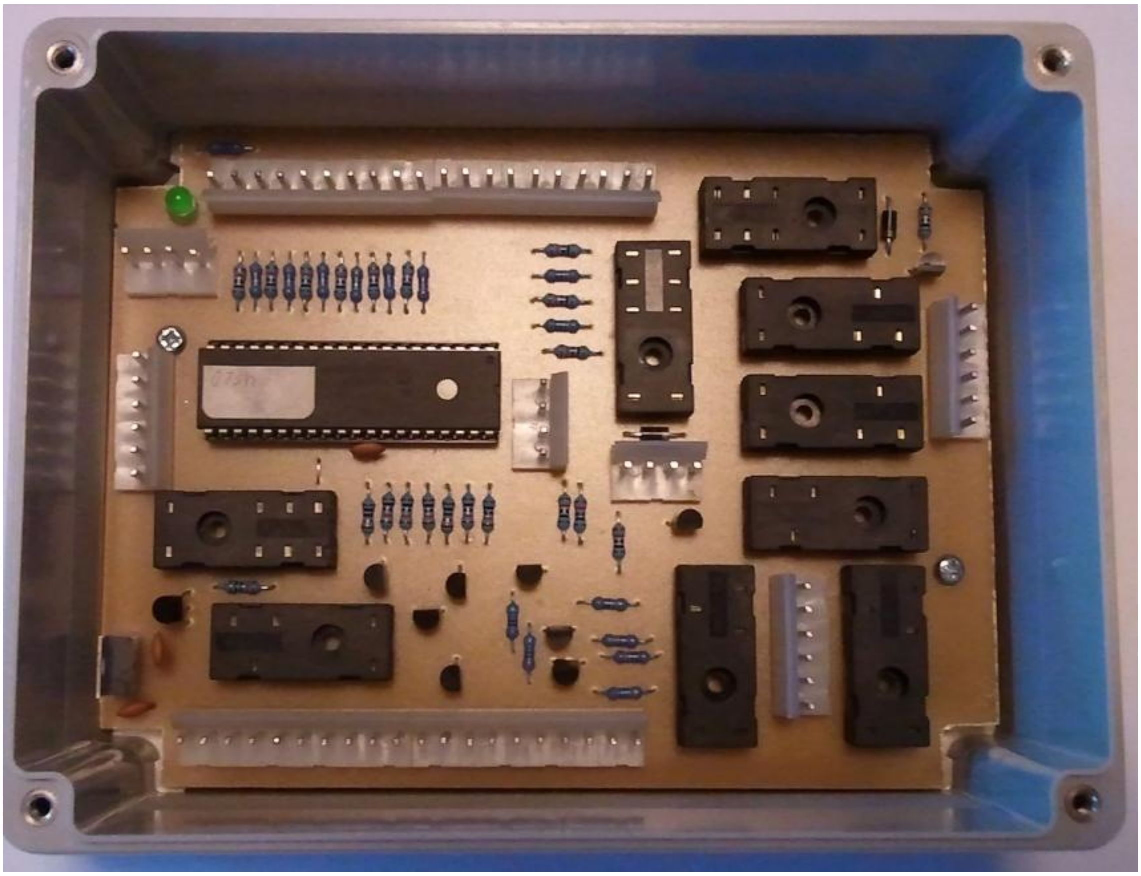


Figure 3.24 Safety Circuit PCB mounted in SCB enclosure

3.4.4 External Safety Element Mounting

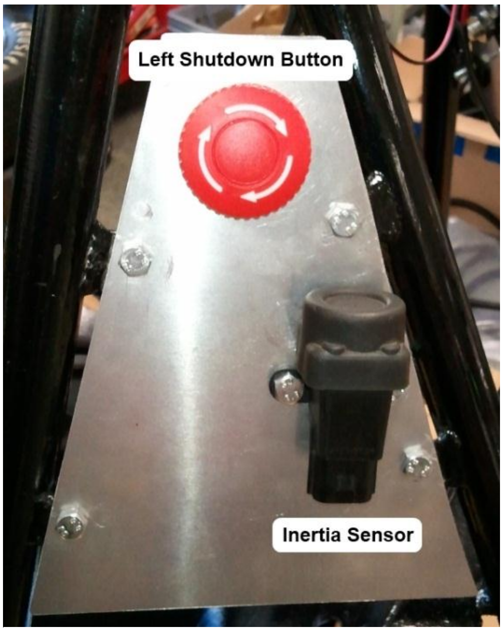


Figure 3.25 Left Mount Plate

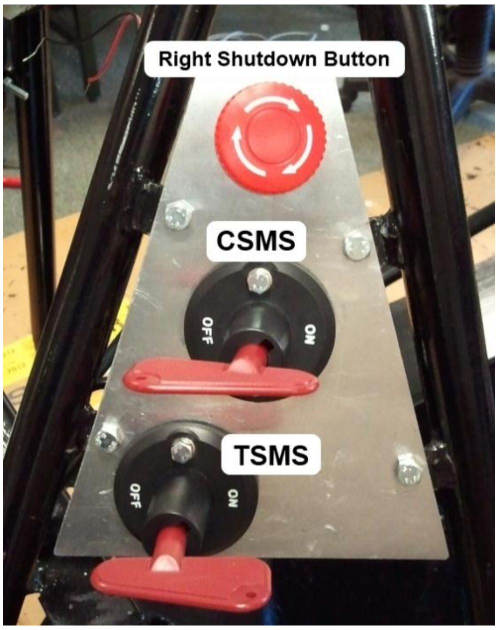


Figure 3.26 Right Mount Plate

3.4.5 Cables and Wiring

3.4.5.1 Complete Safety System Cabling

A complete and comprehensive Safety Control System wiring table is available in Appendix C.

3.4.5.2 Theory

The selection of a cable for a particular application should be a considered, measured and calculated process. The primary specification of any cable is the cross sectional area of the conductor. The cross sectional area relates to a quantity known as the ampacity of a cable, otherwise known as current carrying capacity which specifies the maximum electrical RMS current that can safely flow while remaining in the safe temperature range of the cable. Exceeding this value means the conductor will begin to sustain progressive or immediate deterioration, leading to potentially hazardous situations.

It is important to note however that the determination of the ampacity is not a direct conversion from the cross sectional area as one might expect. The ampacity of the cable really depends on other factors including:

1. Insulation temperature rating
2. Electrical resistance of the conductor material
3. Frequency of the current (AC only)
4. Ability to dissipate heat which depends on conductor geometry and surroundings
5. Ambient temperature

So the question remains, how can one determine the cross sectional area of cable required for a given amperage that ensures safe and reliable operation? Of course you would not want to use a cable with a rated ampacity equal or close to the actual current it will conduct. Instead a generous margin or tolerance must be incorporated in the calculation. Essentially we want a conversion value of conductor cross sectional area per amp which can be easily used to determine the cross sectional area of the cable for a required amperage. Such a value must be experimentally derived, conservatively rated and remain valid for all but extreme cases of the 5 points listed above. [28] states a conversion value of 300cmil/amp as a safe, robust and reliable value to use in practice. Of course in extreme conditions where for example cabling is laid in extremely hot factory conditions or where numerous cables are bundled and run in enclosed conduit, the heat dissipation may be drastically reduced and additional tolerances required of the conversion value i.e. value increased.

Another consideration is the voltage drop over the cable run. While the ampacity requirements may be met, the voltage drops incurred especially in long cable runs or high current applications may become significant. This may lead to the potential problem of insufficient voltage to run circuitry/devices at the other end of the cable run. In addition, this voltage drop across the cable run manifests as wasted power dissipated as heat. For efficiency conscious applications it may be desirable to minimise the wasted power. Ohms Law (3.10) demonstrates the voltage drop across a conductor:

$$V_{drop} = IR \tag{3.10}$$

As current (I) through the cable increases or the length of the cable run increases thereby raising the resistance of the cable, the voltage drop across the cable increases.

Firstly, the current flowing through the cable can be determined by the application it is being used for. If the current is not always constant, using the maximum possible value in the subsequent calculations will give a worst case voltage drop which is what we want to know. Secondly we must determine the resistance of our cable run. Often the manufacturer will specify the resistance per kilometre or similar parameter. However in case it is omitted or spare cable is found and utilized, the resistance of the conductor in a cable can be calculated using formula (3.11) below:

$$R = \frac{\rho L}{A} \tag{3.11}$$

Where:

ρ - resistivity

L – length

A – cross sectional area

The resistivity is a physical property of the metal used. As can be seen in formula (3.11), the length of cable is directly proportional to resistance whereas cross sectional area is inversely proportional to resistance. Normally, we don't have much choice in the material used as the conductor so resistivity is not a variable we can play with greatly.

3.5 Programming the Microcontroller

3.5.1 Purpose

The microcontroller is a major component of the LED Indicator Subsystem. Its use has been thoroughly covered in Section 3.3.3.10.

3.5.2 In Circuit Serial Programming (ICSP)

The microcontroller is programmed on board using the In Circuit Serial Programming protocol via the programming header described in Section 3.3.3.12.

3.5.3 Logic Flow diagram

Before programming commenced, it is always beneficial to draw up some basic state or flow diagrams. This helps to translate the logic of the application into code. The Safety Control System has a concept of state but is also procedural in nature. Therefore it is best represented by a combination of state and flow charts to describe the full picture. The state diagram is given in Figure 3.27

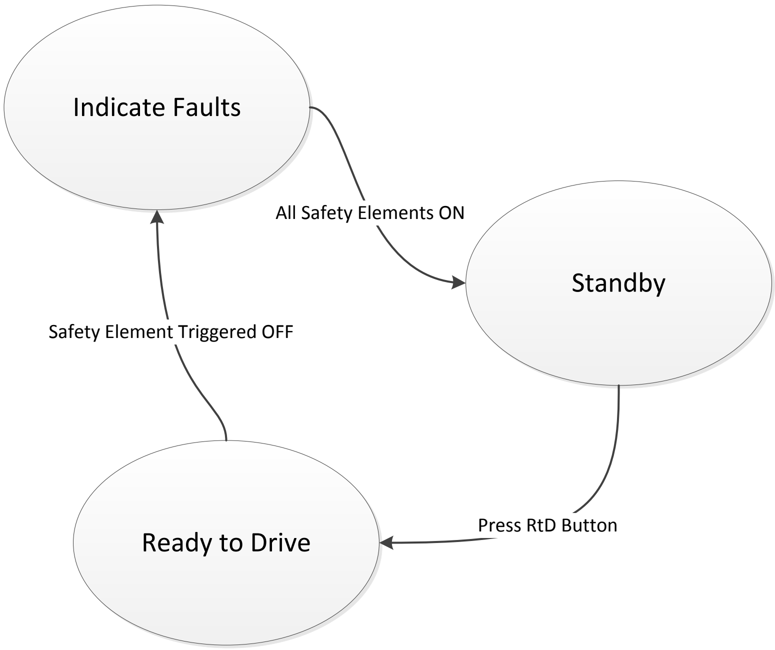


Figure 3.27 Safety Control System State Diagram

Only states relevant to the embedded program are considered here. For example the STANDBY state could be split into a CHARGE state, but its distinction from other states is irrelevant to the program and hence remains merged. The system starts in the INDICATE FAULTS state. If all safety elements are ON/CLOSED, the system transitions to the STANDBY state. Once the RtD button is pressed the READY TO DRIVE state is engage and the car is driveable. If a safety element is trigged OFF, then the system goes back to the INDICATE FAULTS state and continues to cycle.

Each state is broken down into flow charts. First we start with the INDICATE FAULT state of Figure 3.28

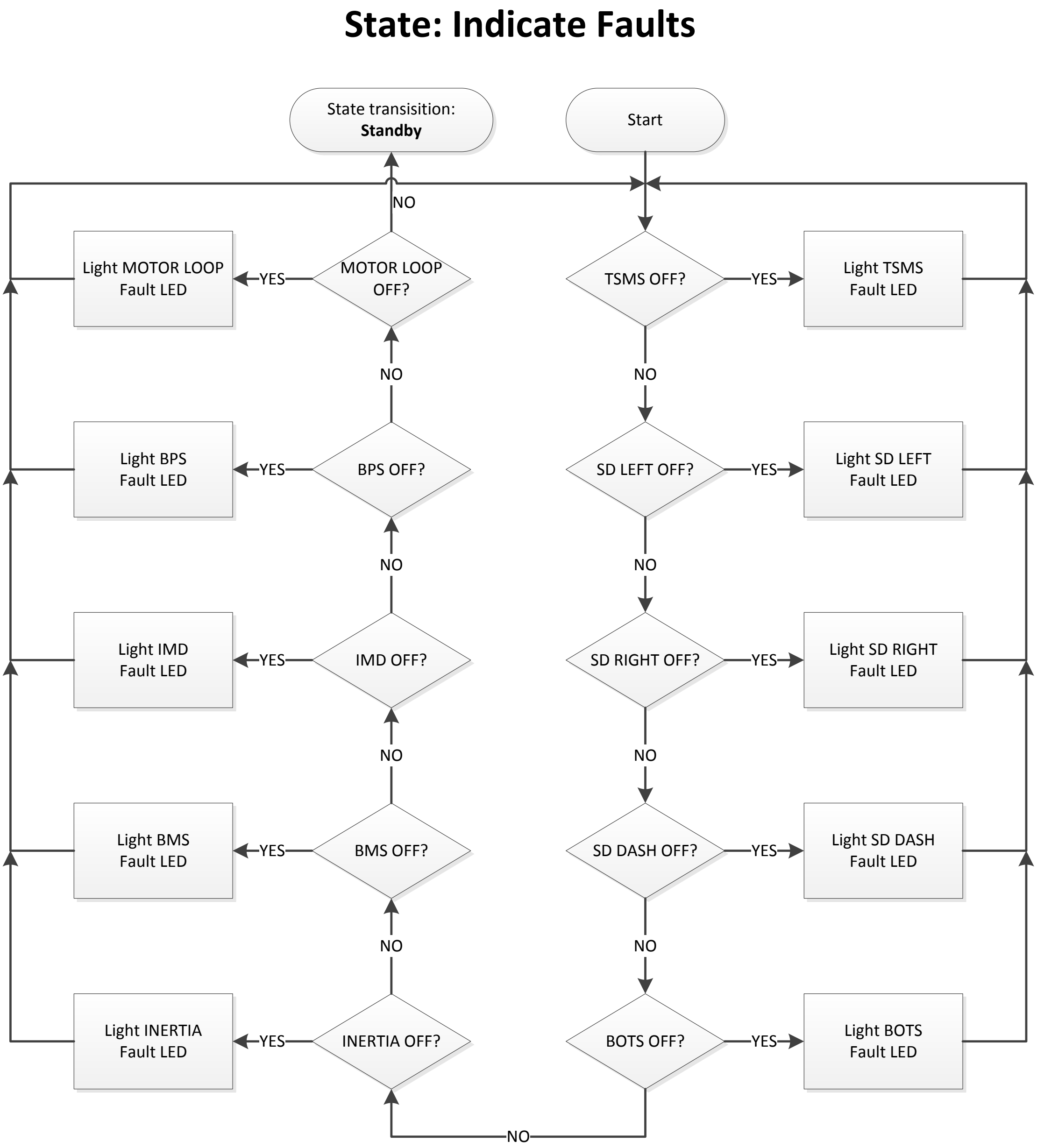


Figure 3.28 Indicate Fault Flowchart

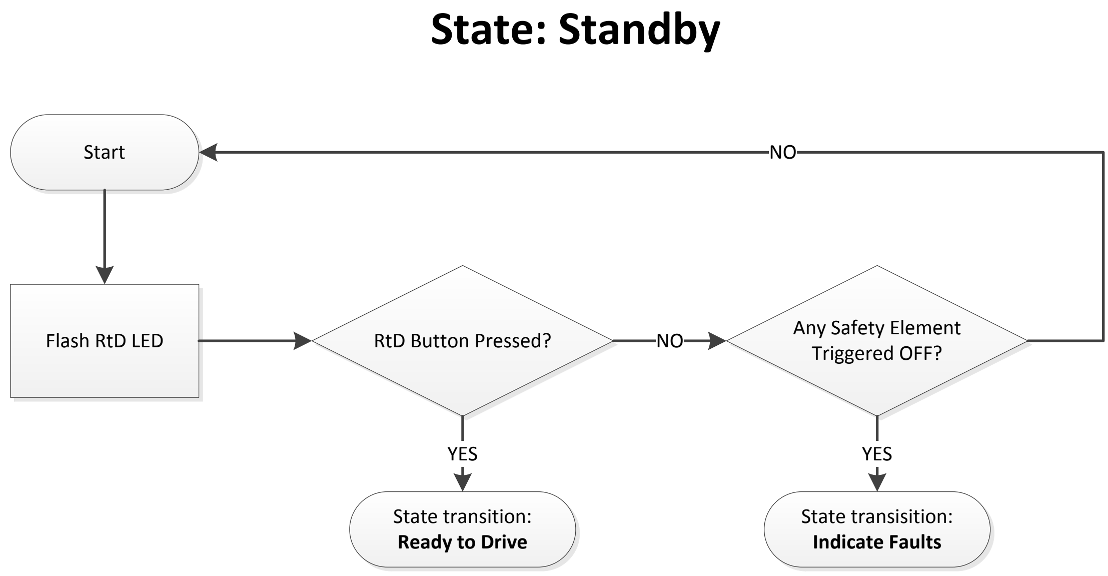


Figure 3.29 Standby Flowchart

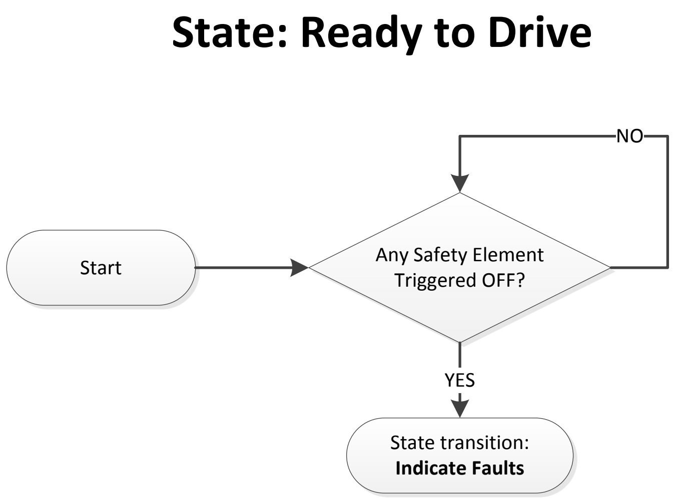


Figure 3.30 Ready to Drive Flowchart

3.5.4 Code

See Appendix B for a listing of the programming code running on the microcontroller of the LED Indicator Subsystem.

4 Dashboard

The dashboard is a module of the Safety Control System particularly relating to the LED Indicator subsystem. It forms the important visual interface between the driver and the current safety status of the car.

4.1 Initial Concept Design

The first step was to draw up a preliminary concept design including all intended components (Figure 4.1). The concept was based on dimensions obtained from the car chassis CAD drawings. Unfortunately the CAD drawings did not reflect the reality of the physical chassis accurately enough. Then the problem was exacerbated by the addition of two steel members near the dashboard. This relinquished the prospect of having a speedometer and TBS energy meter on the dashboard.

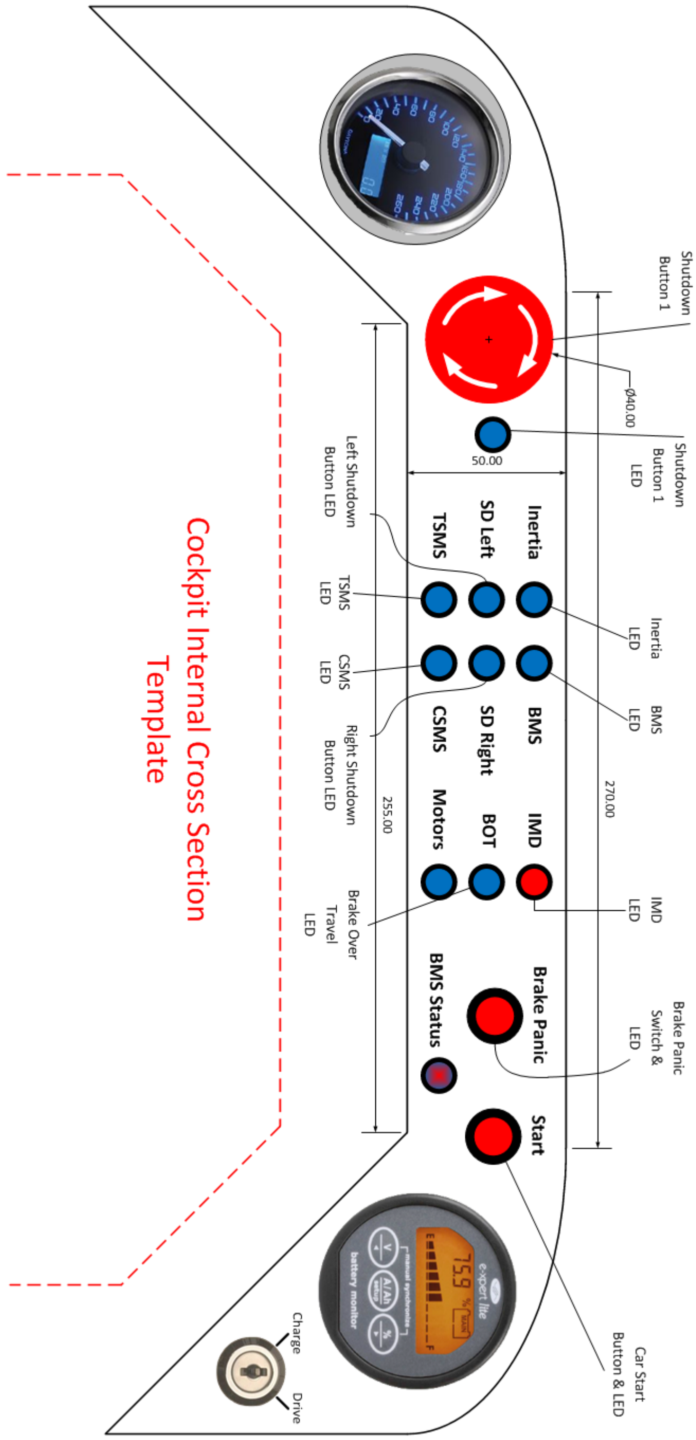


Figure 4.1 Initial Dashboard concept design

4.2 Final Design

The final design that was manufactured is displayed in two parts in Figure 4.2 and Figure 4.3.

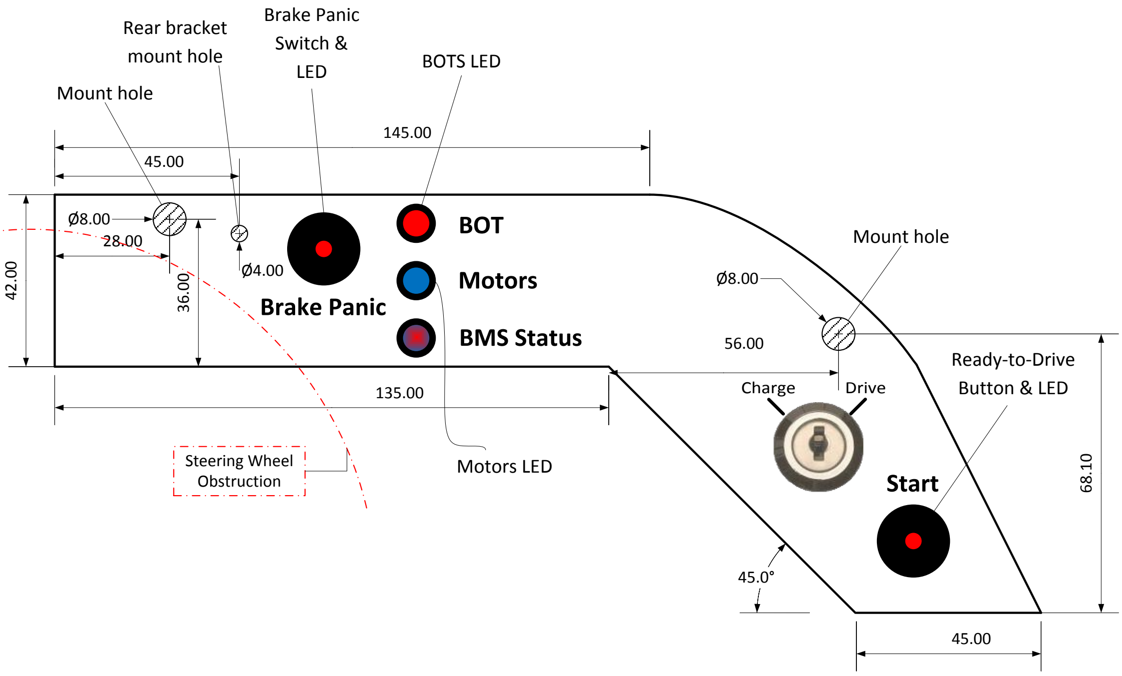


Figure 4.2 Left side of dashboard

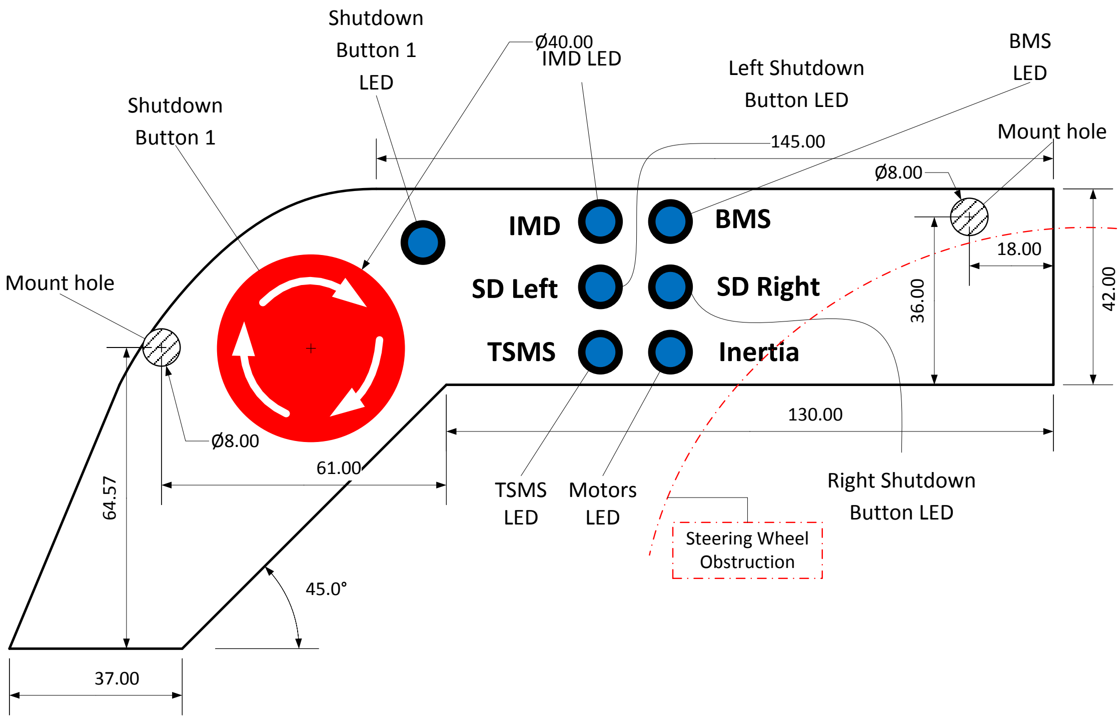


Figure 4.3 Right side of dashboard

4.2.1 Shape and Dimensions

The one and only rule that effects the design of the dash is:

T4.2.1 *A free vertical cross section, which allows the template shown in Figure 9 to be passed horizontally through the cockpit to a point 100 mm (4 inches) rearwards of the face of the rearmost pedal when in the inoperative position, must be maintained over its entire length. If the pedals are adjustable, they will be put in their most forward position. [3]*

That is, the template (seen in Figure 4.1) must be able to pass between the dashboard and the seat. Other than this there is no mention about requirements particular to the dashboard or mention of one at all. The requirements of rule T4.2.1 coupled with the tight and compact nature of the Formula SAE car exacerbates the challenge of designing a full featured, user friendly and unobstructed dashboard. Given this, my approach was to maximise the size of the dashboard while remaining compliant with rule Tt4.2.1. This would give the largest surface area to work with and consequently provide maximum flexibility of element placement discussed next and leave room for possible future addition of elements. Finally, the dashboard design is in two pieces, Figure 4.2 (left side) and 4.3 (right side). This was necessary because the steering wheel mount member would obstruct the placement of the dashboard flush against the tabs. Following these ideas resulted in the final outline of the dashboard.

4.2.2 Placement of elements

Element placements should be made judiciously to ensure a practical, safe and user friendly design. Such considerations include:

- Direct line of sight. The element should not be obstructed by the steering wheel, lacking a direct line of sight. The driver should be able to clearly see the element clearly at all times
- Logical grouping of elements
- Easy actuation of elements that involve driver interaction. Buttons and switches are free from obstructions and easy for the driver to see and

access. This is not only for convenience but can have safety implications as well.

As seen in Figure 4.2 and Figure 4.3, the dashboard is quite limited in area and the driver's view of the dashboard is moderately obstructed by the steering wheel. In conjunction with mechanical students a decision was made to swap with the smaller more compact steering wheel of the old 2010 Formula SAE car. The red dotted line labelled 'Steering Wheel Obstruction' in Figure 4.2 and Figure 4.3 outlines the position of the new steering wheel in front of the dashboard when seated. The portion of the dashboard below the line will be obstructed by the new steering wheel. As the design demonstrates, placement of elements in this area has been avoided.

4.2.2.1 Shutdown Dash Button

This is arguably one of the more important elements as it relates directly to the safety of the driver. It is critical for safety reasons that the driver can freely and easily actuate the Dash Shutdown button in an emergency situation. Therefore it is particularly vital that it is free from all obstructions, particularly the steering wheel in any rotational position. It has hence been placed to the left area of the dashboard, free from clutter of other elements and well clear of the steering wheel.

4.2.2.2 LED Indicators

These LEDs indicate faults within the Safety Control System. When some safety elements are triggered OPEN/OFF, such as the Shutdown Dash button and the Brake Panic Switch, the driver can reset the elements to turn them back ON and hence CLOSE the main safety circuit path. On the other hand, reset buttons for other elements such as the IMD and BMS interlocks are purposely out of reach of the driver (rule requirements). Either way, the purpose of the dashboard is to interface the state of the car with the driver, and so all elements should be unobstructed and clearly visible. I argue that if a particular element is not really required to be viewed by the driver, then it should not be on the dashboard in the first place. The LEDs are placed in groups and positioned in a neat fashion such that room for labelling is available and that there will be no confusion as to which label refers to which element. This can be seen in Figure 4.2 and Figure 4.3.

4.2.2.3 Ready to Drive, Brake Panic Switch Buttons and Key switch

These buttons are simply placed where they can be seen and easily accessed. The Brake Panic Switch fit nicely to the left of the column of LEDs, filling in the gap there but remaining outside the non-visible area. The key switch off course has a protruding key so it was best to keep it right away from the movement of the steering wheel, hands and arms. Thus it was placed to the far right along with the Ready to Start button. It makes logical sense to keep these close as the sequence to start the car involves turning the key succeeded by pressing the Ready to Start button.

4.2.3 Weather Resistance

In a project such as the Formula SAE car that will be invariably exposed to the elements, providing at least some degree of weather resistance shows prudent design that will last for the long haul, a quality that eludes so many commercial products in this day and age. From selecting components with appropriate waterproof ratings to sealing metal exposure, the longevity of the product can be dramatically increased.

All wiring terminals have been protected with heat shrink where practicable and silicon sealed otherwise. The dashboard itself has been sprayed with a clear lacquer to hinder corrosion and upkeep the aesthetic appeal.

4.2.4 Future Expansion and Maintenance

In all my design work I always consider ease of accessibility for maintenance or future expansion purposes. I believe this completes the package in terms of a robust design. Using a modular technique by incorporating a connector exemplifies this approach. The dashboard is now nothing more than a separate component or module of the larger Safety Control System. It is attached to the Safety Control PCB via one simple to use connector and disconnected in the same way. If a fault develops with any element, the dashboard can be quickly disengaged and taken to a workbench for repair. In mission critical situations, it would be possible to plug and play spare dashboards implying minimal downtime. The advantages are stark and it is clear just how difficult a simple maintenance task would be if the cabling was all hard wired.

4.3 Physical Implementation

4.3.1 Dashboard Construction

The manufacturing of a personal design is an immensely satisfying step of the overall product production. I did not use any workshop time for either the dashboard or Safety Circuit PCB. This meant more complicated fabrication for other aspects of the car could be prioritised instead. The REV lab is our pseudo workshop and it can only be best described as modest. While the end results may not be of commercial quality, I take great pride in my work as we will see of the final product (see Appendix).

4.3.1.1 Cut Out

The dashboard is made from 2mm sheet aluminium. It was cut using a jigsaw and appropriate cutting blade. The outline of the dashboard is pencilled on, aluminium sheet secured and using a jigsaw cut free hand. A bracket was also required for mounting the connector to. An aluminium angle (90° bracket) was used and cut to size using a manual hacksaw.

4.3.1.2 Drilling Holes

Following the design, all holes are pencilled in. It is good practise to centre punch all holes before drilling so prevent the drill from slipping. For the larger holes spade drill bits were used. When drilling metal it is important to keep the speed low, preferably resting every 10 seconds to allow the drill bit to cool. Drilling too fast will cause the drill bit to become very hot which will cause the bit to blunt very quickly. Table 4.1 summarises the details of each hole.

	Item	Drill Bit Type	Drill Bit Diameter
1	Shutdown Dash Button	Spade	25mm
2	Ready to Drive Button Brake Panic Switch	Spade	13mm
3	Key Switch	Spade	22mm
4	LEDs	Twist HSS	6.4mm
5	Connector Mount – hole for connector	Spade	25mm
6	Connector Mount – for securing	Twist HSS	3mm
7	Mounting Dash Holes	Twist HSS	8mm

Table 4.1 Details of Dashboard Holes

4.3.1.3 Component Assembly

All components except the LEDs are simply placed in their respective holes and secured by a nut from behind. All elements were chosen that could be mounted in this way. The LEDs were secured by first inserting an LED bezel into the hole. Then the LED is inserted from behind which applies pressure to the bezel and holds it in place. To increase the strength, super glue was applied around the base of the LED bezels.

The connector mount is secured behind the dashboard using a bolt, washer and nut. The connector itself is inserted and tightened using the included plastic nut. In addition, two sets of a bolt, washer and nut are used to provide extra strength in diagonal corners of the connector (see Figure 3.23). Finally labels were printed and applied as per the design.

4.3.1.4 Connector & Wiring

The functionality of the dashboard is driven by the Safety Circuit PCB. Therefore cabling will be required to interface these two systems located at either end of the car. The main cable running between the Safety Circuit PCB (rear of car) and dashboard (front of car) is illustrated in Figure 4.4.

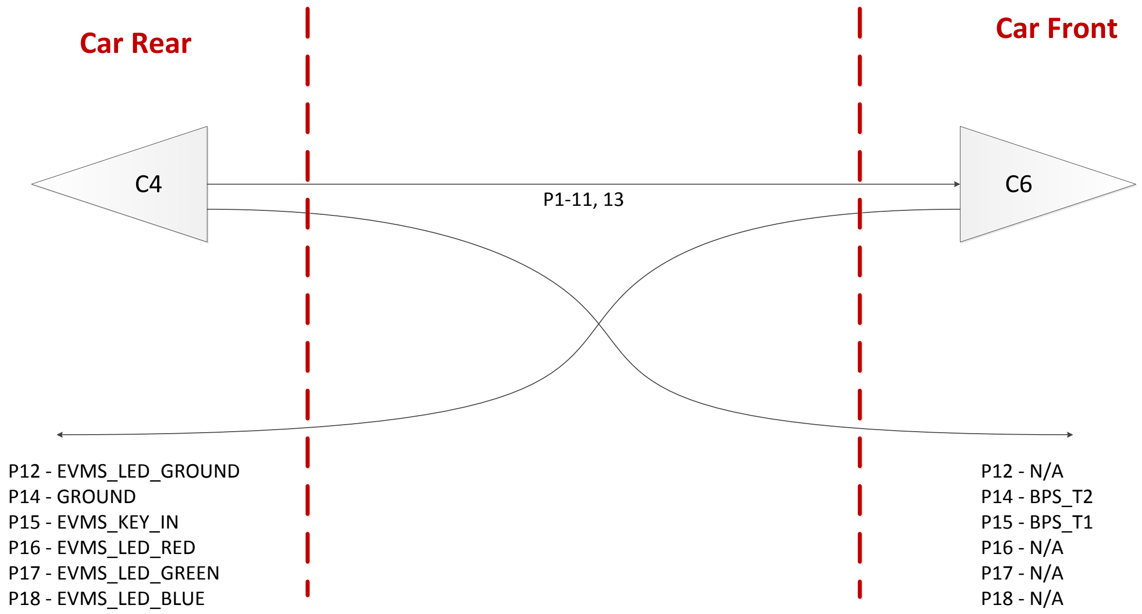


Figure 4.4 Main cable run between front and rear of the car

Connector C4 and C6 terminate each end of a cable that runs from the back of the car (Safety Circuit PCB) to the front of the car (dashboard) via conduit under the seat. Pins 1-11 and 13 are wired directly between C4 and C6. Pins 12 and 14-18 do not terminate at the other connector, instead terminating directly to other devices as illustrated in Figure 4.4. C4 plugs into S4 on the SCB and C6 plugs into S6 on the dash.

The physical wiring internal to the dashboard is summarised in Table 4.2.

S6 Connector Pin	Connection	Internal Dashboard Wiring Detail	SCB Connection & Description
1	Anodes of LEDs TSMS SD Left SD Right SD Dash	S6-P1 > TSMS anode > SD Left anode > SD Right anode > SD Dash anode	H2-P2
2	LED Row 2 Anodes	S6-P2 > BMS anode	H2-P3

		> Inertia anode > BOT anode > IMD anode	
3	LED Row 3 Anodes	S6-P3 > Motors anode > BPS anode > RtD anode	H2-P4
4	LED Column 1 Cathodes	S6-P4 > TSMS cathode > BMS cathode > Motors cathode	H2-P5
5	LED Column 2 Cathodes	S6-P5 > SD Left cathode > Inertia cathode > BPS cathode	H2-P6
6	LED Column 3 Cathodes	S6-P6 > SD Right cathode > BOT cathode > RtD cathode	H2-P7
7	LED Column 4 Cathodes	S6-P7 > SD Dash cathode > IMD cathode	H2-P8
8	Ready to Drive Button – terminal 1	S6-P8 > RtD Button terminal 1	H2-P11
9	Ready to Drive Button – terminal 2	S6-P9 > RtD Button T2	H2-P14
10	Key switch pin 1 & 3	S6-P10 > Key Switch P1 > Key Switch P3	H3-P2 The input signal into the key switch is ON when all elements of the safety circuit are closed. Otherwise the input signal is OFF.
11	Key switch pin 4	S6-P11 > Key Switch P4	H2-P9 This signal line pulled HIGH when the key switch is in the charge position. This powers 'Charge

			Interlock Relay" pulling EVMS_CHG_SENSE LOW
12	BMS LED Cathode	S6-P12 >BMS LED – Cathode terminal	EVMS_GND
13	BPS Reset Button – terminal 1	S6-P13 > BPS Reset Button terminal 1	C4-P13
14	BPS Reset Button – terminal 2	S6-P14 > BPS Reset Button T2	GROUND
15	Key switch pin 2	S6-P15 > Key Switch P2	EVMS_KEY_IN Signal line goes HIGH when the key switch is in the drive position.
16	BMS LED Red	S6-P16 > BMS LED – Red terminal	EVMS_STATUS_R
17	BMS LED Green	S6-P17 > BMS LED – Green terminal	EVMS_STATUS_G
18	BMS LED Blue	S6-P18 > BMS LED – Blue terminal	EVMS_STATUS_B

Table 4.2 Dashboard physical wiring details

Note:

- Column 1 is a list of pins on the connector socket.
- Column 2 states which elements the pin is electrically connected to.
- Column 3 shows the sequence that wiring physically occurs. In cases where multiple elements connect to one pin, the elements and connector pin are daisy chained in series instead of a star configuration from the pin. This minimises wire used and alleviates the cable congestion that would otherwise occur at the connector.

- Column 4 provides a quick reference as to where the signal line is ultimately connected to at the SCB. The Safety Circuit PCB header and pin is given and a small description if necessary.

4.3.2 Final Product Summary

I am pleased with the final manufactured dashboard (see Appendix A.1 & A.2). Keeping in line with my design principles it forms a modular component of the safety circuit and car overall. Precautions have been taken to ensure weather resistance as much as practicable. The layout of the elements has been given consideration for easy driver viewing, labelling has made it intuitive to use and space remains for small additions of various instrumentation in the future. Last of all, it is compliant will all rules effecting the design of the dashboard.

5 Testing and Debugging

For all but the most basic of circuits, thorough testing of the hardware and debugging of software is a fundamental part of the development process. We saw in Section 3.3.1 that at the prototyping stage the design is thoroughly put to the test and all problems identified and fixed. No matter how well a circuit is reviewed, often there will be oversights and some problems are difficult to foresee and only become evident once the device is operated in practise. The Safety Circuit PCB design is no different and therefore required some minor revisions. In a commercial setting the circuit would be remanufactured, however since the faults only required small design adjustments, they could be easily integrated on the current board. This solution is not ideal but is a trade of I am willing to make for the sake of time and budget constraints. In this chapter I will outline the small design faults discovered during the test procedure. Full solutions to these faults will be thoroughly detailed, including modified designs and the approach to physically implement the alterations.

5.1 Circuit Faults

5.1.1 No resistor on transistor base

A number of transistors on the PCB did not have current limiting transistors on the base pin. These include the transistors T2 and T3 from the BMS and IMD interlock circuits respectively. While reviewing the circuit initially, the resistors on the transistor bases were mistaken for current limiting resistors when they were really pull up and pull down resistors. During circuit testing this was discovered after the transistors successively emitted a noise and burnt out internally. A removed damaged transistor is seen in Figure 5.1 where a crack can be seen.

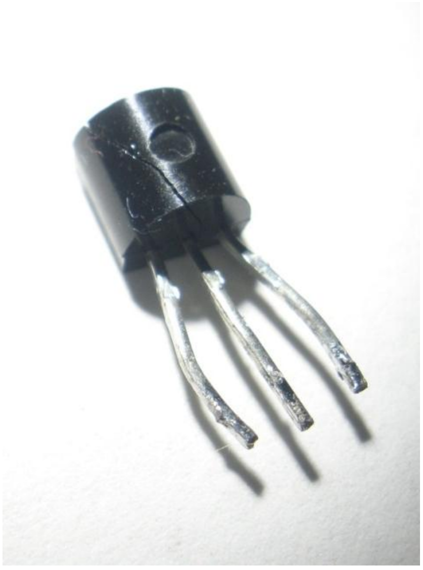


Figure 5.1 Transistor damaged by excessive base current

Now a solution is required. The transistors are easily de-soldered, removed and replaced. However base resistors need to be added. The base of each transistor is routed to a PCB pin header. The easiest and cleanest way to add a resistor is to simply insert it inline from the wire going from the PCB header plug HP5-P1 to S5-P4 (T2) and HP4-P1 to S5-P5 (T3).

The last transistor without a base current limiting resistor is T10 which is part of the Ready to Drive Sound circuit. The base pin is directly driven by a microcontroller pin and not by an external device such as in the case of the BMS and IMD interlock transistors. This means there is no wire to insert the resistor in line with. Instead the trace on the PCB is cut and the resistor soldered over the broken track. This is a neat and simple fix.

5.1.2 R1 not necessary on charge interlock

The resistor R1 as seen in the charge interlock Figure 3.3.3.9 does not serve any useful purpose. When the car is not in charge state, EVMS_CHRG_SENSE is pulled high by CHG_INTLK/MICROC_12V/BUZ+ which is HIGH so long as the CSMS is switched on. The EVMS has no requirement to limit current into EVMS_CHRG_SENSE via a resistor. During design, I was probably stuck in the mindset of using a resistor for all pull up functions (which is often required) but not in the case of this circuit. The next important step is to perform is a quick analysis as to whether the resistor will affect the operation of the circuit and as it turns out, it does not. Technically, the resistance coupled with any input capacitance (which is negligible in this case) will increase the rise time according to the time constant $\tau = RC$. The pull up of EVMS_CHRG_SENSE is not a time critical operation and hence inconsequential to the correct operation of the charge interlock. Due to this the circuit will not require any modification. Nevertheless in a final product design for mass production, the resistor would be eliminated from the circuit.

5.1.3 BPS Reset Button Issue

The Brake Panic Interlock requires a normally closed (NC) reset button to operate correctly. Please refer to Section 3.3.3.4 for more detail. The assumption was made that such a part would be easily available. Unfortunately a NC variant of the BTN_SPST_IP67 (Table 3.8) did not exist. In fact no NC IP67 momentary buttons were available at local suppliers. Instead of going to the expense and waiting for delivery times, the NO BTN_SPST_IP67 button would be used. However the circuit would need modification to work correctly.

If a major logical or design fault was identified then there would be little choice but to redesign the circuit board and remanufacture. However as we will see the solution to this fault only requires the addition of two components. Off course doing this directly on the board would be very difficult as the PCB routing was done in an efficient and compact manner. The revised design can nevertheless be easily implemented by placing the components in line with the wiring running between the PCB header plugs and socket connectors on the lid.

The revised schematic for PCB header H4 is shown in Figure 5.2. In section 3.3.3.4 we saw that once the BPS is actuated current flows through the C-NO contact, through the normally closed BPS reset button and then through the relay coil to ground. This keeps the relay R1 latched in this position and so the main safety circuit path is OPEN. However we now know we are using a NO BPS reset button. A NPN transistor is connected between the H4-P6 and H4-P5 where the BPS Reset button would normally connect to. The transistor is pulled high via R1 turning ON the transistor and imitating a normally closed BPS button. Then terminal 1 of the BPS reset button is connected to the base (via a resistor), with terminal 2 connecting to ground. Now when the BPS reset button is actuated it will pull the base to ground turning the transistor OFF. Just as in Section 3.3.3.4, this cuts power to the relay R1 resetting it to its normal contact position of C-NC. The circuit still operates as described in Section 3.3.3.4, just the implementation of the actual BPS button has some added complexity as just described.

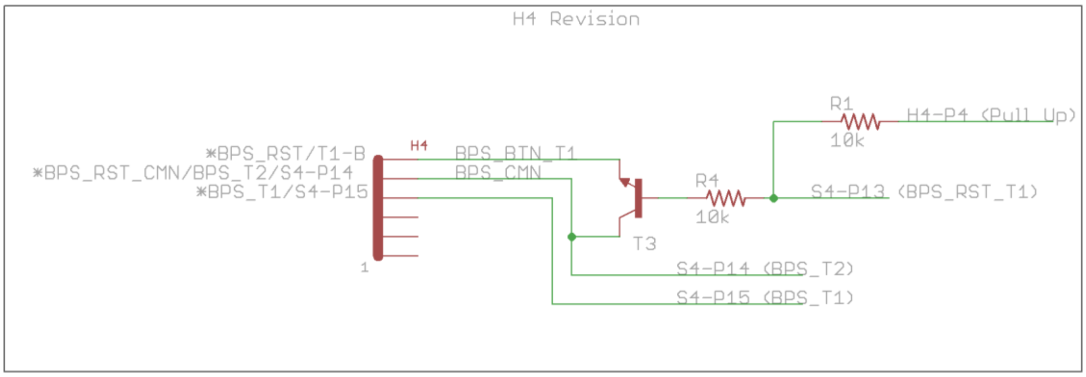


Figure 5.2 Revised schematic for BPS issue

A transistor is now in series with the relay coil. The topic of inductor spikes covered in Section 3.1.4 now applies to this modified circuit. Freewheeling diodes as utilised in the BMS and IMD interlocks in a similar scenario, must be used to ensure the voltage spikes do not damage the transistor. However it must be added to the physical board. The ideal way to do this was by soldering it underneath the board as shown in Figure 5.3.

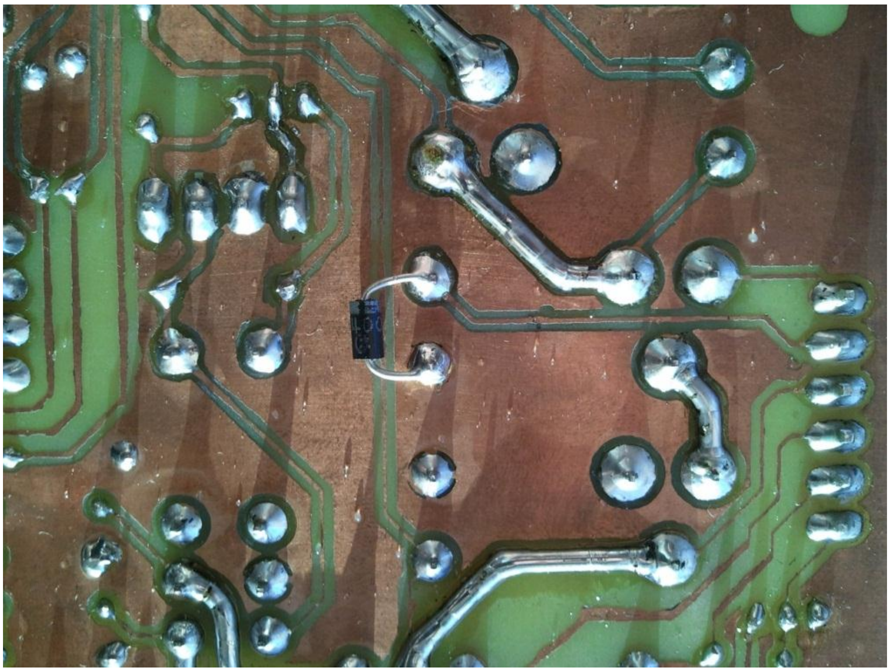


Figure 5.3 Addition of required diode

It is within the clearance of the PCB standoffs in the SCB enclosure and so does not interfere in any way.

5.1.4 IMD Interlock Trigger Issue

As we have seen the Safety Circuit PCB consists of a series of interlock circuits that either OPEN or CLOSE the main safety circuit path. When viewing the IMD interlock circuit in its own right, there are no issues. However it is only until a higher level view it taken that an issue surfaces. We know from Section 3.3.3.3 that the IMD interlock draws from the main safety circuit path to power its relay and the interlock itself is situated after the BMS interlock. Now if an IMD fault occurs and IMD_SIG is pulled low, the IMD interlock opens and the IMD fault light will activate. If the IMD fault is rectified implying IMD_SIG is pulled HIGH, then the IMD reset button can be pressed to close the interlock. Everything is so far ok.

If however the BMS interlock is triggered, opening the main safety circuit path which powers the IMD interlock, the IMD interlock will lose power and open also. The outcome is that both interlocks have triggered when only the BMS interlock should have. The effect on operation will be that both the BMS and IMD reset buttons will need pressing to close both interlocks again. While the circuit can still operate in this way it is neither as intended nor intuitive to the user.

Essentially we want to source power for the IMD interlock from an area which is not controlled or influenced by the BMS interlock or any other safety element. We do not want the tripping of another safety element to also trip the IMD interlock as is currently occurring due to the BMS interlock. The solution to this problem involves a cut to a small PCB trace. This makes the disconnection as seen in Figure 5.4.

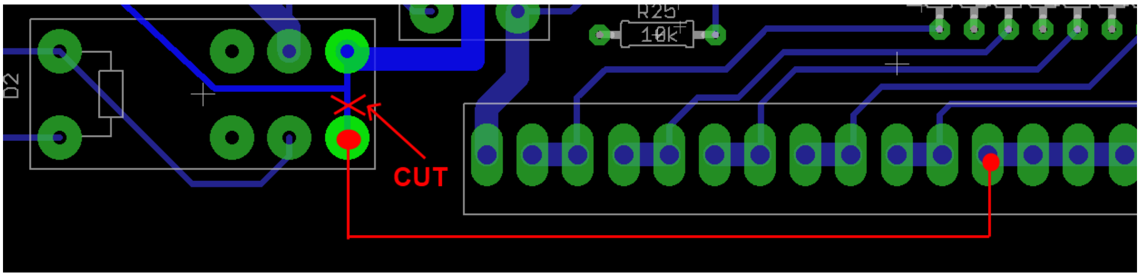


Figure 5.4 IMD Fix

A nearby source of power as described above needs to be identified so it can be fed into the cut trace. This is done as shown in Figure 5.4 by feeding from power after the CSMS. This new point will provide power so long as the CSMS is ON. The point is not influenced by any safety circuit element or interlock. Now if the BMS interlock trips, power to the IMD interlock will not be interrupted and hence remain CLOSED as required.

6 Conclusions

The aim of this thesis was to design, build and implement a reliable and robust safety system that would adhere to all relevant rules stipulated by the SAEA, but first and foremost protect the driver and crew from potentially dangerous situations. The heart of the Safety Control System is the centralized Safety Circuit Box. It contains the custom designed Safety Circuit PCB that was tested, manufactured, tested again and revisions made to rectify small faults. It is also heavy in regard to IO since it requires myriad connections to the wider Safety System.

The LED Indicator Subsystem and dashboard module work to alert the driver of faults in the Safety Control System and form the visual interface between the state of the car and driver.

Importantly, the Safety Control System and wider LV Electric System have been implemented in the Formula SAE car and are proving to be working well. The final working product is arguably the most important step of the engineering product development cycle which this thesis traverses from start to finish.

6.1 Future Work

The Formula SAE car is not a matured project that has been refined over many years. It therefore leaves exciting future potential for enhancements, additions and expansions, particularly in the electronics department.

One addition that I have kept at the back of my mind is a logging system that would log a myriad number of car sensors that have not even been implemented as yet such as:

1. Speed
2. Accelerometer
3. Gyroscope
4. GPS location
5. Various heat sensors

Not only would such a project include sourcing various sensors and hardware, it would require circuit design to interface with hardware and store the data in an efficient way. As we saw in Section 3.3.3.13, I have left provisions on my custom designed Safety Circuit PCB for future expansions. In particular the communication peripherals of the microcontroller such as SPI, EUSART and I^2C have been left free and broken out to a PCB header. By adding new code on the microcontroller and wiring this interface to the new logging system, all sorts of information relating to the state of the Safety Control System could be determined. For example, the time when the car was driven, charged or when a particular safety element was triggered could be logged.

Further, a mechanism to upload the data to a PC would be necessary, be it RS232, USB or even wirelessly for a nice challenge. This data could be analysed by custom written software, an example of which could be to average the speed of trips, plotting values such as instantaneous speed or plotting the GPS locations on a map to show the travelled route. The complexity of this analysis is limited only by your imagination.

Appendix A

Figures

A.1. Dashboard

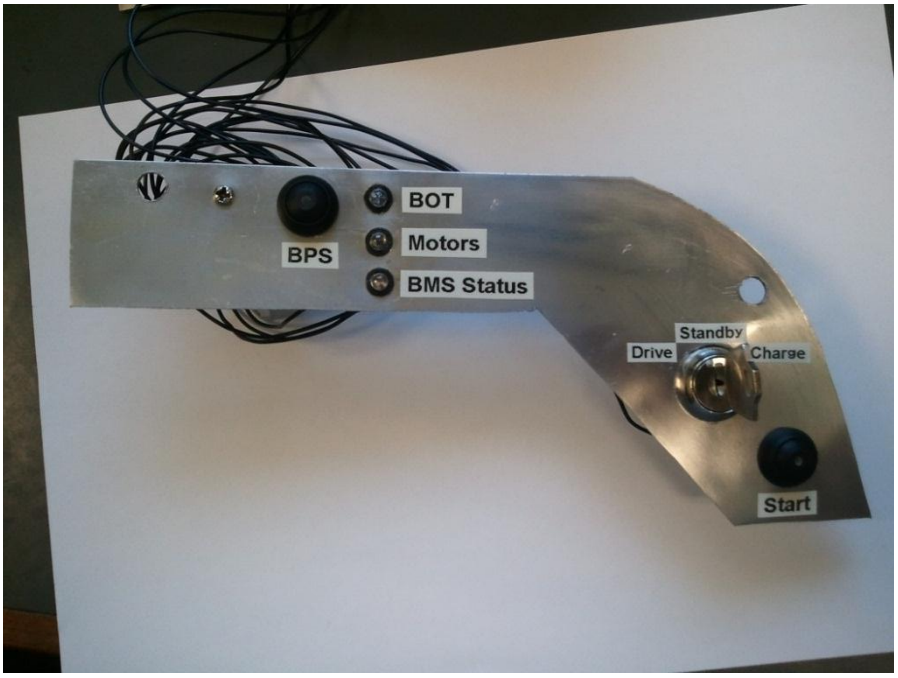


Figure A.1.1

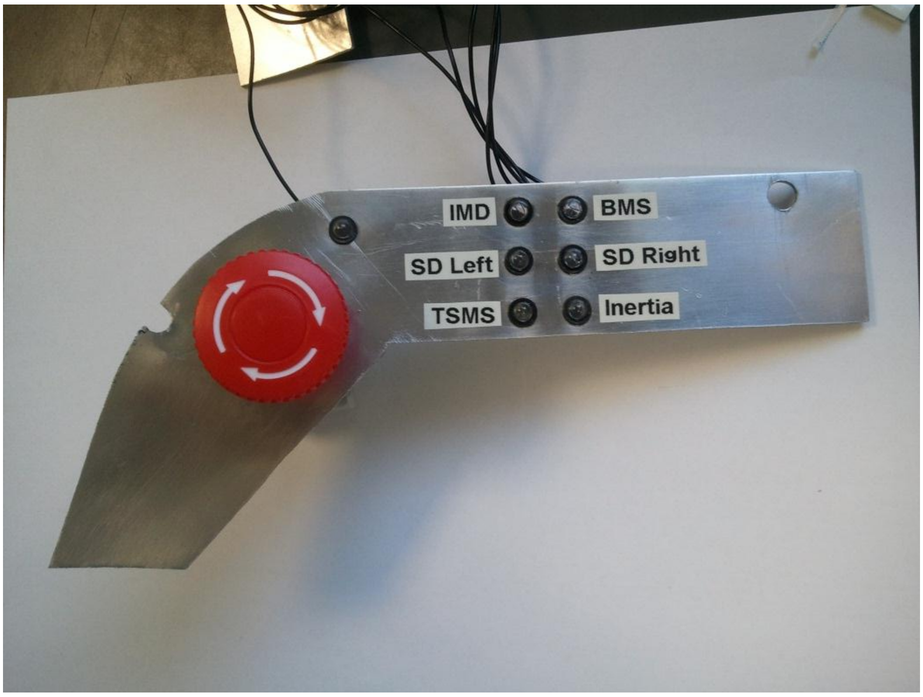


Figure A.1.2

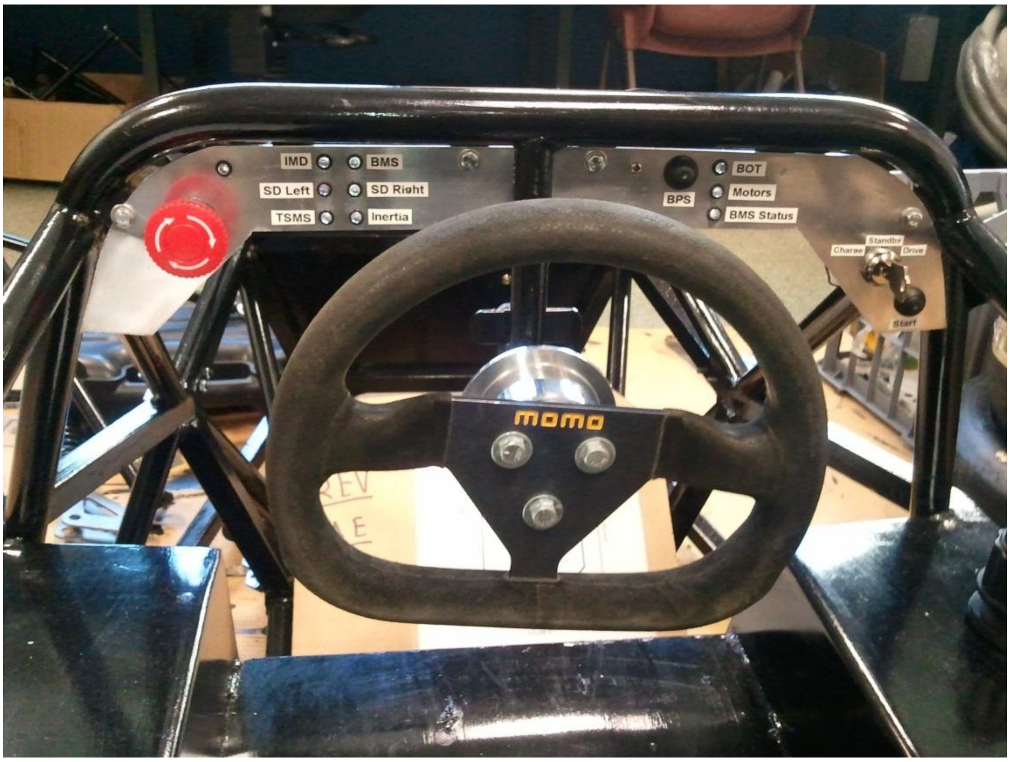


Figure A.1.3

A.2. PCB Manufacturing

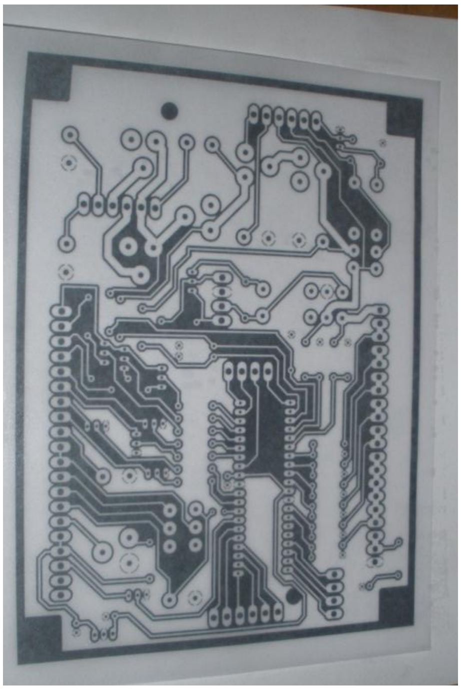


Figure A.2.1

Figure A.2.2

Figure A.2.3

Figure A.2.4

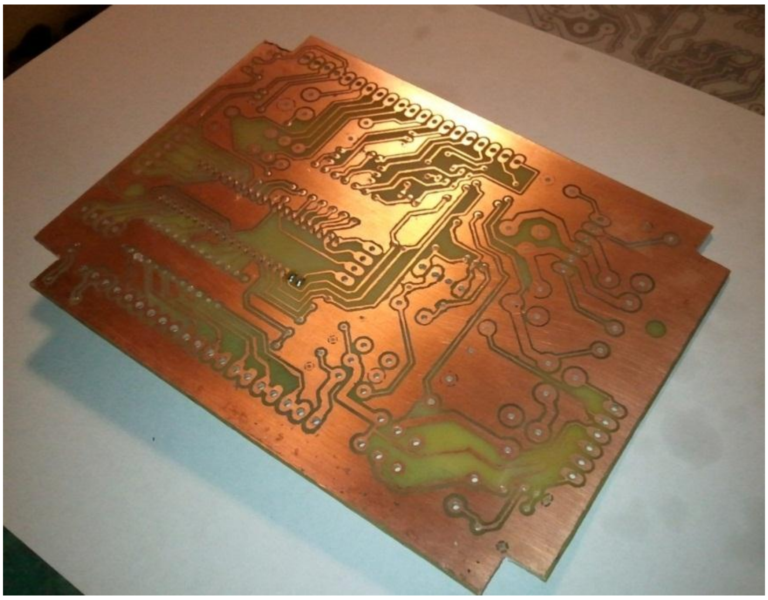
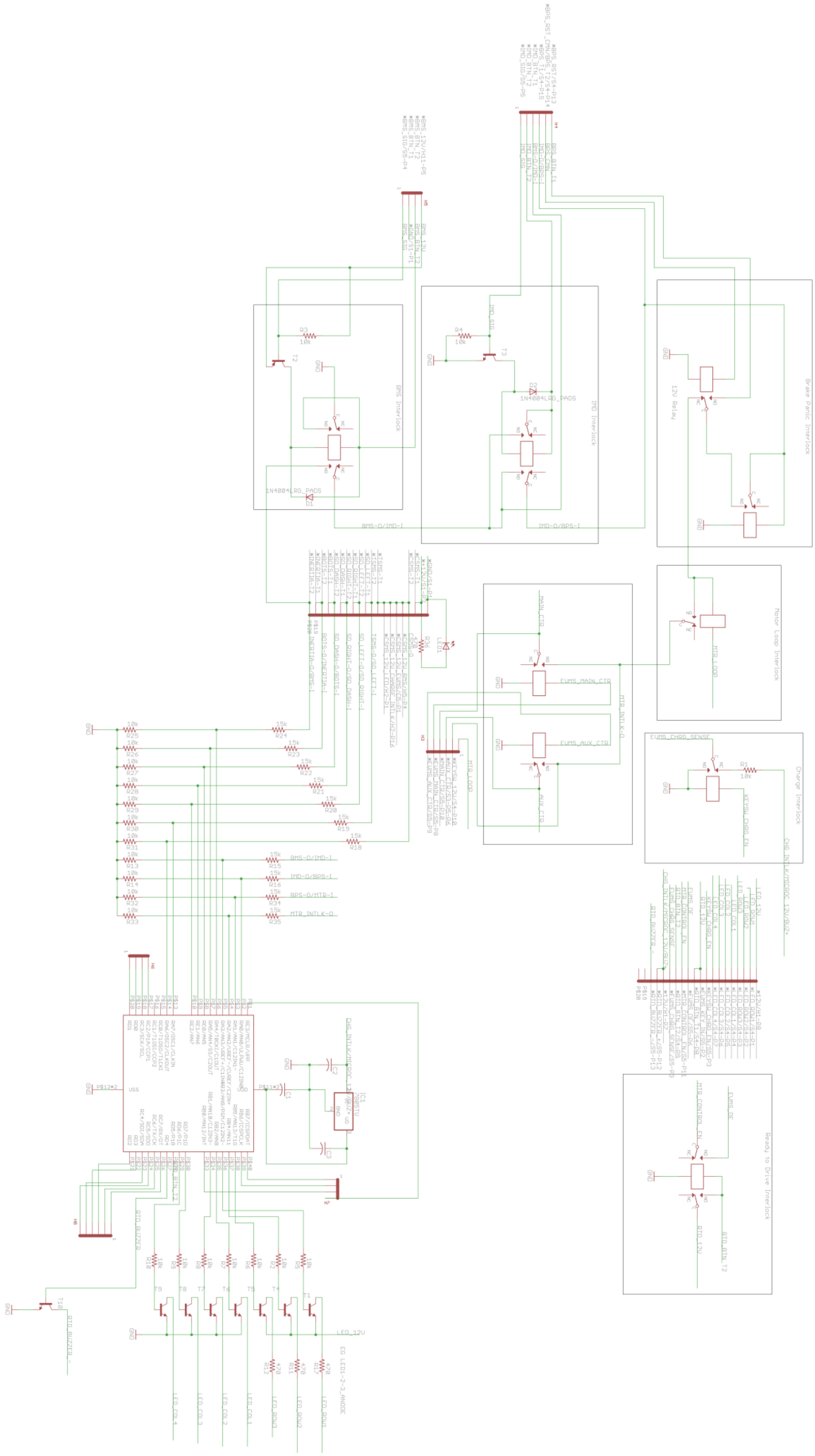


Figure A.2.5

A.3. Safety Circuit Schematic



Appendix B

Program code listing

```
/*
 * File:   main.c
 * Author: Matthew Michalek
 *
 * Created on 18 September 2012, 12:34 PM
 */

//#include <stdio.h>
//#include <stdlib.h>

#include <xc.h>

#define _XTAL_FREQ 4000000
#define R1 RB3
#define R2 RB4
#define R3 RB5

#define C1 RB2
#define C2 RB1
#define C3 RD7
#define C4 RD6

__CONFIG(MCLRE_ON & CP_OFF & BOREN_OFF & WDTE_OFF & PWRTE_OFF &
FOSC_INTRC_NOCLKOUT & FCMEN_OFF & LVP_OFF);
/*
 *
 */

//Function Prototypes
void CheckSafetyElementFault();
void LightSafetyElementFault();
void PreRtD();

   int safetyElementStatus1 = 0b11111111;
   int safetyElementStatus2 = 0b11111111;

void main()
{
   //INITIALISE-----------------------------------------------------------------
```

```
    TRISB = 0;
    TRISD = 0;

    ANSEL = 0x00;
    ANSELH = 0x00;

    //-----------------------------------------------------------------------
    for(;;)
    {
        CheckSafetyElementFault();
        if (safetyElementStatus1 && safetyElementStatus2 == 0)
        {
            PreRtD();
        }
        else
        {
            LightSafetyElementFault();
        }
    }

    //return (EXIT_FAULT);
}

void CheckSafetyElementFault()
{
    if (RA7 == 0) //TSMS FAULT
    {
        safetyElementStatus1 = 255;
    }
    else if  (RE2 == 0) //SD LEFT FAULT
    {
        safetyElementStatus1 = 127;
    }
    else if  (RE1 == 0) //SD RIGHT FAULT
    {
        safetyElementStatus1 = 63;
    }
    else if  (RE0 == 0) //SD DASH FAULT
    {
        safetyElementStatus1 = 31;
    }
    else if  (RA5 == 0) //BOTS FAULT
    {
        safetyElementStatus1 = 15;
    }
    else if  (RA4 == 0) //INERTIA FAULT
    {
        safetyElementStatus1 = 7;
    }
    else if  (RA3 == 0) //BMS FAULT
    {
        safetyElementStatus1 = 3;
    }
```

```
    else if  (RA0 == 0) //IMD FAULT
    {
       safetyElementStatus1 = 1;
    }
    else if  (RA1 == 0) //BPS FAULT
    {
       safetyElementStatus1 = 255;
    }
    else if  (RA2 == 0) //MOTOR LOOP FAULT
    {
       safetyElementStatus1 = 127;
    }

    safetyElementStatus1 = 0b00000000;
    safetyElementStatus2 = 0b00000000;

}

void LightSafetyElementFault()
{
    while (safetyElementStatus1 && safetyElementStatus2 == 0)
    {
       if (safetyElementStatus1 == 255) //TSMS FAULT
       {
          RB3 = 1;
          RB2 = 1;
       }
       else if  (safetyElementStatus1 = 127) //SD LEFT FAULT
       {
          RB3 = 1;
          RB1 = 1;
       }
       else if  (safetyElementStatus1 = 63) //SD RIGHT FAULT
       {
          RB3 = 1;
          RD7 = 1;
       }
       else if  (safetyElementStatus1 = 31) //SD DASH FAULT
       {
          RB3 = 1;
          RD6 = 1;
       }
       else if  (safetyElementStatus1 = 15) //BOTS FAULT
       {
          RB4 = 1;
          RD7 = 1;
       }
       else if  (safetyElementStatus1 = 7) //INERTIA FAULT
       {
          RB4 = 1;
          RB1 = 1;
       }
       else if  (safetyElementStatus1 = 3) //BMS FAULT
```

```
        {
            RB4 = 1;
            RB2 = 1;
        }
        else if  (safetyElementStatus1 = 1) //IMD FAULT
        {
            RB4 = 1;
            RD6 = 1;
        }
        else if  (safetyElementStatus1 = 255) //BPS FAULT
        {
            RB5 = 1;
            RB1 = 1;
        }
        else if  (safetyElementStatus2 = 127) //MOTOR LOOP FAULT
        {
            RB5 = 1;
            RB2 = 1;
        }
        CheckSafetyElementFault();
    }
    return;
}

void PreRtD()
{


        CheckSafetyElementFault();
        while (safetyElementStatus1 && safetyElementStatus2 == 0)
        { //flash Rtd LED
            RB5 = 1;
            RD7 = 1;
            __delay_ms(1000);
            RB5 = 0;
            RD7 = 0;

            if (RD5 = 1) //RtD pressed, turn off Rtd LED
            {
                RB5 = 0;
                RD7 = 0;
            }
        }
        return;
```

Appendix C

Connector Table

PCB Header	Mates with . . .	PCB Header Plug & pin	Cable	Socket connection & pin	Mates with . . .	Plug Connector & pin	Cable	Plug Connector & pin	Mates with . . .	Socket connection & pin	Device Connection	Description	Name
H1-1-P1		HP1-1-P1		S1-P1		C1-P1		N/A		N/A	Negative terminal Aux Battery / DC-DC converter		GND
H1-1-P2		HP1-1-P2		S1-P2		C1-P2		N/A		N/A	Positive terminal Aux Battery / DC-DC converter		+12V
H1-1-P3		HP1-1-P3		S1-P3		C1-P3		N/A		N/A	Control System Master Switch terminal 1		CSMS_t1
H1-1-P4		HP1-1-P4		S1-P4		C1-P4		N/A		N/A	Control System Master Switch terminal 2		CSMS_t2
H1-1-P5		HP1-1-P5		N/A		N/A		N/A		N/A	JMP JP5 - pin 4	Supply power to BMS Interlock. Jumper Wire	CSMS_t2
H1-1-P6		HP1-1-P6		S5-P1		C5-P1		N/A		N/A	EVMS_+12VDC	Supply power to EVMS	CSMS_t2
H1-1-P7		HP1-1-P7		N/A		N/A		N/A		N/A	JMP HP2-2P16	Supply power to Charge Interlock. Jumper Wire	CSMS_t2
H1-1-P8		HP1-1-P8		N/A		N/A		N/A		N/A	JMP HP2-1-P1	Supply power to LED module. Jumper Wire	CSMS_t2
H1-1-P9		HP1-1-P9		S1-P5		C1-P5		N/A		N/A	Tractive System Master Switch terminal 1		TSMS_t1
H1-1-P10		HP1-1-P10		S1-P6		C1-P6		N/A		N/A	Tractive System Master Switch terminal 2		TSMS_t2
H1-2-P1		HP1-2-P1		S2-P1		C2-P1		N/A		N/A	Left Shutdown button - terminal 1		
H1-2-P2		HP1-2-P2		S2-P2		C2-P2		N/A		N/A	Left Shutdown button - terminal 2		
H1-2-P3		HP1-2-P3		S2-P3		C2-P3		N/A		N/A	Right Shutdown button - terminal 1		

H1-2-P4		HP1-2-P4		S2-P4		C2-P4		N/A		N/A	Right Shutdown button - terminal 2		
H1-2-P5		HP1-2-P5		S2-P5		C2-P5		N/A		N/A	Dash Shutdown button - terminal 1		
H1-2-P6		HP1-2-P6		S2-P6		C2-P6		N/A		N/A	Dash Shutdown button - terminal 2		
H1-2-P7		HP1-2-P7		S3-P1		C3-P1		N/A		N/A	Brake Over Travel Switch - terminal 1		
H1-2-P8		HP1-2-P8		S3-P2		C3-P2		N/A		N/A	Brake Over Travel Switch - terminal 2		
H1-2-P9		HP1-2-P9		S3-P3		C3-P3		N/A		N/A	Inertia switch - terminal C		
H1-2-P10		HP1-2-P10		S3-P4		C3-P4		N/A		N/A	Inertia switch - terminal NC		
H21-P1		HP21-P1		N/A		N/A		N/A		N/A	JMP HP11-P8	Supply power to LED module. Jumper Wire	LED_12V
H21-P2		HP21-P2		S4-P1		C4-P1		C6-P1		S6-P1	LED Anodes Row 1		LED_ROW1
H21-P3		HP21-P3		S4-P2		C4-P2		C6-P2		S6-P2	LED Anodes Row 2		LED_ROW2
H21-P4		HP21-P4		S4-P3		C4-P3		C6-P3		S6-P3	LED Anodes Row 3		LED_ROW3
H21-P5		HP21-P5		S4-P4		C4-P4		C6-P4		S6-P4	LED Cathodes Col 1		LED_COL1
H21-P6		HP21-P6		S4-P5		C4-P5		C6-P5		S6-P5	LED Cathodes Col 2		LED_COL2
H21-P7		HP21-P7		S4-P6		C4-P6		C6-P6		S6-P6	LED Cathodes Col 3		LED_COL3
H21-P8		HP21-P8		S4-P7		C4-P7		C6-P7		S6-P7	LED Cathodes Col 4		LED_COL4
H21-P9		HP21-P9		S4-P11		C4-P11		C6-P11		S6-P11	Key switch-P4	Powers relay when key is in charge position which pulls 'EVMS_CHRG_SENSE' LOW	KEYSW_CHRG_EN
H21-P10		HP21-P10		S5-P2		C5-P2		N/A		N/A	EVMS_KEY_IN	Supplies power to Ready to Drive Interlock that has passed entire Safety	RTD_12V

												Circuit & Key switch	
H22-P1		HP22-P1		S4-P8		C4-P8		C6-P8		S6-P8	Ready to Drive button - terminal 1		RTD_12V
H22-P2		HP22-P2		S5-P6		C5-P6		N/A		N/A	EVMS_ENABLE_DRIVE		EVMS_DE
H22-P3		HP22-P3		S5-P7		C5-P7		N/A		N/A	Motor Controller Enable terminals		MTR_CONTROL_EN
H22-P4		HP22-P4		S4-P9		C4-P9		C6-P9		S6-P9	Ready to Drive button - terminal 2		RTD_BTN_t2
H22-P5		HP22-P5		S5-P3		C5-P3		N/A		N/A	EVMS_CHG_SENSE		EVMS_CHRG_SENSE
H22-P6		HP22-P6		N/A		N/A		N/A		N/A	JMP HP11-P7	Supply power to Charge Interlock. Jumper Wire	CHG_INTLK/MICROC_12V/BUZ+
H22-P7		HP22-P7		S5-P12		C5-P12	Ready to Drive Buzzer - terminal +ve	N/A		N/A	Ready to Drive Buzzer +ve	Connection to Ready to Drive Buzzer +ve	CHG_INTLK/MICROC_12V/BUZ+
H22-P8		HP22-P8		S5-P13		C5-P13	Ready to Drive Buzzer - terminal -ve				Ready to Drive Buzzer -ve	Connection to Ready to Drive Buzzer -ve	RTD_BUZZER_-
H3-P1		HP3-P1		S5-P11		C5-P11		N/A		N/A	Motor Loop	Connects to one end of the motor loop. Other end grounded to chassis	MTR_LOOP
H3-P2		HP3-P2		S4-P10		C4-P10		C6-P10		S6-P10	Key switch-P1&P3	Current path to keyswitch. Position will determine car state: Idle, Drive, Charge	12V_SDC_OUT
H3-P3		HP3-P3		S3-P5		C3-P5		N/A		N/A	Battery Box 1 – AUX contactors 1 & 2	Supplies power to Aux contactors in the battery boxes. Jump connector pins 5 & 6.	AUX_CTR
				S3-P6		C3-P6		N/A			Battery Box 2 – AUX contactors 3 & 4		

H3-P4		HP33-P4		S5-P10		C5-P10		N/A		N/A	Main contactor	Supplies power to Main contactor	MAIN_CTR
H3-P5		HP3-P5		S5-P8		C5-P8		N/A		N/A	EVMS_MAIN_CTR	Drives the Aux Main relay which in turn powers the Main relay	EVMS_MAIN_CTR
H3-P6		HP3-P6		S5-P9		C5-P9		N/A		N/A	EVMS_AUX_CTR	Drives the Aux Aux relay which in turn powers the Aux relays	EVMS_AUX_CTR
H4-P1		H4-P1		S5-P5		C5-P5		N/A		N/A	IMD Signal	High/Low status signal from IMD	IMD_SIG
H4-P2		H4-P2		N/A		N/A		N/A		N/A	IMD Reset Btn - terminal 1	IMD Reset button mounted on enclosure	
H4-P3		H4-P3		N/A		N/A		N/A		N/A	IMD Reset Btn - terminal 2	IMD Reset button mounted on enclosure	BMS-O/IMD-I
H4-P4		H4-P4		S4-P15		C4-P15		BPS_T1		N/A	Brake Panic Switch terminal 1		IMD-O/BPS-I
H4-P5		H4-P5		S4-P14		C4-P14		BPS_T2		N/A	Brake Panic Switch terminal 2		BPS_CMN
			Not a direct connection. See Modified circuit	N/A		N/A		N/A		N/A	JMP HP4-P4		
H4-P6		HP4-P6	Not a direct connection. See Modified circuit	S4-P13		C4-P13		N/A			BPS_RST_T1 Brake Panic Switch reset button terminal 1		BPS_BTN_T1

H5-P1		HP5-P1		S5-P4		C5-P4		N/A		N/A	EVMS_BMS_IN	High/Low status signal from BMS modules	BMS_SIG
H5-P2		HP5-P2		N/A		N/A		N/A		N/A	BMS Reset Btn - terminal 1	BMS Reset button mounted on enclosure	GND
H5-P3		HP5-P3		N/A		N/A		N/A		N/A	BMS Reset Btn - terminal 2	BMS Reset button mounted on enclosure	BMS_BTN_T2
H5-P4		HP5-P4		N/A		N/A		N/A		N/A	JMP HP11-P5	Supply power to BMS Interlock. Jumper Wire	BMS_12V
N/A		N/A		N/A		EVMS_GROUND		C6-P14		S6-P14	Brake Panic Switch reset button terminal 2		
N/A		N/A		N/A		EVMS_GROUND		C6-P12		S6-P12	BMS LED Cathode		
N/A		N/A		N/A		EVMS_KEY_IN		C6-P15		S6-P15	Key Switch P-2		
N/A		N/A		N/A		EVMS_RED		C6-P16		S6-P16	EVMS LED – Red Anode P-R		
N/A		N/A		N/A		EVMS_GREEN		C6-P17		S6-P17	EVMS LED – Green Anode P-G		
N/A		N/A		N/A		EVMS_BLUE		C6-P18		S6-P18	EVMS LED – Blue Anode P-B		

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