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MEMS 411: Racecar Cruise Control

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Mechanical Engineering Design Project
MEMS 411, Fall 2022

Racecar Cruise Control

The WashU Racing team is a student group at formula student which annually designs, builds, and tests a 1/3rd scale formula racecar. This project explores the use of an electronically actuated throttle to implement cruise control on the WashU Racing formula student racecar. Through the use of new and existing sensors on the car, in depth engine modeling, and vehicle dynamics, our team was able to make the car accelerate up to and maintain a certain speed. This report centers on the mechanical modeling and implementation of the system. There were three main focus areas: 1. mechanical modeling of the car's acceleration at different engine states and speeds using an acoustics and thermodynamics software called GT-Suite 2. the design of an adapter and control system for an off the shelf electronic throttle body unit from Bosch Motorsport and 3. the design of a system to allow the car's existing mechanical throttle to control the electronic throttle via a rotary potentiometer.

Multiple designs were attempted, but the most minimally intrusive was chosen for the car, as the main customers, the team's aerodynamics and suspension system's valued the ability to change from an electronic throttle to a manual cable throttle in as little time as possible. Further, the system had to be lightweight, waterproof, corrosion resistant, vibration resistant, and able to withstand temperatures up to 140F. Ultimately, the final design allowed the car to get up to speed in a representative test on jack stands. Additional work is needed to be safe to test with an occupant in the vehicle.

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1 Introduction

This project began with a cited need from the WashU Racing team for some sort of cruise control for testing their vehicle. The team annually builds an open cockpit formula race car and competes at a collegiate design competition in Michigan. The car is judged on it's design by industry experts, and tested in the harsh conditions of motorsport racing. [**SAE**].

Figure 1: The WashU Racing WUFR-22 vehicle competing.

The team approach us with an issue they experience regularly during testing: there is no easy way to test the steady state response and handling of the vehicle. Specifically, the team wanted a speed limiter/cruise control that was able to hold the car to a specified speed for aerodynamics and vehicle dynamics testing and validation.

2 Problem Understanding

2.1 Existing Devices

Cruise control has existed on automobiles for over 100 years, however before the 1960's it was largely in a rudimentary form. Early versions of cruise control used mechanical linkages and locks to hold the throttle open a certain amount. More recent versions adopted complete computer control of the throttle and fuel injection, allowing them to maintain speed despite changes in the engine or road conditions, by adjusting throttle as needed. Motorsport is devoid of cruise control for the most part, except for pit lane speed limiters.
Link: https://www.youtube.com/watch?v=bp4Q_tLnayw
Description: Toyota's implementation of cruise control started with the Camry in 1973 during the oil crisis. The standard form of cruise control uses a stalk on the side of the steering column, usually under the turn stalk. As computers have advanced, so has the abilities of cruise control. Beginning in 2000, Toyota brought adaptive cruise control to the US in Lexus products, which

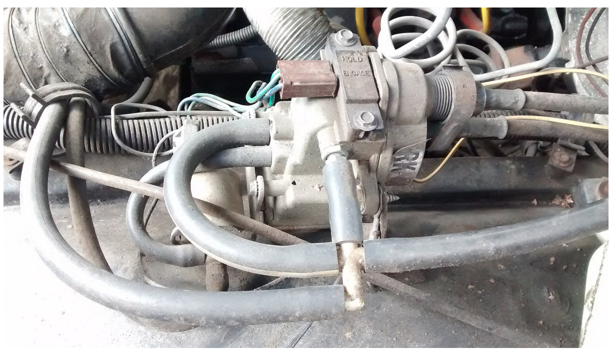


Figure 2: A vacuum tube and speedometer cable used to control the throttle for cruise control (Source: Toyota USA)

Figure 3: A button in the 1967 AMC Ambassador to engage and disengage cruise control (Source: American Cars, 1960-1972: Every Model, Year by Year

uses and additional suite of radar sensors to distance relative to the car /object in front of the vehicle. This implementation also requires the ability to control the brakes. While these off the shelf systems are well developed, they could not be used in any capacity for this project as they are proprietary and impossible to adapt to the WashU racing's architecture. These system's did inspire the implementation on the racecar, however, as cruise control is actuated via a switch in the cockpit, and uses very similar techniques for sensing the vehicle's speed.

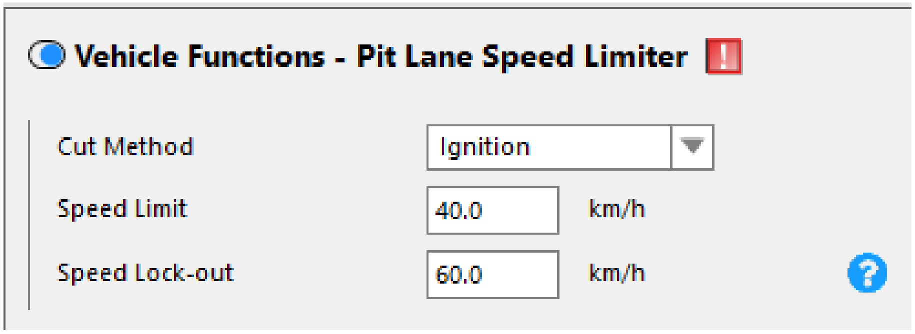


Figure 4: The pit lane speed limiter function in some high end ECU's. this is Haltech's implementation, for reference.

Link: https://support.haltech.com/portal/en/kb/articles/pit-lane-speed-limiter

2.1.1 Existing Device #2: Motorsports Pit Lane Limiters

Formula 1 and other motorsports series have required the use of a "pit lane speed limiter" for some time. This requirement was brought about to increase safety in an area where the cars are most likely to collide. These limiters are usually a button on or next to the steering wheel, which, when pushed, keeps the car at a constant speed. These speed limiters are usually implemented in the vehicle's engine control unit, or ECU. Unfortunately the ECU used in the WashU Racing vehicle does not have this feature.

2.2 Patents

2.2.1 Cruise control system (US6081762A)

This patent combines wheel speed sensing, cockpit sensing (brake, throttle, and clutch pedals), and an analysis of road conditions to inform the vehicle's speed through the ECU. This patent also describes the many safety concerns related to cruise control in a street legal vehicle, many of which were issues we were required address in the software involved with this project.

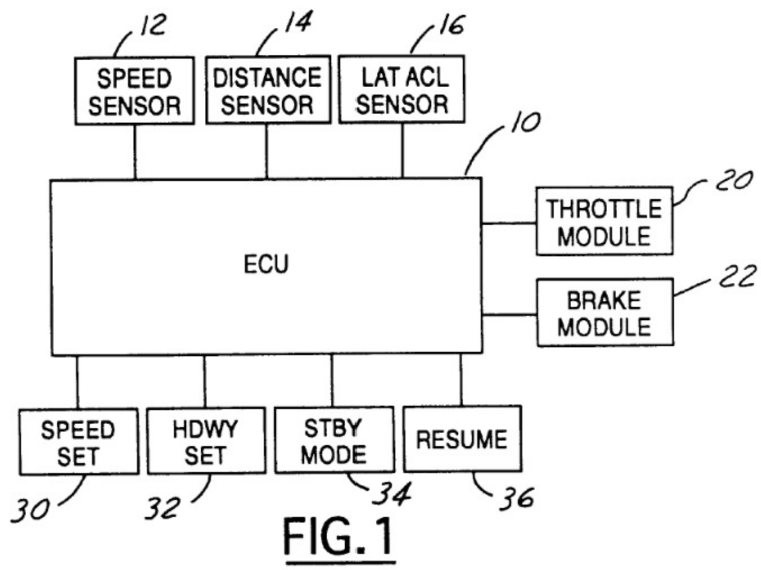


Figure 5: Block diagram of cruise control system

2.3 Codes & Standards

2.3.1 Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles (J3016_02104)

This international standard defines a range of terminology and common systems relating to autonomous driving, which is paramount for classifying this system and understanding the critical safety considerations when working with both autonomy and humans in and around the vehicle.

2.3.2 Accelerator Pedal Position Sensor for Use with Electronic Controls in Medium- and Heavy-Duty Vehicle Applications—Truck and Bus (J1843_02207)

This standard describes the standards related to throttle position sensing in road going vehicles. It is used as the baseline for the electronic throttle in the race car, and shows multiple methods of detecting throttle position.

2.4 User Needs

In order to determine what the race team would need this electronic speed control for, two interviews were conducted. The first was with the leads of the aerodynamics system, Alex Nunez and Howard Wu, who talked about their need for data to validate their CFD on the vehicle's outer surfaces and wings. The second interview was with suspension member Taylor Southwick, who talked about the need for constant velocity tuns to test the suspension and get driver feedback on handling.

2.4.1 First Customer Interview

Interviewees: Alex Nunez, Howard Wu
Location: Lopata Gallery, Washington University in St. Louis, Danforth Campus
Date: Sep 12^{th}, 2022
Setting: I asked Alex and Howard to describe the testing scenarios they envisioned with constant speed holding, and asked what they currently do to mimic a constant speed. The entire interview was in Lopata gallery, and too around 60 min. to nail the specifics.
Interview Notes:
What kind of testing do you currently do?

- Constant velocity testing in a straight line. Uses linear potentiometers on suspension to get downforce data from front and rear of the car.
- Coast down testing, where the car must get up to a certain speed and then coast down in neutral to see drag induced from aero kit.
- Constant velocity turns, where the potentiometers are again used to analyze the wing performance.
- We test in all conditions.

What are you doing right now to gather this data?

- Right now we just tell the driver to try to keep the engine at the same speed. They have no way of knowing how fast they are going besides an RPM readout on the dashboard. We have to tell them what gear and RPM to try to hit for each test. It is not accurate at all.

How much time do you have in between different tests?

- Most tests are run back to back, but there can be periods up to 30 min between the different types of tests. Ideally the car is moving as much as possible and there is little downtime.

2.4.2 Second Customer Interview

Interviewees: Taylor Southwick
Location: Zoom
Date: September 13^{th}, 2022
Setting: I asked Taylor to describe how suspension gathers and analyzes data on the car, and how it is used in design. I also asked them how driver feedback is used to tune the car's handling.
Interview Notes:
What kind of data does suspension gather?

- Speed, gear, compression of all four corners, lateral acceleration, position, speed.

How is driver feedback gathered and used? How are they trained?

- Drivers are really bad at giving us feedback, so we really rely on knowing what the car is doing at any particular time. Fortunately we have a system which records all of the sensor data with respect to time and the car's position, so we mainly rely on that. The constant velocity "thing would be sick" because you can look at the vehicle in different conditions which are as close to steady state as you can reasonably get.
- Drivers are trained in a bunch of different obstacles mimicking what they see at the event. It is hard to show them the car can actually push harder sometimes.

2.4.3 Interpreted User Needs

We interpreted the use needs from the above interviews and condensed them into the following list:

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	The system can hold a constant speed at any speed	5
2	The throttle is easy to control when driving, and ”feels the same” as the mechanical throttle	3
3	The throttle is easy to mount and dismount	4
4	The throttle is well packaged and able to run in all weather conditions	5
5	The system can be deactivated by the driver at any time	5

2.5 Design Metrics

The race team’s requirements lead to a few agreed upon numerical requirements below:

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	4	Total weight	kg	2	0.5
2	1	Maximum speed deviation from intended speed	MPH	± 2.5	± 0.5
3	2,5	Time to throttle deactivation	s	< 1.000	< 2.000
4	2	Throttle feel, av. from all drivers	scale 1-5	2	5
5	3	Time to change to/from electronic thorttle system from/to mechanical system	min	< 30	< 5

2.6 Project Management

The Gantt chart in Figure 6 gives an overview of the project schedule.

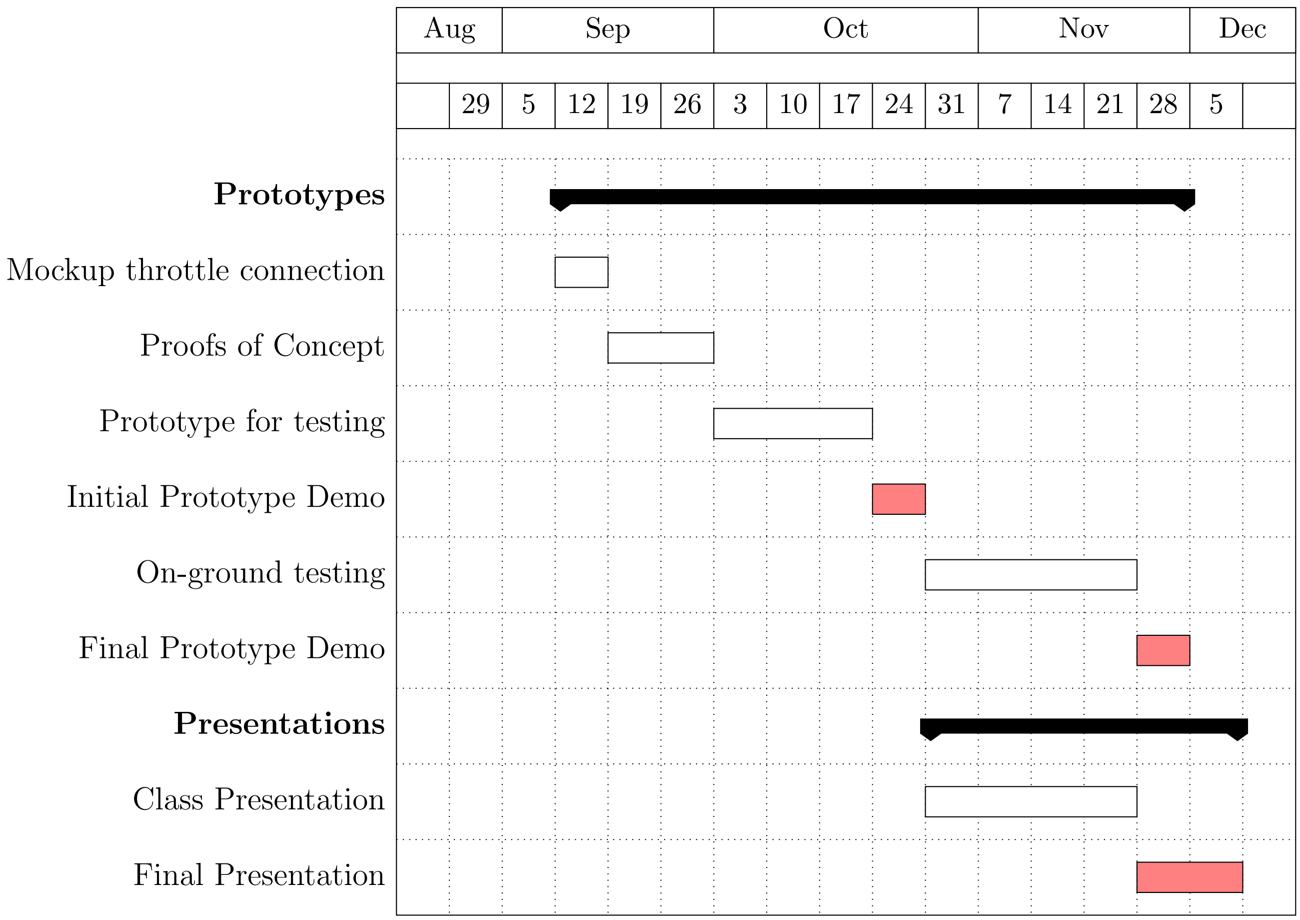


Figure 6: Gantt chart for design project

3 Concept Generation

3.1 Mockup Prototype

Our mock-up prototype consisted of placing a linear potentiometer around the vehicle cockpit in different locations, CAD modeling, and testing different options for electronic throttle bodies. Electronics were prototyped at first on a bread board, then a proto-board. Prototyping on the software side was done in GT-suite, an advanced gas dynamics and acoustics modeling software which can simulate engine response under different conditions.

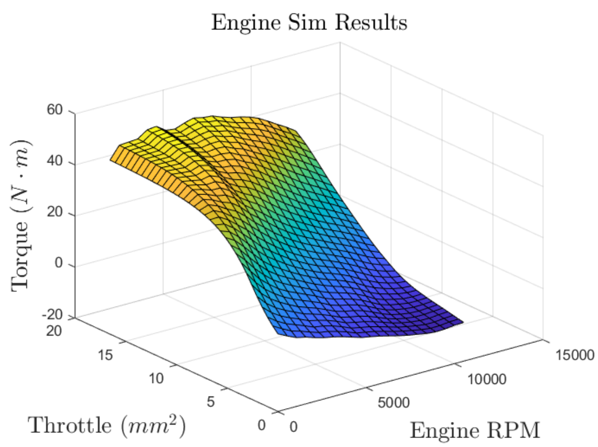


Figure 7: Throttle opening vs. torque response

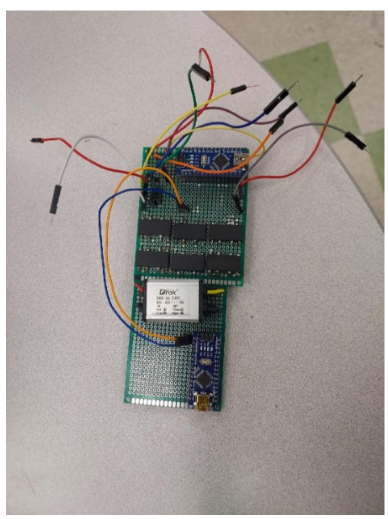


Figure 8: Breadboard prototyping

3.2 Functional Decomposition

Below are a few functions that we identified as critical

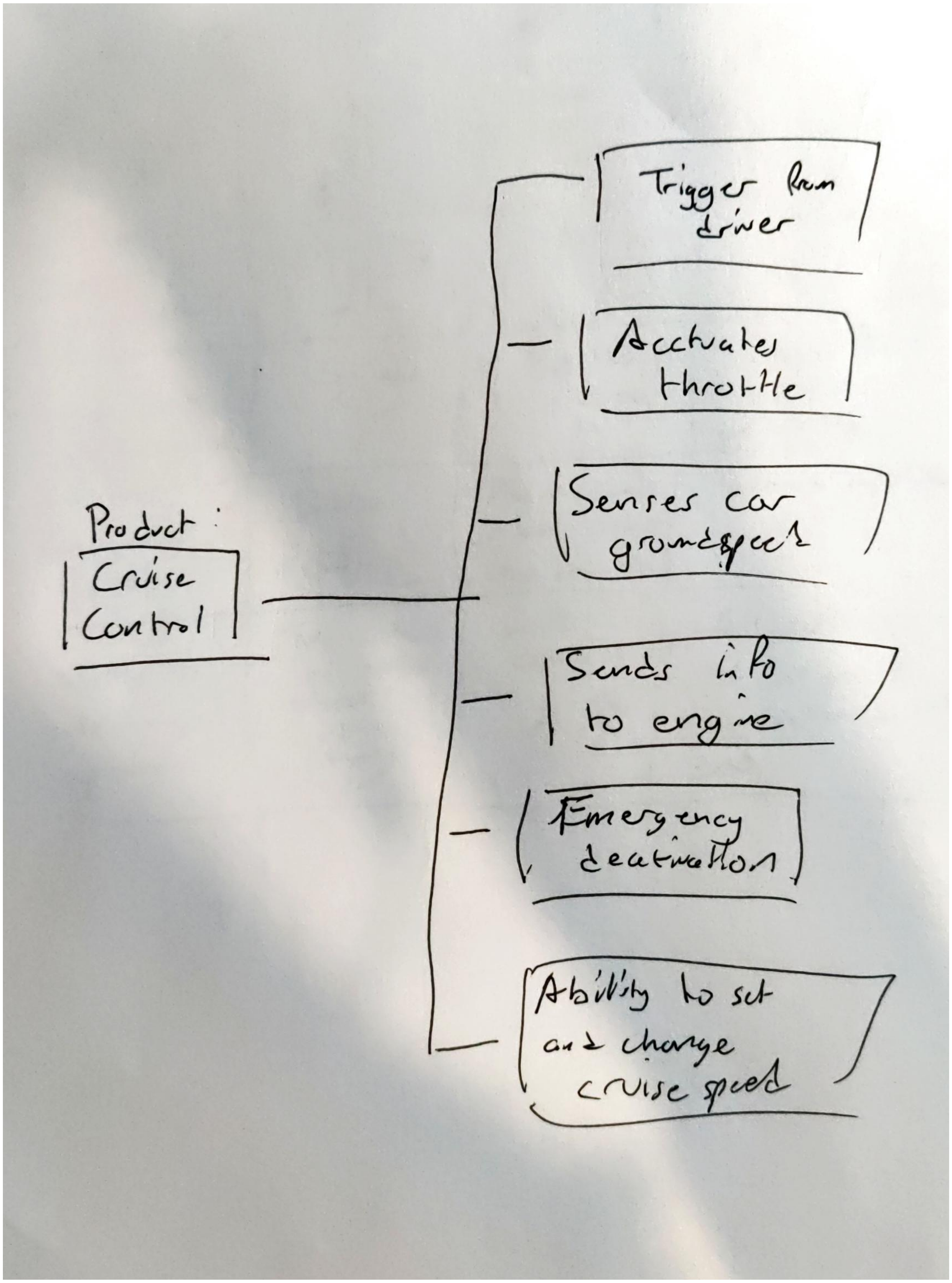


Figure 9: Function tree for the cruise control system

3.3 Morphological Chart

The below chart lays out the device requirements and potential solutions we brainstormed.

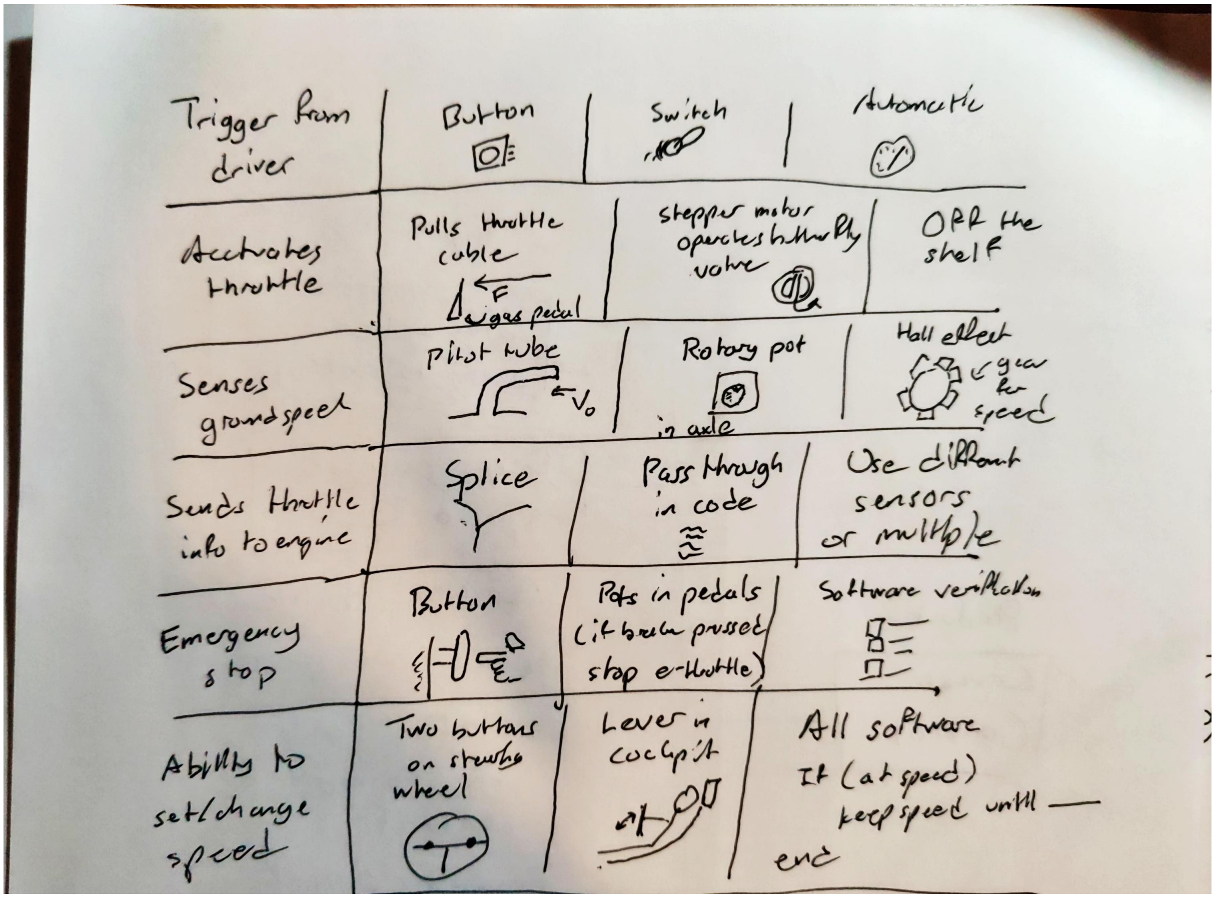


Figure 10: Morphological chart for cruise control

3.4 Alternative Design Concepts

3.4.1 Concept #1: The Huge Stepper Motor

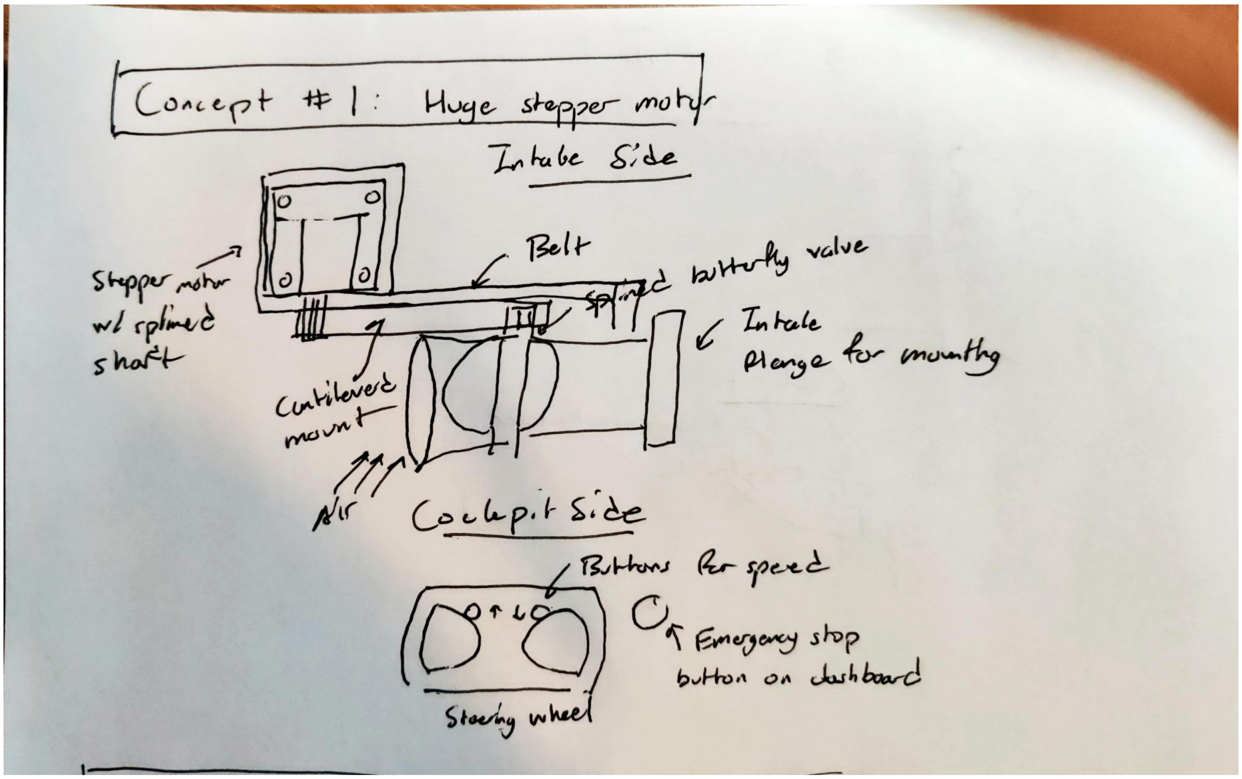


Figure 11: Sketches of Huge Stepper Motor Concept

Description: A giant stepper motor we had laying around in the garage is connected to the existing butterfuly valve on the mechanical setup via a belt. The butterfly valve would need a splined portion affixed to it somehow, possibly aluminum welding. On the control and cockpit side of the device, cruise control would be activated and deactivated by pushing two buttons down on the steering wheel at the same time. These buttons would then increase and decrease speed. An emergency stop button would also be added to the vehicle

The advantages of this setup are excellent accuracy and speedy control (the large stepper motor in the garage moves very quickly and can be geared to have a very fine adjustment of throttle position. It is also able to run off the 12V architecture already on the racecar.

Disadvantages of this setup are that it is extremely heavy and cantilevered far outside the racecar, which could be dangerous if the car were to be in a side impact. Additionally, it is best to avoid cantilevering heavy objects off of the side of the intake, as it could induce additional stresses while the vehicle is vibrating from normal engine operation.

3.4.2 Concept #2: Bosch Throttle w/ Pedal Based Control

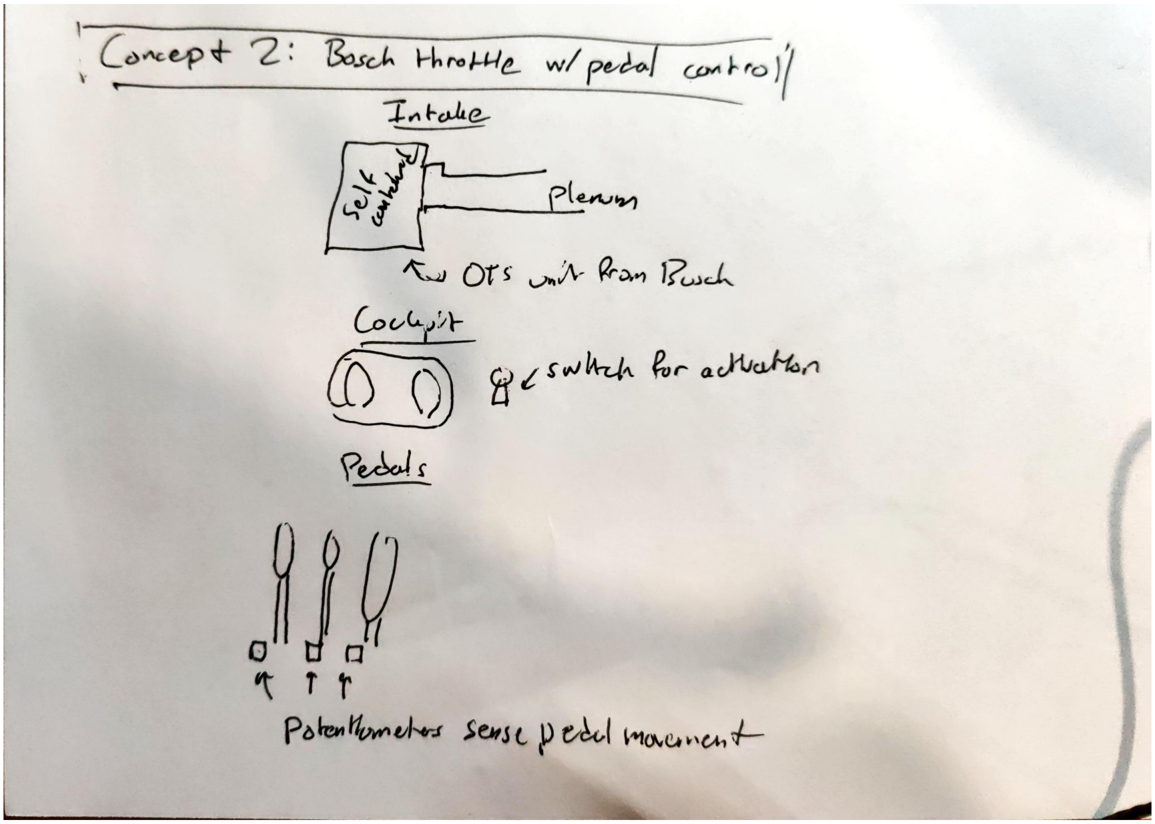


Figure 12: Sketches of the OTS concept

Description: This solution sees an off the shelf Bosch electronic throttle body mounted via an adapter plate of some sort to the intake plenum. This system includes a butterfly valve, nice mating surface, and a datasheet. The cockpit and control scheme for this solution depends on a switch in the cockpit which simply toggles on/off cruise control whenever it is flipped up. If cruise control is deactivated by any other method then the switch has to be flipped down and back up again, so down is always off. Potentiometers are also mounted in the pedalbox in this design, allowing any changes in pedal position outside a certain dead zone to deactivate cruise control.

Advantages of this system are the reliability and quality of an off the shelf motor, speed, and most importantly safety. Using a tested system for the actual butterfly valve is a huge plus when it comes to drive confidence since it has a robust return spring, meaning it will always default to the closed position.

Disadvantages of this design are that this unit needs both 12V and 6V rails to run properly, which makes it difficult to interface with the car's electrical system. Further, the potentiometers will require significant modifications to the pedalbox. This would make quickly changing from the e-throttle system to the legacy mechanical cable difficult and slow.

3.4.3 Concept #3: Sliding Plate with Linear Potentiometer

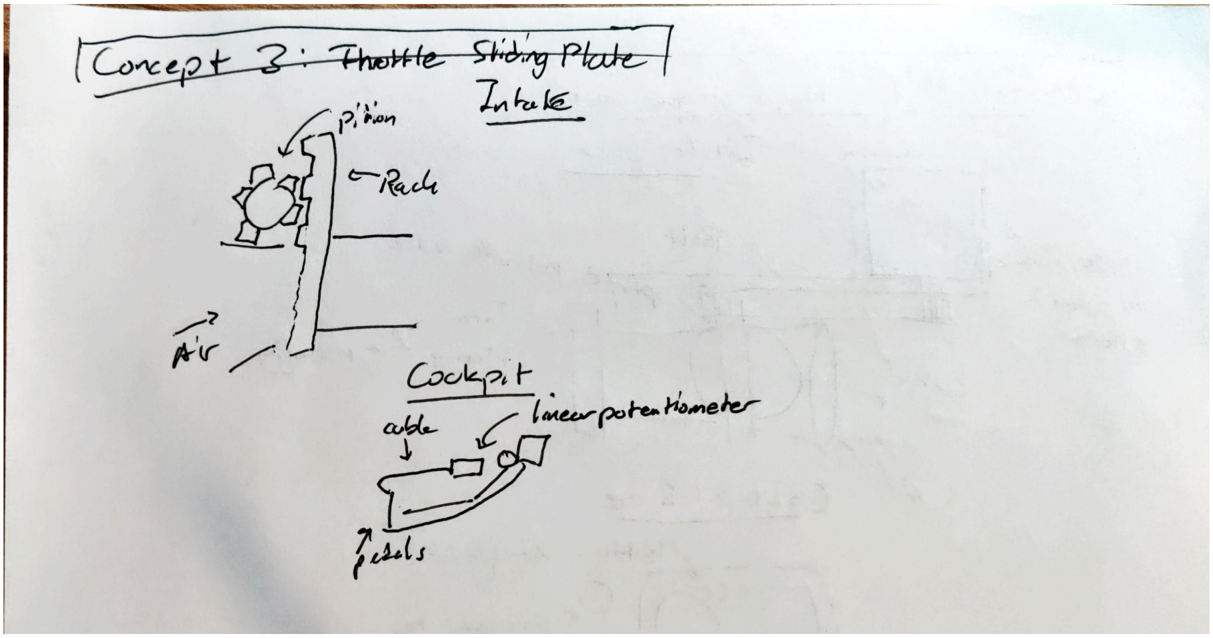


Figure 13: Sketches of the Sldiing Plate Concept

Description: This solution implements the throttle control using a plate that moves vertically on the end of the intake plenum via a rack and pinion.In the cockpit this system uses a linear potentiometer mounted to one of the frame tubes. This potentiometer mounting would require a shorter throttle cable, but otherwise wouldn't require adapting the intake besides a 3D printed gear and slider with the rack on one side.

Advantages of this system are the price, disadvantages are pretty much everything else: slow to put on, poor accuracy, heavy, etc. We also foresaw issues with the rack falling off of the pinion gear, which would be unsafe.

4 Concept Selection

4.1 Selection Criteria

From the concept generation stage and background research, we generated five critical criteria to judge all of the mechanical, electrical, and software options off of. The three options below are ideas I came up with, mainly for the hardware side of the project, although they inevitable also involve some electrical and programming considerations.

	Price	Safety	Accuracy/Actuation Speed	Ease of instalation	Weight	Row Total	Weight Value	Weight (%)
Price	1.00	0.14	1.00	0.33	0.33	2.81	0.05	4.85
Safety	7.00	1.00	9.00	7.00	7.00	31.00	0.54	53.50
Accuracy/Actuation Speed	1.00	0.11	1.00	0.33	0.20	2.64	0.05	4.56
Ease of instalation	3.00	0.14	3.00	1.00	5.00	12.14	0.21	20.96
Weight	3.00	0.14	5.00	0.20	1.00	9.34	0.16	16.13
					Column Total:	**57.94**	**1.00**	**100.00**

Figure 14: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

These five criteria were judged for each concept in a weighted scoring matrix, which then presented which options were most viable.

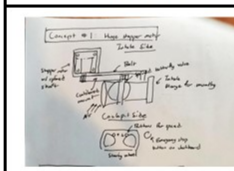
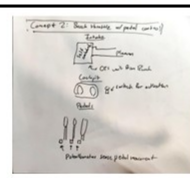
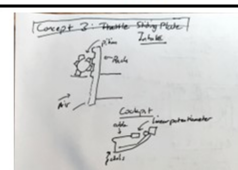
Alternative Design Concepts		**Concept #1**		**Concept #2**		**Concept #3**	
							
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Price	4.85	2	0.10	5	0.24	4	0.19
Safety	53.50	3	1.61	5	2.68	1	0.54
Accuracy/Actuation Speed	4.56	3	0.14	4	0.18	1	0.05
Ease of instalation	20.96	3	0.63	4	0.84	3	0.63
Weight	16.13	3	0.48	4	0.65	5	0.81
	Total score	**2.952**		**4.584**		**2.210**	
	Rank	**2**		**1**		**3**	

Figure 15: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

There were multiple parts to each concept, mostly the choice of a sensing mechanism for the e-throttle positioning based on pedal input, a method for actuating the throttle, and a method for setting/changing speed. Each of these were considered in the selection process, and we eventually decided that no single concept had all of the features we wanted, although concept#2 came the closest. We valued safety most, by far. Considering we plan to use this system for testing with a driver in the vehicle, using the Bosch system on the end of the intake made the most sense, as it is certified to run on other motorsport vehicles and comes with proper documentation. The throttle also has multiple mechanisms to ensure it is never open when the driver intends it to be closed.

On the cockpit side, we chose to implement the toggle switch, as it was intuitive, simple to mount and make for prototyping, and offered the basic functionality the suspension and aerodynamics team's requested. This setup also meant we could avoid making changes to the pedalbox entirely. Unfortunately, that meant in order to change the speed of cruise control the software had to be flashed.

4.4 Engineering Models/Relationships

The most important mechanical model for our project was the throttle sweep in GT-Suite. GT-Suite is a gas dynamics, combustion, and general thermodynamics tool designed originally for engine simulation. As a part of the competition Jonah developed a model for the engine in the previous year, which was modified and updated to resemble the engine with the e-throttle on it. GT-suite essentially models the system as a series of pipes, orifices, etc. and ensures conservation of mass and energy at all of the system boundaries to determine parameters such as the air pressure, velocity, engine speed, etc. GT-suite was used here to determine the torque the engine could output at a given throttle, measured in mm^2 of open area (although this value was later translated into deg of throttle opening to make programming the controller easier), and engine RPM. Below is the results of this sweep.

Torque [Nm]

Throttle Body Eq. Diameter [mm] \ RPM	2000	2525	3050	3575	4100	4625	5150	5675	6200
3.5	0.338196	-1.46332	-3.10822	-3.88336	-5.09124	-6.05768	-6.75841	-7.69778	-8.80699
4.01562	2.518316	0.417111	-1.43245	-2.49595	-3.84006	-4.9912	-5.54401	-6.53961	-7.70964
4.53125	5.03418	2.46881	0.475529	-0.91685	-2.32983	-3.8084	-4.36409	-5.33117	-6.60589
5.04688	7.951986	4.832181	2.522754	0.837232	-0.63576	-2.27276	-3.07824	-4.08021	-5.42632
5.5625	11.24505	7.509252	4.806158	2.864128	1.183077	-0.504	-1.59605	-2.76661	-4.20467
6.07812	14.84822	10.50981	7.384903	5.065519	3.114503	1.334359	0.037549	-1.24958	-2.76124
6.59375	18.41463	13.78356	10.17107	7.475617	5.192511	3.385961	1.851905	0.433043	-1.06995
7.10938	21.5668	17.27615	13.17009	10.12592	7.465413	5.463105	3.864101	2.236688	0.703513
7.625	24.24007	20.65248	16.40509	12.9619	9.940049	7.684043	5.848813	4.082005	2.432987
8.14062	26.56522	23.75144	19.7711	15.99848	12.61485	10.06799	8.014983	6.128885	4.262826
8.65625	28.56027	26.4864	22.98732	19.19733	15.49603	12.6218	10.34682	8.231234	6.218884
9.17188	30.20058	28.89965	25.91968	22.30067	18.57031	15.35123	12.85276	10.49871	8.321175
9.6875	31.57198	30.97971	28.485	25.17734	21.80456	18.25148	15.49	12.92946	10.54613
10.2031	32.69115	32.78352	30.69962	27.72721	24.85992	21.29421	18.25551	15.48416	12.90187
10.7188	33.61469	34.33854	32.62209	30.03016	27.6418	24.37012	21.13872	18.19645	15.38186
11.2344	34.37528	35.66661	34.26535	32.03878	30.19761	27.27868	23.85058	20.97193	17.99359
11.75	35.00213	36.82452	35.66911	33.7951	32.52562	29.90715	26.43255	23.63821	20.79852
12.2656	35.52426	37.84926	36.84899	35.30495	34.64282	32.32264	28.72634	26.09686	23.53768
12.7812	35.95371	38.72479	37.85119	36.59984	36.47677	34.43493	30.84349	28.37348	26.19443
13.2969	36.31075	39.45247	38.6929	37.70851	38.03047	36.30035	32.72069	30.43691	28.62692
13.8125	36.60762	40.0674	39.4097	38.65822	39.35772	37.93829	34.3975	32.31466	30.86469
14.3281	36.85249	40.57493	40.02578	39.47263	40.48743	39.34077	35.87361	34.00694	32.89154
14.8438	37.05784	41.00653	40.55519	40.16584	41.45101	40.54847	37.18584	35.51082	34.7439
15.3594	37.22863	41.3736	41.01257	40.75492	42.27241	41.591	38.32752	36.8418	36.42844
15.875	37.37226	41.6784	41.41738	41.2559	42.97301	42.4896	39.32086	38.01531	37.90471
16.3906	37.49758	41.93189	41.76248	41.6845	43.56966	43.25883	40.19014	39.04323	39.19608
16.9062	37.6058	42.13916	42.05389	42.04931	44.08397	43.92025	40.94681	39.93975	40.34014
17.4219	37.703	42.31667	42.30062	42.36235	44.52414	44.4886	41.60789	40.72102	41.34288
17.9375	37.78582	42.46519	42.51498	42.63268	44.90498	44.97704	42.18148	41.40073	42.21194
18.4531	37.86172	42.59317	42.69982	42.86676	45.23087	45.39889	42.67754	41.99229	42.96677
18.9688	37.93358	42.70434	42.86303	43.07217	45.5134	45.76186	43.11028	42.50197	43.62238
19.4844	38.00002	42.80416	43.00657	43.25248	45.75798	46.07788	43.48874	42.94356	44.18601
20	38.05944	42.89401	43.13205	43.40798	45.97109	46.35236	43.81727	43.32676	44.66886

Throttle Body Eq. Diameter [mm] \ RPM	6725	7250	7775	8300	8825	9350	9875	10400	10925	11450
3.5	-9.94884	-10.5994	-11.3458	-12.2649	-13.1991	-13.9896	-14.6102	-15.2451	-15.6128	-15.4519
4.01562	-9.12663	-9.78866	-10.4738	-11.434	-12.4343	-13.3283	-14.0096	-14.7042	-15.1628	-15.0681
4.53125	-8.14452	-8.89622	-9.56188	-10.5411	-11.6208	-12.6979	-13.4708	-14.109	-14.6204	-14.6083
5.04688	-7.01328	-7.84392	-8.5089	-9.55309	-10.7381	-12.0105	-12.933	-13.6007	-14.0025	-14.0758
5.5625	-5.78682	-6.68689	-7.3368	-8.39155	-9.75174	-11.245	-12.3506	-13.09	-13.5683	-13.5878
6.07812	-4.3975	-5.41056	-6.10031	-7.11866	-8.62516	-10.2901	-11.6097	-12.4404	-12.9921	-13.1695
6.59375	-2.86263	-4.04717	-4.81532	-5.82092	-7.31387	-9.12665	-10.6918	-11.6417	-12.2583	-12.6134
7.10938	-1.20717	-2.52964	-3.4667	-4.49338	-5.87205	-7.75755	-9.5788	-10.6898	-11.3693	-11.9662
7.625	0.544834	-0.85623	-1.96824	-3.05666	-4.4616	-6.19583	-8.26538	-9.56808	-10.4013	-11.1949
8.14062	2.495154	0.975204	-0.3635	-1.52742	-2.92304	-4.56057	-6.73175	-8.26253	-9.30197	-10.2435
8.65625	4.445864	2.773848	1.288322	0.105618	-1.31178	-2.94304	-5.0178	-6.74663	-8.06444	-9.12573
9.17188	6.400471	4.599756	3.046384	1.772619	0.354407	-1.23587	-3.23071	-5.0143	-6.67745	-7.85902
9.6875	8.455631	6.547512	4.883677	3.480151	2.054227	0.504506	-1.32246	-3.16502	-5.10663	-6.46658
10.2031	10.63833	8.609365	6.80882	5.274887	3.798252	2.242075	0.536019	-1.30974	-3.34434	-4.91708
10.7188	12.93776	10.77181	8.830029	7.171169	5.600841	3.996822	2.367204	0.608678	-1.37229	-3.18947
11.2344	15.35864	13.03957	10.95489	9.163601	7.49022	5.808138	4.148603	2.5394	0.690298	-1.25452
11.75	17.90949	15.42088	13.19129	11.25803	9.472314	7.698015	5.971685	4.365802	2.687386	0.767575
12.2656	20.61664	17.92529	15.54244	13.4601	11.55311	9.674525	7.86072	6.198675	4.622201	2.771889
12.7812	23.39189	20.58883	18.01395	15.77217	13.73261	11.74179	9.83409	8.098249	6.508789	4.751726
13.2969	26.16618	23.33489	20.60245	18.20043	16.01628	13.90614	11.89137	10.07427	8.439462	6.698957
13.8125	28.73641	26.09022	23.34297	20.74604	18.41221	16.17124	14.041	12.13281	10.43828	8.671869
14.3281	31.13269	28.64519	26.1513	23.42882	20.96479	18.54154	16.28808	14.27888	12.51087	10.70173
14.8438	33.336	31.01624	28.77831	26.15367	23.60088	21.05941	18.67863	16.5171	14.66132	12.79253
15.3594	35.30618	33.18506	31.26522	28.70441	26.27759	23.66585	21.12863	18.89077	16.89974	14.95351
15.875	37.09429	35.12827	33.49238	31.11869	28.7678	26.32883	23.75309	21.36014	19.26673	17.24086
16.3906	38.69391	36.89766	35.47603	33.27919	31.07439	28.82972	26.34743	23.90116	21.70924	19.59904
16.9062	40.13195	38.50183	37.26883	35.19405	33.18806	31.21111	28.87112	26.45815	24.18922	22.00554
17.4219	41.38976	39.92048	38.88116	36.92628	35.10706	33.35165	31.28105	28.94754	26.68865	24.4129
17.9375	42.49828	41.17183	40.32401	38.48093	36.79369	35.25414	33.45134	31.32555	29.01769	26.73604
18.4531	43.46869	42.2791	41.58904	39.87751	38.30859	36.98324	35.38942	33.42297	31.18459	28.91296
18.9688	44.31572	43.25094	42.70136	41.09449	39.6623	38.53922	37.15234	35.37371	33.1476	30.88474
19.4844	45.0507	44.10223	43.674	42.1625	40.85777	39.92461	38.73885	37.10856	34.94752	32.71771
20	45.68789	44.84292	44.52244	43.09211	41.90793	41.15669	40.15275	38.6702	36.57659	34.36078

Figure 16: Torque outputs at different engine states used to program the controller

From this sweep we are able to determine the tractive force of the vehicle in any reasonable operating state, which, when compared to the drag, allows us to balance out the forces and reach a steady speed.

Another model that was considered for the control of the vehicle was the drag and rolling resistance. The drag can be modeled from the following equation:

$$F_{drag} = \frac{1}{2}\rho C_D A$$

Where F_{drag} is the force resisting forward motion due to air resistance, ρ is the density of air, C_D is the drag coefficient of the vehicle, which was kindly provided by the aero team on WashU Racing, and A is the frontal area, which was also provided by the aero team.

To determine if we needed to account for it in the model, we also tried to calculate the rolling resistance of the vehicle. The force due to rolling resistance can be calculated from the following formulas:

$$F_r = cgm$$

Where F_r is the force due to rolling resistance, m is the mass, and c is the coefficient of rolling resistance, which can be found by:

$$c = 0.005 + (1/p)(0.01 + 0.0095(v/100)2)$$

Where p is the tire pressure in bar, and v is the velocity in KM/H. The WashU Racing car can be assumed to travel at a maximum of 100kph on cruise control (60 MPH) with a minimum tire pressure of 0.6bar, which yields a maximum coefficient of 0.005, which is negligible. Therefore we did not include rolling resistance in the PID controller for cruise control.

5 Concept Embodiment

It was very obvious at first that the actual initial prototype would not work. The below pictures describe where we were trying to place the potentiometer to register the throttle cable inputs and the original throttle adapter plate design. Both had issues with mounting, stability, and just plainly didn't work.

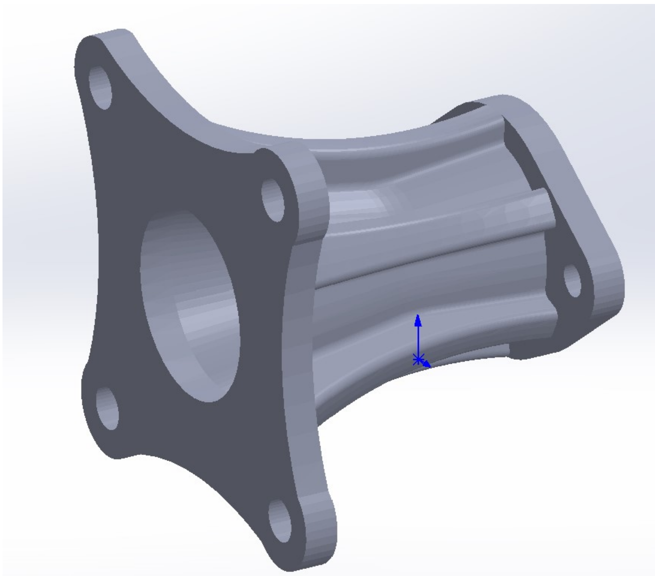


Figure 17: First prototype of the adapter plate

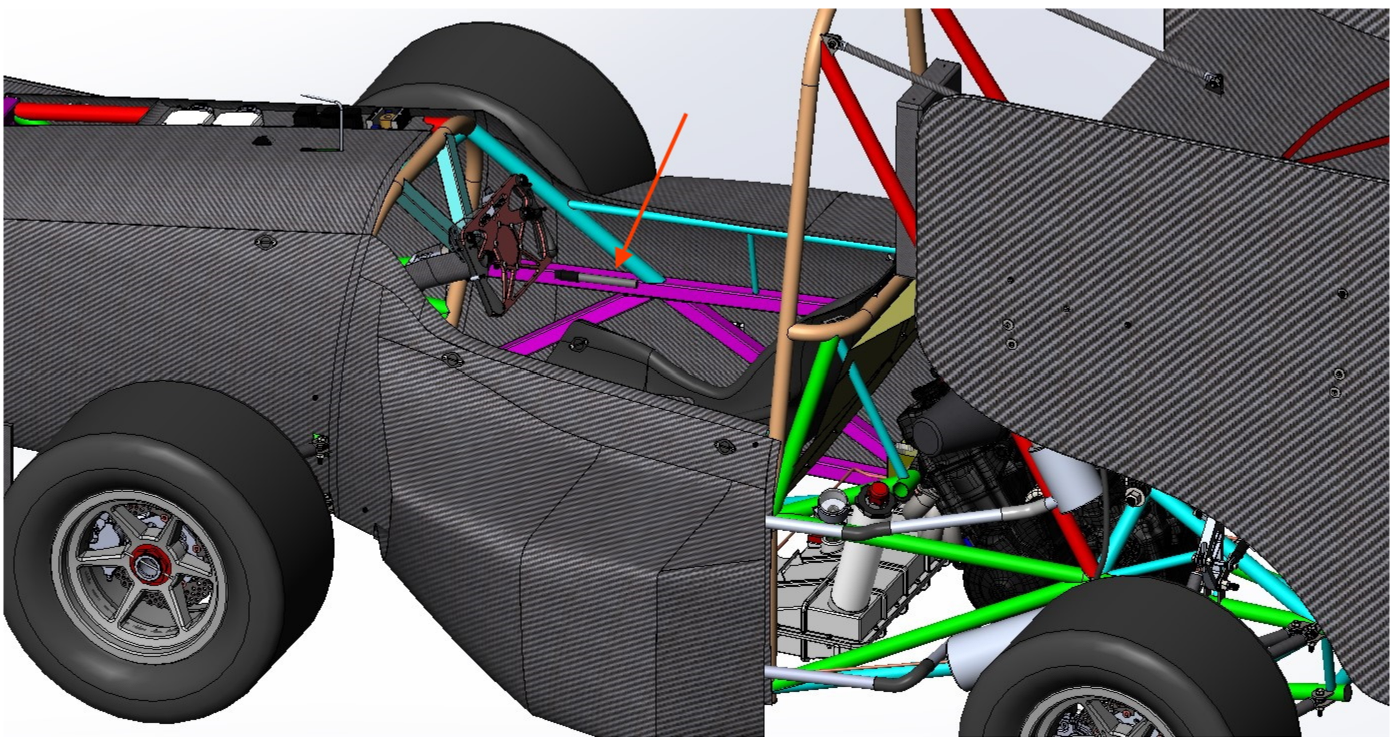


Figure 18: Initial placement of the potentiometer

5.1 Initial Embodiment

The real initial prototype is the V2 described below. We immediately jumped to an outsourced SLS 3D printed component because none of the materials at WashU were strong enough and had UV/chemical resistance, which would not work for any actual testing. In the first prototype that would be tested on a running car there were a few critical performance requirements:

-The prototype must be able to seal fully

-The E-throttle plate must not yield at all under full engine load, causing the engine runaway effect

-The engine model and tune must be accurate enough for the PID controller to hold a constant speed

-The whole assembly must be rigid enough to inspire confidence in the drivers

This second prototype was able to accomplish all of the above goals, but the model was a bit shaky and required a lot of tuning. Part of the reason could be that I had to re-tune the engine on the fly using my laptop while actuating the throttle with my other hand (not recommended).

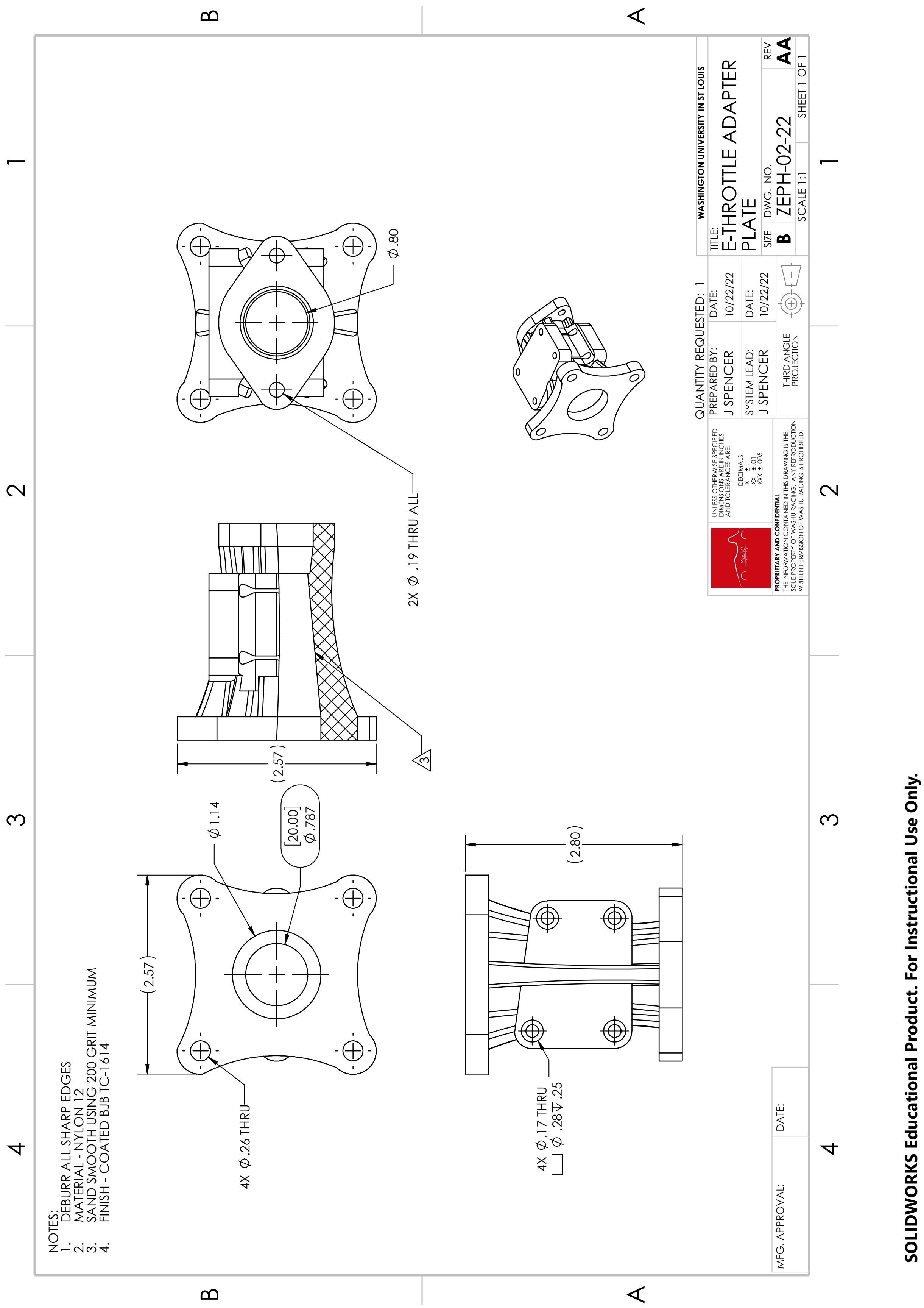


Figure 19: The E-throttle adapter plate component

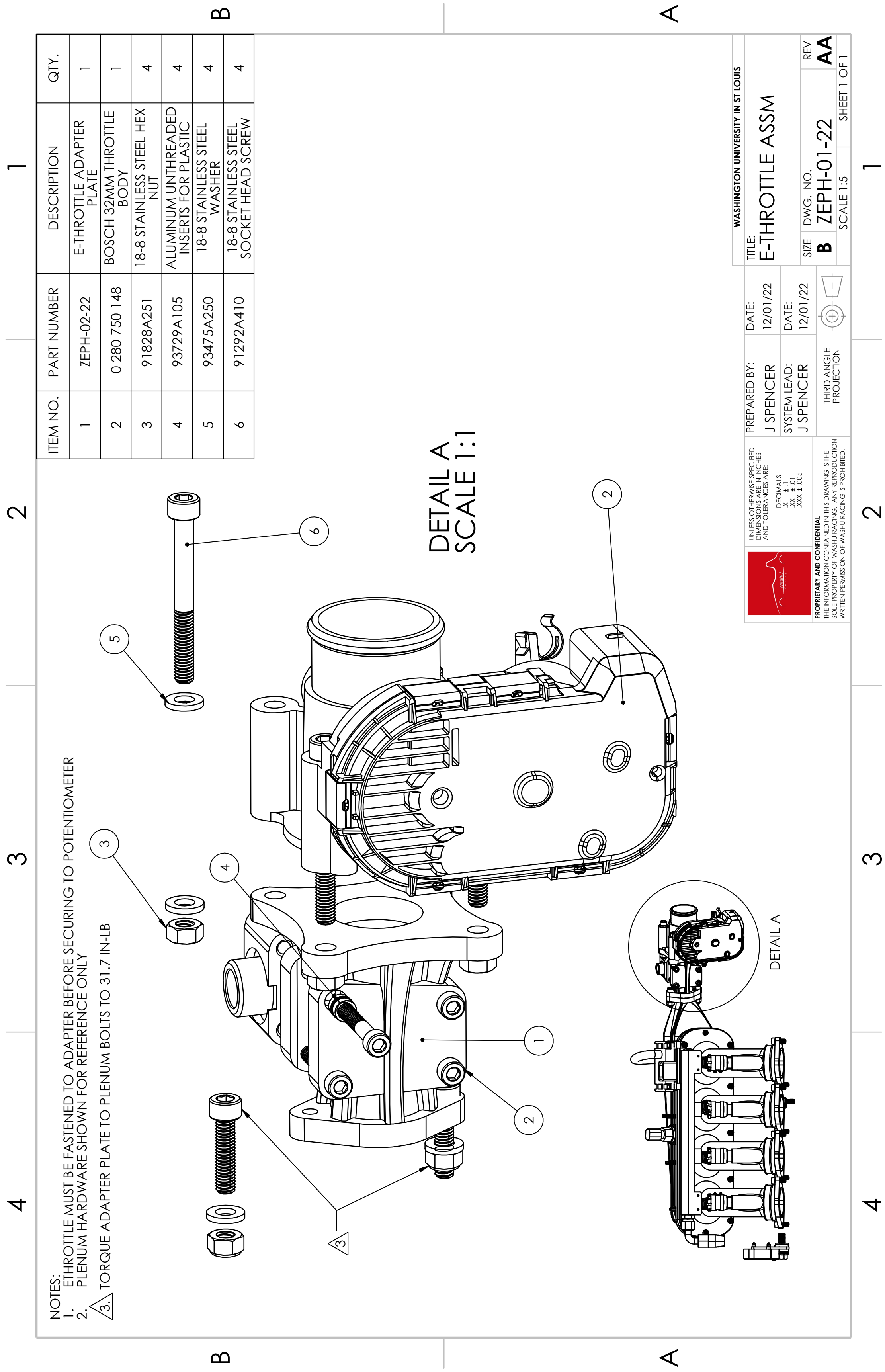


Figure 20: Assembly and context drawing with BOM

5.2 Proofs-of-Concept

After testing with the initial prototype and connecting the throttle to a linear potentiometer mounted in the cockpit, our group realized that in order to meet our goal of quickly switching from the nominal throttle cable system to our system, we needed an entirely different mounting solution for the potentiometer.

It was also realized that PLA was not sufficient for the final prototype, as under the high vacuum induced by high engine loads it was not air tight, and would cause a runaway effect in the throttle, where the engine RPMs climb, causing more vacuum, which in turn raises the engine RPM even higher, and so on.

Finally, as with most first designs on the WashU Racing vehicle, there were numerous issues accessing certain bolts with commonly available tools in the garage, and many bolts had to be re-positioned to allow for better tool fitment. Unthreaded inserts with a chamfer on one side were also added to avoid any direct contact between the 3-D printed portions of the part and threaded components, which had a habit of digging into the part and destroying it over time.

5.3 Design Changes

To reduce the time to mount the e-throttle to the vehicle, we used the same butterfly valve and throttle actuation system as the normal mechanical throttle cable, which included a rotary potentiometer so the ECU had information on the throttle inputs, to control the electronic throttle. This meant the throttle cable could remain exactly the same length, with largely the same routing, and neatly provide information to both the ECU e-throttle about the user's intended throttle position. The material was also changed from PLA to nylon 12, which was much stronger, easier to seal, and had a much better surface roughness since it used SLS 3D printing, which has a much higher resolution than the FDM printing used for the first prototype.

6 Design Refinement

6.1 Model-Based Design Decisions

Multiple models were developed, and existing models changed to account for the addition of this component to the vehicle. This paper will cover the mechanical models, although the paper by Kejriwal and Wheelock [**FSAEpaper**] gives a more in-depth description of the PID controller used to regulate the vehicle's speed based on the engine model explained here, and the wheel-speed collected from the car in real time.

1. Heat

The effects of heat on this part were considered by estimating the possible heat transfer under the worst case scenario of the car motionless with engine at high RPMs and after the engine block has reached its maximum operating temperature. All modes of heat transfer were considered. Convection was determined to be negligible by measuring the air temperature to the side of the engine where the adapter plate is located. Even stagnant air in the garage did not reach higher than 120F at this point, not nearly hot enough to be a concern for the adapter plate. Similarly, conduction was determined negligible because the plenum and runners which connect the adapter plate to the engine block are made of Ultem 1010, which has a very low thermal conductivity of $0.24\frac{W}{mK}$

Radiation was analyzed by assuming the engine head to be a gray body with the thermal properties of black enamel paint (which coats the outside of the engine) [**emissivity**]. Half of the head area was used for area, the temperature of the head was 140F, and the temperature of the surrounding air was 70F. Of course in a real scenario, not even 10% of this power will be turned into heat in the adapter plate, but without complicated thermal FEA determining an imperical value is very difficult. This rough conservative estimate should suffice.

$$P = \sigma \epsilon A (T - T_c)^4$$

$$P = 5.67E - 8 * 0.80 * 0.0322 * (60 - 21)^4$$

$$P = 0.0034W$$

0.0034W is a negligible amount of heating power.

2. Structural

A structural analysis was preformed using solidworks FEA using known material properties from Formlabs for SLS nylon 12 printed components. [**formlabs**]

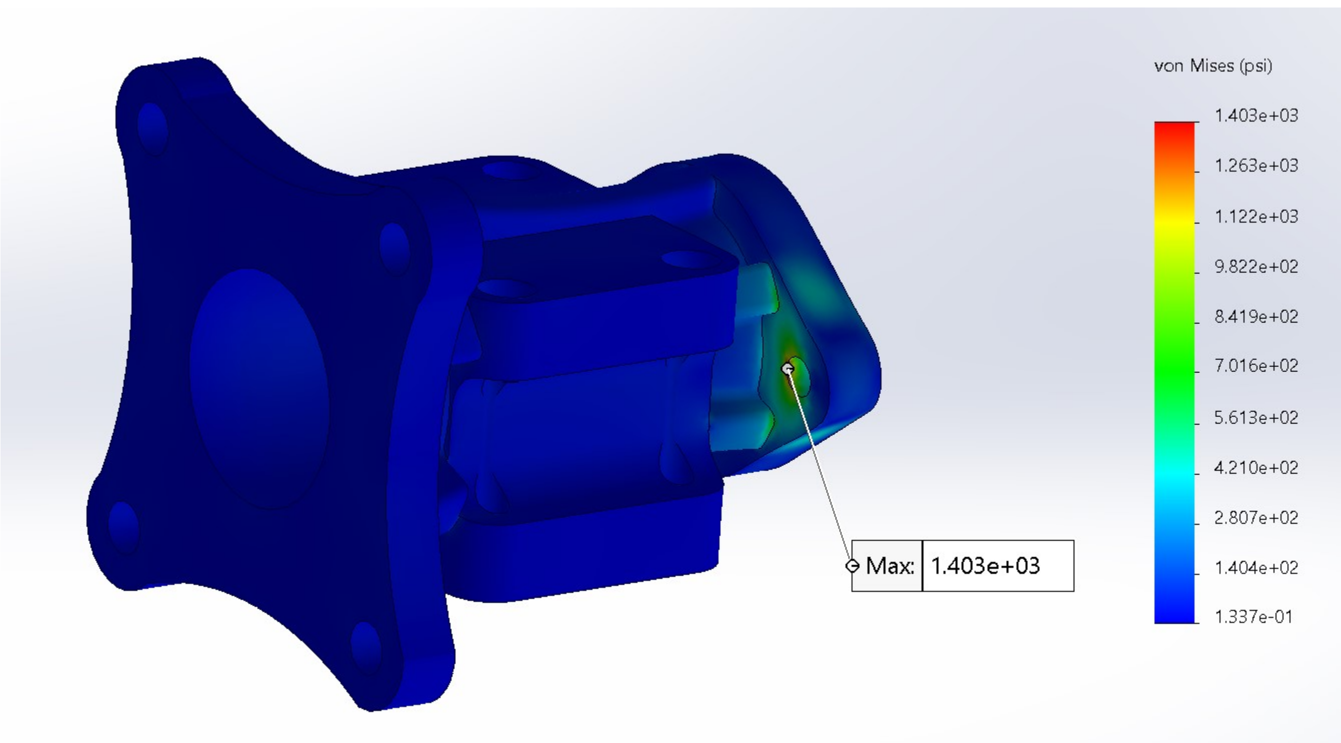


Figure 21: Static FEA analysis of the component

The base of the throttle was fixed at the bolted connection to the plenum. A load was applied at the mounting bolts for the e-throttle which was 3x it's weight under static conditions, meant to represent the team's widely agreed upon worst case loading scenario of a 3-g bump (since the e-throttle is a sprung component - which are isolated from bump loads by the suspension - it is unlikely to even see this high of a load). Another pressure was added to the internal surface for the vacuum load from the GT-suite values. A maximum stress of 1400 psi occurred, while the yield strength of the material was 7000 PSI

3. Vibrations

Another simulation was used to determine the natural frequencies of this component when fixed at one end and loaded at the other using the weight of the e-throttle. The two main resonant frequencies to avoid are the idle frequency of the component, which is around 2,500 RPM and the red-line of the car which is around 13,000 RPM. The engine passes through all other values rather quickly.

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	1,557.3	247.85	0.0040347
2	3,717.8	591.7	0.00169
3	7,078.2	1,126.5	0.00088768
4	10,261	1,633	0.00061236
5	15,087	2,401.1	0.00041647

Figure 22: Vibration study results showing natural frequencies

Fortunately non of the natural frequencies with significant displacements (1 & 3) were anywhere near idle or red-line.

6.2 Design for Safety

Design for safety, beyond simply ensuring the part wouldn't fail under vacuum loading, or in any possible running conditions, was mostly on the software side. In summary, if the driver places their foot on the throttle, presses the cockpit killswitch, or steers too hard/quickly, the e-throttle will disengage itself automatically. Further, if the wheelspeed varies too quickly or far from the target wheelspeed (which would be indicative of the car accelerating much too quickly for nominal cruise control) the system will deactivate. Drivers were all instructed in the functionality of the system in some depth as well to make sure they aren't going in to testing blind.

6.2.1 Risk #1: Engine runaway

Description: Engine runaway is when an improperly sealed intake leads the engine to rev above where the user intends, uncontrolled.
Severity: Critical
Probability: Occasional
Mitigating Steps: Seal adapter plate as well as possible, ensure surface is sanded or finished by manufacturer, use a gasket, preform structural and vibrational analysis

6.2.2 Risk #2: Unintended throttle variation

Description: Throttle variation from the intended user input can make the car uncontrollable, and lead to a crash. We need multiple mechanisms to make sure that the throttle does not deviate from the directions of the user at any time.
Severity: Catastrophic
Probability: Likely
Mitigating Steps: To ensure the throttle matches what the user directs, we implement hardware based throttle verification through multiple sensors on the throttle cable. We also adde multiple driver shutdown options, so if the throttle does vary, the user can shut the car down quickly. Finally, we bench tested the throttle for a few hours before using it on the car, to validate our setup.

6.2.3 Risk #3: Throttle Flutter

Description: The e-throttle will occasionally flutter when powered. This will degrade engine preformance slightly.
Severity: Marginal
Probability: Frequent
Mitigating Steps: We have tried to mitigate throttle flutter as much as possible by switching away from PWM control. At this point it seems mostly harmless, if not a bit annoying to listen to.

6.2.4 Risk #4: Structural Failure

Description: The e-throttle adapter plate could fall off of the car if it is not strong enough under the full vacuum load.
Severity: Catastrophic
Probability: Seldom
Mitigating Steps: The e-throttle adapter has been designed from a strong material, using FEA to estimate our safety margin. The part was also designed with a high safety factor of 4 to ensure it never approaches yielding, or displaces too much and fails to seal with the intake or the e-throttle.

6.2.5 Risk #5: Melting

Description: The e-throttle adapter plate could melt.
Severity: Catastrophic
Probability: Unlikely
Mitigating Steps: Nylon 12 is used for the e-throttle, which has a rather high heat deflection temperature of 340F. The top of the engine was measured, and the highest the head ever sees is around 200F, so melting should not be an issue.

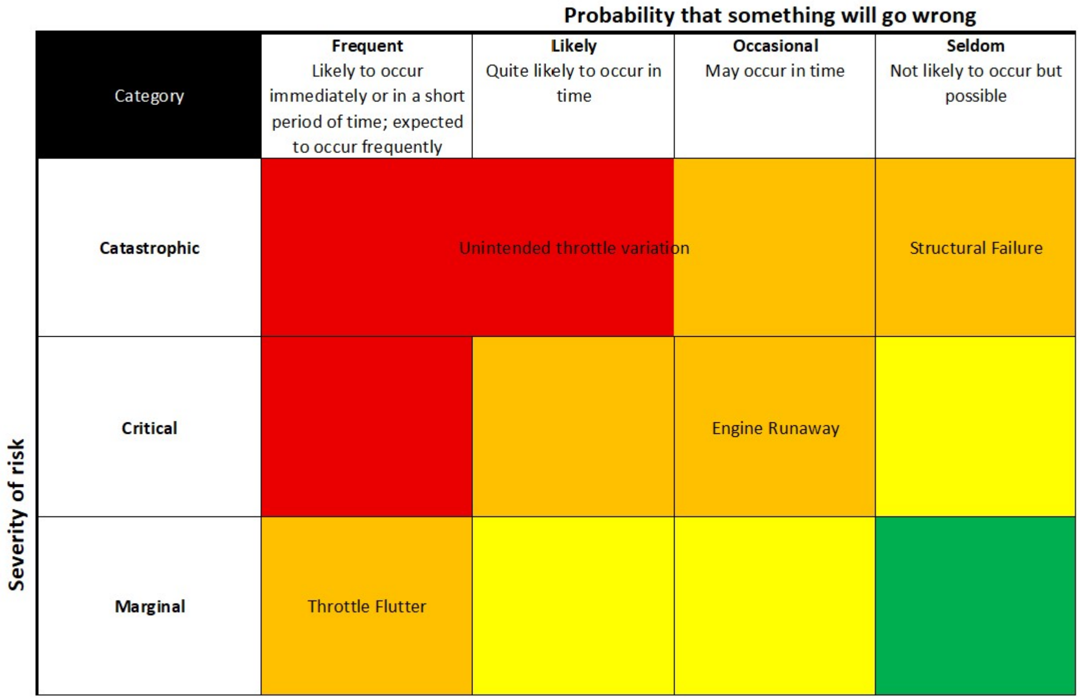


Figure 23: Heatmap of final risk assessment

6.3 Design for Manufacturing

Number of components (excluding fasteners): 5
Number of threaded fasteners: 10
Nmber of NTC parts: 5

We do not believe there are any unnecessary components in our current design, and would actually add a sealed ball bearing to decrease the friction of the device to rotation if we had another prototype.

Most of the DFM for this component was ensuring approach and departure angles were shallow enough to be printed properly on the SLS printer. Xometry has extremely capable SLS printers so this turned out not be a significant issue. Some other major considerations for manufacturing included: -Using threaded inserts wherever possible to avoid threading into 3D printed plastic (SLS printed threads are bad, FDM ones are completely non-viable).

-Calling out a surface roughness on the flanges for better sealing

-Leaving a bit of extra material on the inside of the adapter plate so it could be sanded down while still maintaining the minimum 20mm restriction required by the competition.

6.4 Design for Usability

The e-throttle was designed to be as intuitive as possible. To reduce the learning curve and keep muscle memory from the mechanical system, the actuation of the e-throttle was mapped to match the pedal actuation required for the same opening amount for the original mechanical system, and the engine tune was kept as similar as possible. This ensured that the driver would get the expected amount of power from the engine at a certain throttle position. The throttle was also tuned to respond as quickly as possible to changes on the throttle pedal side - being able to go from fully open to fully closed in less than 50ms.

Unfortunately, impairments were not considered when making this design, as the current driver pool is only able bodied, with no visual, motor control, or hearing impairments. Regardless, there is no sound or sight related to the e-throttle, only feeling through the right foot and motions with the right arm, which should not pose any difficulty to the hearing or visually impaired.

7 Final Prototype

7.1 Overview

Our final prototype is the culmination of my efforts in the mechanical space refining the adapter plate, throttle cable mounting, and sensor mounting, my work in the mechanical modeling, and my groupmates work in designing a PID controller and circuit board which is used to control the E-throttle [**FSAEpaper**].

This prototype uses an Arduino connected to hall effect sensors mounted around the rear wheel hubs to gather wheel-speed data. The data from these sensors is compared to the target wheel speed on board the Arduino, and the throttle is opened or closed to adjust the engine torque.

We tested the final prototype by placing the car on jackstands at all four corners, mounting the e-throttle and controller near the firewall, and setting the cruise control to activate once the wheel speed sensors on the car read 20 miles per hour. We then turned the car on shifted the car into second gear, and manually actuated the throttle up to 5000 RPM, which correlated to 20 mph. We saw variations of no more than ±150 RPM, which would suggest the system could keep the car steady within ±0.5 MPH.

7.2 Documentation

Fig. 24 demonstrates the top view of the e-throttle mounted on the car. Note the cable orientation allows the same length throttle cable to be used with this system, as with the stock mechanical system. In this configuration the e-throttle is also minimally cantilevered, and was able to support at least a 10 lb load (which we tested by hanging a weight from the e-throttle).

Fig. 25 demonstrates the rear view of the e-throttle. The throttle cable had to be zip-tied in places to the intake and frame to work in this configuration. To further refine the device I would suggest 3D printing and gluing guides along the path of the cable to ensure as smooth of actuation as possible.

Finaly, Fig. 26 shows the configuration the e-throttle was in while we were actually running the vehicle. This configuration would not be suitable for actual driving, as it requires a second power source and has many exposed wires, however with a PCB and waterproof enclosure it could very well see a testing day.

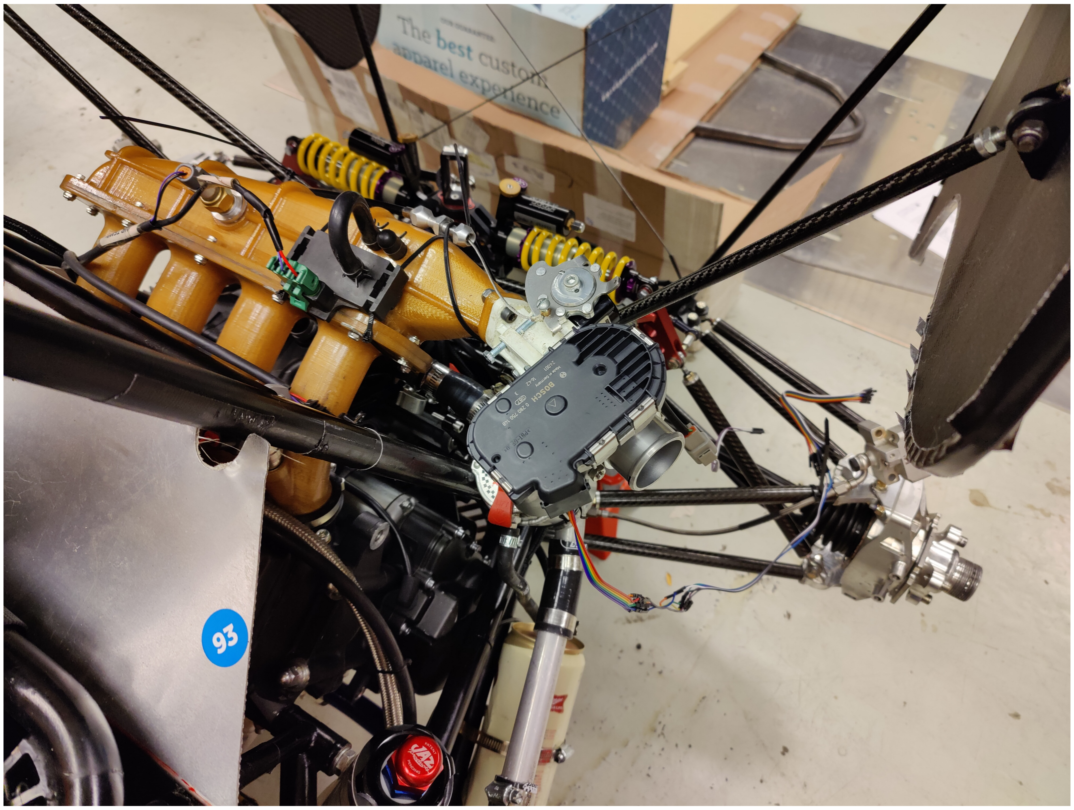


Figure 24: Top view of e-throttle

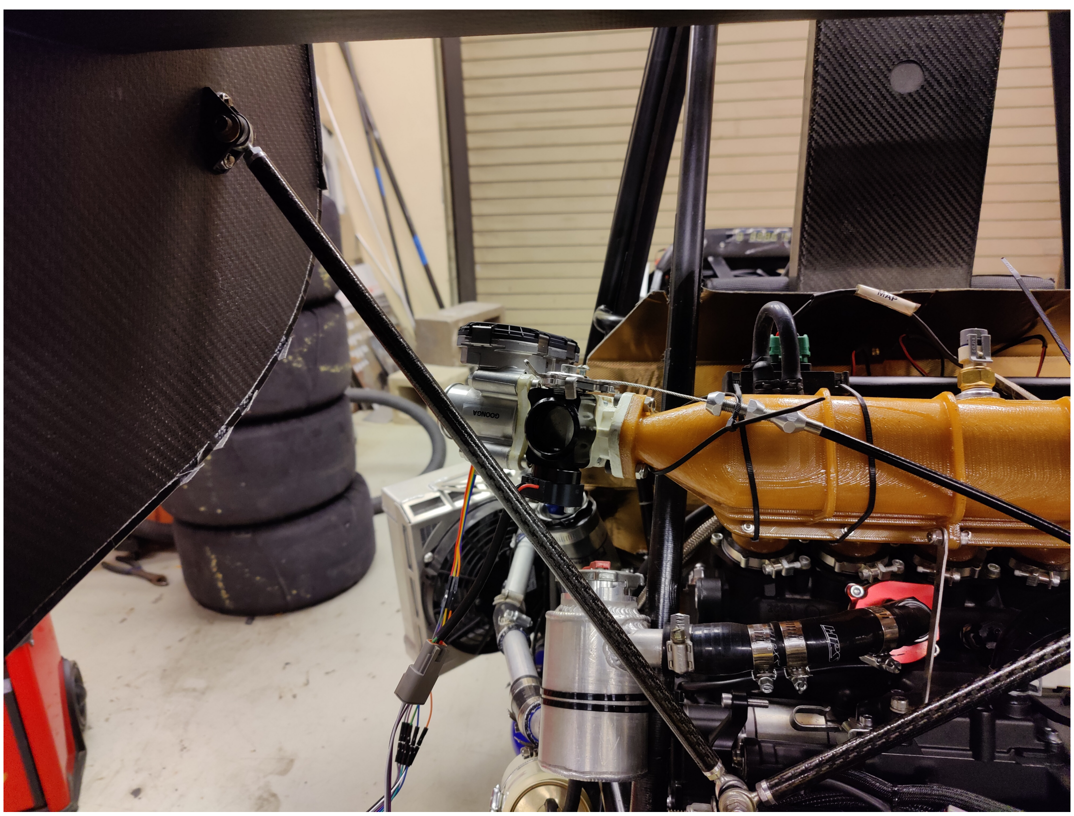


Figure 25: Rear view of e-throttle

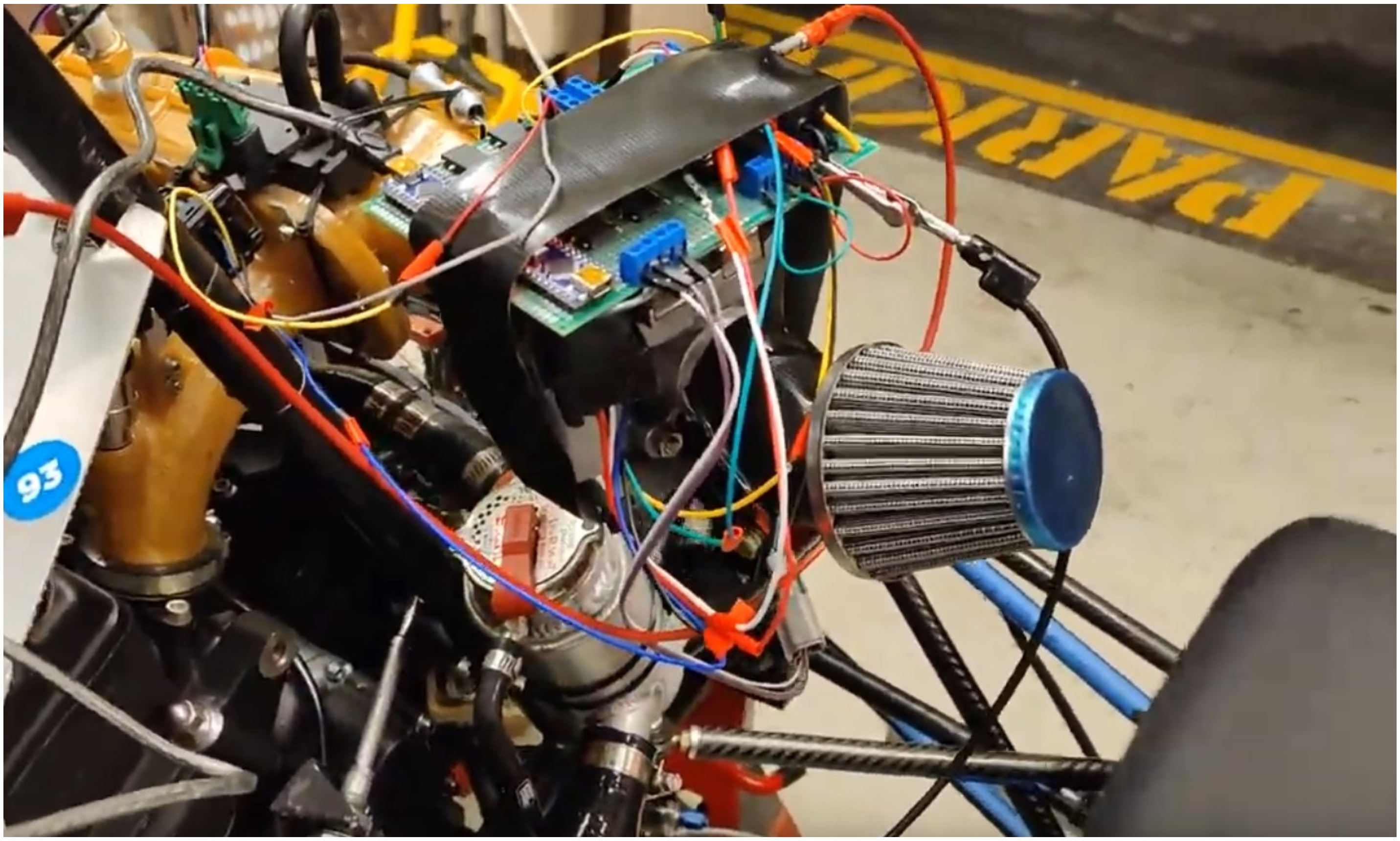


Figure 26: Final e-throttle mounting while car was running