Western Michigan University
NFPA Fluid Power Vehicle Challenge
Project Report

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RESTRICTED INFORMATION

Any reference required by University

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1. ABSTRACT OR EXECUTIVE SUMMARY

Transportation is a key component of a balanced and sustainable development which increases the accessibility and the opportunities of different social groups, but with a direct effect on the environment. In this case, the automobile has always been the most popular, used, and produced mode of transportation that contributes to the large amount of CO2 in our environment.

Bicycles have been a very popular mean of transportation all over the world with few constraints, such as space to accommodate more than one person and the distance that a human can travel. While the space has been accommodated by designing different types of bicycles with larges frames, distance is still a problem we are currently facing, because it is usually based on human power and control. One alternative to the human-powered improvement, is to build a bicycle that can be electronically controlled and powered with hydraulic fluid through a system that can combine both technologies.

One of the main advantages of hydraulic systems is their high-power density with a direct power advantage. Meaning that a small input can produce a multiplying effect, thus allowing a more efficient use of the energy placed into the system. Such benefit can be utilized to have a mode of transportation that can be used for longer distances. Similarly, the use of a hydraulic system will present the opportunity to think of efficiency and energy storage.

This main objective is for the design, fabrication and testing of a unique energy-efficient, safe, and cost effective vehicle that will serve as a human-powered vehicle competitive in the Fluid Powered Vehicle Challenge sponsored by the National Fluid Power Association. The goal will serve to increase awareness about alternative transportation and the value of fluid power combined with motion controls.

2. PROBLEM STATEMENT

The NFPA recognize the need for innovations in the hydraulic power field, and have led them to host the 2017 fluid power competition, which aims at students developing a human-assisted fluid power vehicle. The competition also focuses on implementing practical fluid power/motion control education and developing new technologies. The rules that were distributed describe the criteria for the design, fabrication, build, and the competition. The vehicle that is designed must be driven by hydraulics without any direct chain drive mechanism. The vehicle should be operated by a single rider, while keeping the weight under 210 lbs. The design and build of the system will be judged on factors such as ingenuity, safety, manufacturability, and cost analysis among others. The competition will be judged based on the performance of the vehicle in the three races: sprint, efficiency, and durability. The combination of these factors will decide the best overall design.

2.1. BACKGROUND

The power production of a conventional bicycle is limited to the capabilities of the human to input energy and limits the performance of the bicycle. The basic design of a bicycle lacks technical innovation, since the frame and drivetrain have remained the same over the past 100 years while presenting the opportunity to develop innovative modifications to the conventional bicycle design. The ideal design of a human assisted vehicle would optimize the performance of the vehicle in multiple conditions, while requiring minimal rider input.

The challenge of innovating the vehicle is to successfully combine two technologies — The hydraulic power and the electronic controls combined with a mechanical drivetrain to produce a functioning transportation vehicle. The first challenge is to utilize these technologies that are not usually associated with each other to create an efficient, safe, and cost effective vehicle.

2.2. UNDERSTANDING THE SYSTEM

At Western Michigan University, the fluid power vehicle has been conducted as a senior design project. The senior design is a capstone project in which students utilize knowledge and skills through their coursework to complete a research/design oriented project. The students involved in the Fluid Power Vehicle Challenge are required to design and build the drive train, hydraulic and electrical system for the vehicles, as well as being able to participate in a final design competition. Components for the hydraulic system such as the pump/motor, accumulators, valves, hoses, fittings, and fluid will be provided by different sponsors such as EATON, Parker and SunSource through the NFPA. For the current hydraulic system design, our team decided to utilize multiple components from previous year's design, thus supporting the concept of reuse/recycle, and only order the remaining needed components such as valves and fittings from SunSource.

While understanding previous systems, our group decided to assess these by detecting some key interests. Having a bicycle with a lower center of mass, with a better weight distribution, and a bicycle that could be completely balanced are some of the essential interests that our group decided to improve.

Sometimes it is quite easy to come up with solutions, because the problem is obvious, but even if the problem is evident it is not certain that the solution chosen is the best. According to the famous philosopher Plato “The beginning is the most important part of any work”. The main reason is to create a clear picture of the problem and to get a strong foundation for a successful solution.

Furthermore, our group decided to pursuit different methods and definitions of the system we needed to understand prior any design selection or creation. The system development methods and the system technical concepts are the two phases within the research content of this project.

2.2.1 Development Process

A good project that is being develop has a general method that generates basic and complex concepts (Jackson, 2010). A concept generation process leaves the design team confident that the whole design has been explored and that the bicycle will be competitive after it’s done. A well thought concept is crucial for our team, because a concept with good quality always reflects on the quality of the final product. It is very important that the entire design team is involved in this part of the research, because is where creativity takes place.

During this process, there are several drawbacks to look out for:

- Team members who think they have the answer for everything can leave others feeling unappreciated.
- Lack of commitment by team members
- Failure to understand the project
- New and innovative solutions can be abandoned in this stage due to poor integration.

The development process can be summarized in two steps:

- Discover the concepts: The search for conceptual solutions for each problem through a brainstorming or a creative process that could try to bring ideas for solutions.
- Combination of concepts: Since our team discovered new solutions for problems from previous bicycles, the solutions can then be expanded and combined with other solutions. This process could generate several combined ideas that could potentially innovate our final product based on variations in problem’s characteristics.

2.2.2 Technical Concepts

Engineers can solve problems, but they need to know what problem to solve. During the research process, our group had to understand different concepts and problems. Each concept is an important structure of the system which performs specific functions that could approach the system design. Therefore, the group decided to follow the research and design phase in terms of behavior, function, and finally structure within the bicycle.

We organized the development of the system into a sequence of major areas:

- Bicycle designs: Ergonomics and frame designs.
- Previous chainless bicycles: From 2012 to 2016
- Hydraulic systems: Hydraulic circuit, components, flow rate, fluid friction, and efficiency.
- Safety and cleanliness within the system
- Gears: Types of gears, gear wear, gear friction, and gear ratios
- System configurations: Behavior of the system while coasting, braking, charging, and discharging.

2.3 WMU IN PREVIOUS COMPETITONS

Western Michigan University has participated in every competition since 2004/2005. For each competition, a new design was implemented for use as a senior design project. This year, our group analyzed and researched previous WMU concepts to improve the hydraulic system design. The 2014, 2015 and the 2016 designs from WMU are the primary focus for this year's engineering design process. Our team analyzed the hydraulic systems and the bicycle designs to promote ideas/innovations for the new hydraulic vehicle.

Image 1: 2014 Chainless Bicycle

The 2014 bicycle (Image 1) was evaluated by the current team to determine if any improvements could be made by the overall design to be implemented. The upright frame provides low cost, but has no certainty to support heavy weight. It also provides the smallest amount of mounting area for components, which could problematic for this project. Our team also thought that this bicycle was very unbalanced and hard to manage by the rider causing safety and aesthetic to be few of major issues on this bike.

The 2015 chainless bicycle (Image 2) was analyzed to provide input into the current design. The 2015 tricycle can hold heavy components with its spacious area in the back to place components as the team pleases. This bicycle used H3 pump/motor which provided high efficiency at low RPM. The hydraulic circuit for this design was messy, due to the amount of hosing and valves they had. The circuit is operated electronically, so the operator does not have to manually manipulate valves to change the fluid flow.

Image 2: 2015 Chainless Bicycle

Image 3: 2016 Chainless Bicycle

The most recent WMU vehicle was the 2016 upright bicycle, which was adapted and design intelligently. The team eliminated the conventional frame triangle and built a more spacious frame for the placement of few components such as the gears, hubs, pedals, pump, and the battery. Although, last year's bicycle frame was innovative, the upright frame was still not pleasant to the current mechanical team. Our team wanted the rider to feel safe while riding in an efficient vehicle.

Based on the bike designs from previous WMU designs entries, the current team has focused on the improvement of multiple aspects of these designs. For this year, the system has been designed for maximum efficiency, and weight stability. The team idea is to minimize the amount of hoses and fittings, while making sure the rider is safe and able to use the bicycle in an easy manner. The electrical control system will also be used to control the valves to direct flow of the fluid, charging, and discharging.

2.3.1 WMU Previous Electrical Overview

In the previous design, one microcontroller was responsible for all input and output logic. Through a com bus, the microcontroller interfaced with the control circuitry in the Power Box which configured the valves and returned the adjusted pressure signals through the com bus. The microcontroller then processed the returning signals and sent the data to the user by passing the data to the screen controller. The rider would then make decisions about what to do next and input their selection into the mode selection buttons. The microcontroller would then process the input and alter the valves accordingly.

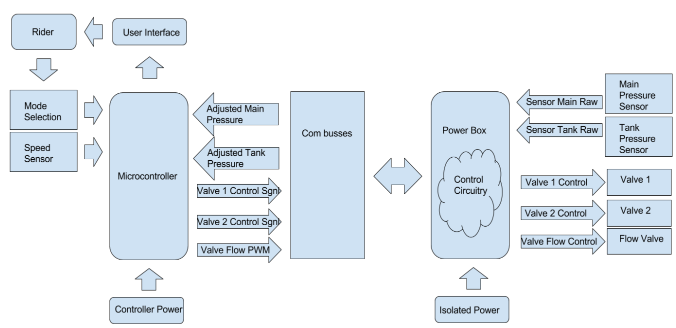


Figure 1: 2016 Vehicle Control Block Diagram

The results of this control scheme were unable to be assessed due to a solenoid failure burning up the MOSFETs in the power box. This is the motivating factor for reparability and modularity in this year's design. This single point of failure made the entire system unusable and ultimately fail to meet all the specifications. However, it appears the pressure sensors, speed sensor, user interface, and associated circuitry worked.

The specifications from last year and the upcoming competition are similar. As such, the specifications listed in the previous proposal gave a good idea of what parameters must be considered for the design. Also provided are the schematics for the mechanical and electrical circuit designs. These are helpful when tinkering with the previous design to understand how it works in practical terms. They also help when it comes to looking at components to utilize in the design.

The most prominent of these components was the microcontroller. The 2016 design includes the control's layout as well as the code and power supply it utilizes. The microcontroller used was an STM32F4 Discovery board. This board is not expensive; however, the libraries that must be used to program it, are not the most user-friendly, complicating its design process. This aspect was motivation for the decision to use a different controller. Along with the controller, there was several other design components described by last year's report. These include the smart display, speed sensor, power control box, linear voltage isolator circuit, solenoid driver circuits, linear voltage-controlled source, and programming code. All of which were inspected for possible improvements or simplifications.

3. PROJECT PLAN /OBJECTIVES

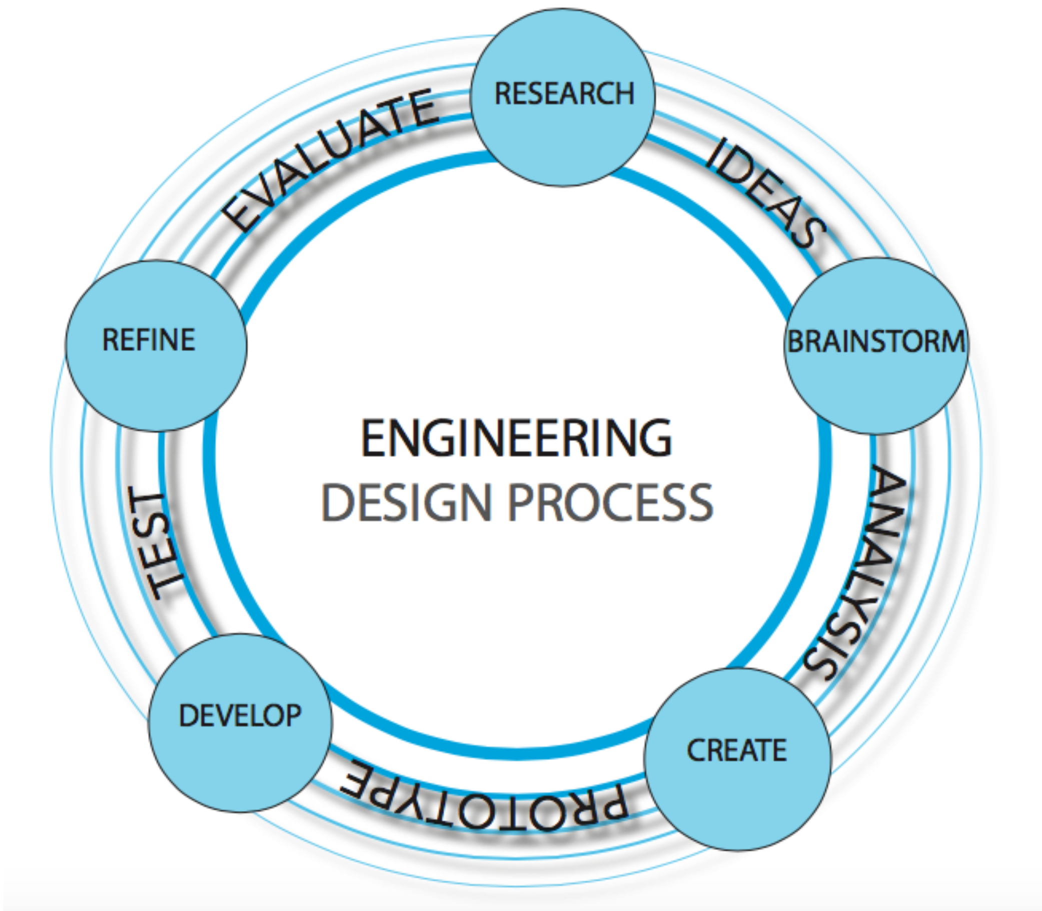


Figure 2: WMU Chainless Challenge 2017 Design Process

The engineering design process, also referred as the application development, is a visualization that helps to describe the process for planning, creating, testing, and deploying the information of the system. Our team decided to arrange the design process in five phases:

- Research: The stage in which you plan, investigate and explore similar systems.
- Brainstorm: Here is where the team starts piling ideas and start getting creative on new ideas that should or could be implemented in the system.
- Create: Analyzing components, analyzing systems, creating prototypes, and choosing materials.
- Develop: Testing is a great component in any product development and here is where we must analyze the calculated results vs the collected data.
- Refine: After fabricating and delivered the final product, you probably want to analyze the overall system and improve it if the proper time is available.

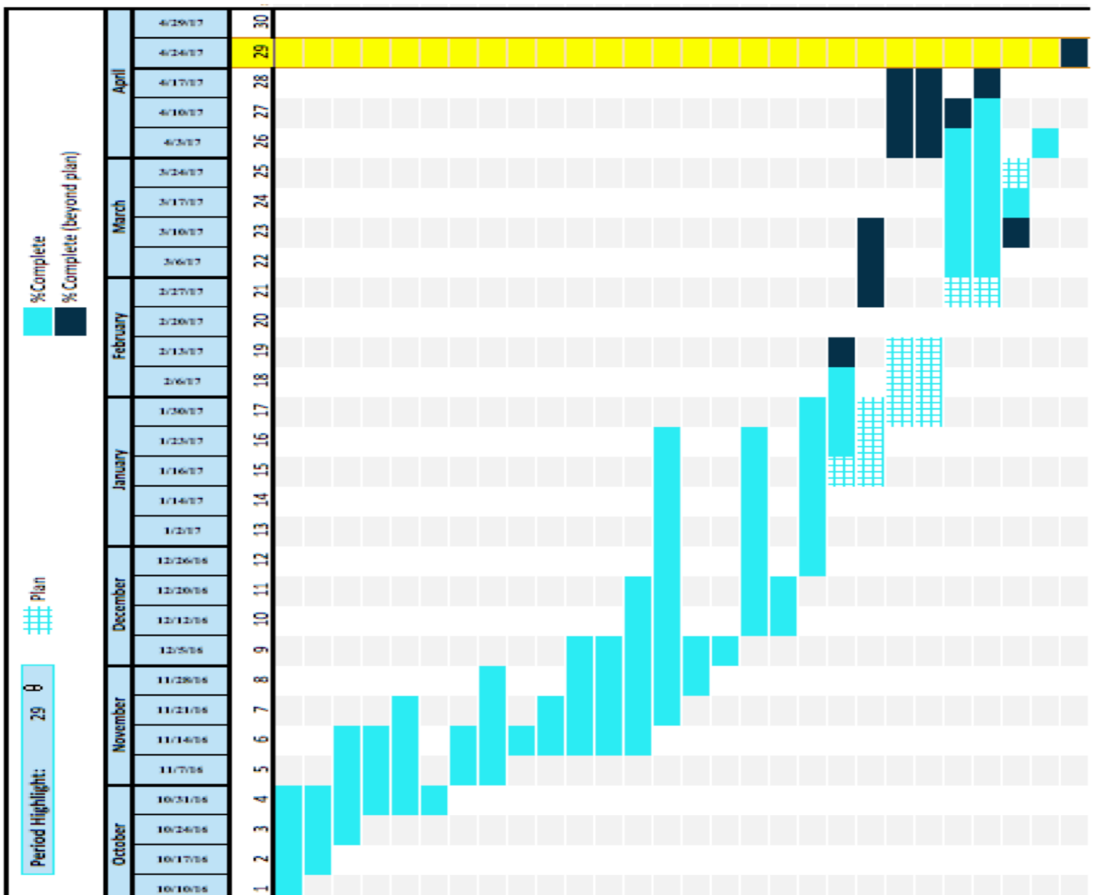
3.1 TIMELINE

The timeline or Gantt-chart have helped us to clearly identify the amount of work done or production completed in certain periods of time called milestones. Our goal was to follow the proposed deadlines and to try our best to not fall behind.

Table 1: WMU Chainless Challenge 2017 Gantt-Chart

WMU Chainless Challenge 2017

Activity	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	% COMPLETE
RESEARCHING	1	4	1	4	100%
Existing Vehicles	2	3	2	3	100%
Power Systems	3	4	3	4	100%
Complementary Systems	4	3	4	3	100%
BRAINSTORMING	4	4	4	4	100%
Specifications	4	1	4	1	100%
Desired Features	5	2	5	2	100%
Desired Changes	5	4	5	4	100%
Concept Generation	6	1	6	1	100%
Evaluate Concepts	6	2	6	2	100%
DESIGNING	6	4	6	4	100%
Vehicle Frame Decision	6	4	6	4	100%
CAD Model Initial	6	6	6	6	100%
CAD Model Final	7	10	7	10	100%
Power/FEA Analysis	8	2	8	2	100%
MIDWAY	9	1	9	1	100%
DEVELOPING	10	7	10	7	100%
Purchase Components	10	2	10	2	100%
Developing Frames	12	6	12	6	100%
Assemble Mechanical System	15	4	16	4	100%
Implement Hydraulic / Electrical	15	3	21	3	100%
TESTING	17	3	26	2	150%
Run Each System Individually	17	3	26	3	100%
REDESIGN	21	6	22	6	100%
Implement modifications	21	7	22	7	100%
Test in Roads	24	2	23	2	100%
Shipping the vehicle	26	1	26	1	100%
FINAL COMPETITION	29	1	29	1	100%



3.2 OBJECTIVES

The objectives of this project were clear from the beginning. The idea is to develop an environmentally friendly alternative mode of transportation while designing a safe, low-cost, and energy efficient human powered hydraulic vehicle. Our team will be designing realistic and possible concepts, while narrowing down and selecting the best design proposal. The WMU 2017 will then build the product, test, refine the design, and create specifications for the design. Testing and improving the design will be areas to focus on throughout this process.

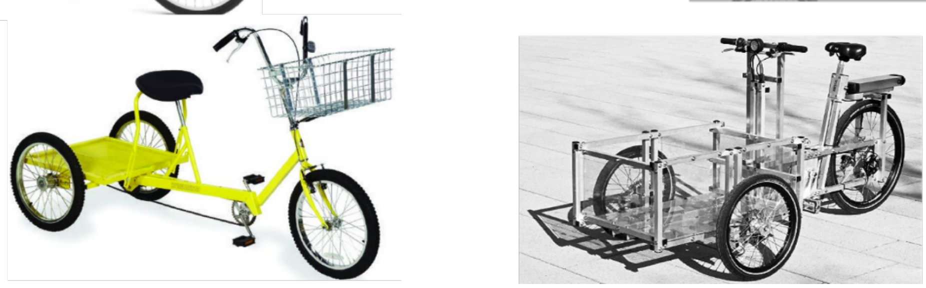
Furthermore, our team should meet all the criteria and rules specified by the National Fluid Power Association. Our ultimate goal will be to optimize the vehicle performance in all three categories of the final design competition.

4. SELECTION PROCESS & COMPONENTS SELECTION

For the selection process, we used Pugh-matrixes, and ranked the choices. Each product factor was weighted to find the ones that are most important. Our criteria were based on the requirements of the system and the solutions that we as a team thought could possible solve the problems.

4.1 FRAME SELECTION

When selecting the type of frame to use for the chainless challenge, it was important to take many different factors into account before making a final selection. Our group evaluated over a dozen different frame designs, and narrowed them down to five possible choices, as seen in the images below. Important design criteria factors were chosen and organized into four categories such as design, manufacturability, functionality, and weight. After choosing, the team created a Pugh-matrix and evaluated each design individually. For each design, the total scores from the members were averaged, and the design with the highest average score from the team would be the frame selected to use for the competition. In this case, this turned out to be the regular tricycle frame. The results of the final selection are shown below (Table 2). Each member evaluated individual criteria on a scale of 1 to 5, and each criteria had a weight factor of 2 to 10.



Images 4-5-6 - Frame types: From left to right – Top (regular tricycle, delta recumbent, and cargo bike)

Images 7-8 - Frame types: From left to right – Bottom (expanded tricycle, and n55 long front)

Table 2: Frame Decision Matrix Final Results

FINAL DECISION					
Scores by Team member	***3-wheel (trike)***	***3-wheel - delta recumbent***	***3-wheel - long front (N55)***	***3-wheel - expanded back tricycle***	***2-wheel - long back cargo***
Andrew	651.5	554	561	638.75	587.75
Adam	600.25	539	534.2	502.3	537
Luis	446.5	425.05	493.65	408.1	469.95
Matthew	596	540	520.5	562.5	557.5
Average	**574**	**515**	**527**	**528**	**538**
Position	**1**	**5**	**4**	**3**	**2**

Table 3: Frame Decision Matrix Results on each Criteria

	trike	**recumbent**	**n55**	**expanded**	**cargo bike**
Design	4.30	3.89	4.08	4.05	3.87
Manufacturing	4.42	3.45	3.29	4.08	4.13
Function	3.93	4.40	3.56	3.78	4.04
Weight	4.68	4.17	3.75	4.08	3.92

The four criteria specified by the team were identified after understanding and evaluating previous WMU chainless bicycles. The criteria for the frame was relevant because of the following suggestions:

- Design: Aesthetically and technologically advanced.
- Manufacturability: Easy to fabricate and assemble while having a low cost of material.
- Functionality: System should work as planned with minimal or no failures.
- Weight: Weight should be evenly distributed and should be less than 210 lbs.

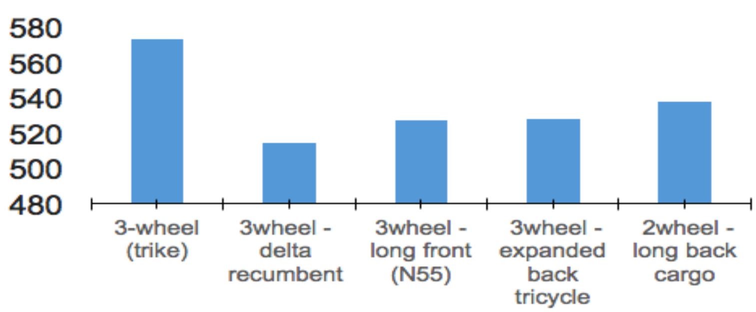


Figure 3: Frame Decision Matrix Results Chart

4.2 PUMP/MOTOR SELECTION

Table 4: Motor Specifications

Pump / Motor	Size	Efficiency	Weight	Disp.	Cost
F11-5	83.66 in^3	90.4%	11 lb	4.9 CC/rev	$600
F11-10	118.13 in^3	88.4%	16.5 lb	9.8 CC/rev	$715
AM1C-31	38.25 in^3	84%	4 lb	5.1 CC/rev	$800

The criteria used to select the pump was that was taken into consideration was efficiency, pump displacement, size, weight and cost. The Parker F11-5 had the highest efficiency of all the pumps. The larger version, the F11-10, had the largest displacement volume of all the pumps, and the Parker AM1C-31 had the smallest size and the least amount of weight. When comparing these pumps on a Pugh matrix, the highest scoring pump was the AM1C-31. With this result, it was decided that the AM1C-31 would be the pump for the vehicle.

Table 5: Motor Selection Pugh Matrix

Factors	Weight Factors	F11-5	F11-10	AM1C-31
Efficiency	10	9.375	8.25	7.275
Disp. Volume	8	6.25	9.75	7.625
Size	6	6.75	5	9.25
Weight	4	6.25	4.25	9.25
Cost	2	9.25	6	4.75
	Total:	227.75	219.5	235.75

4.3 ACCUMULATORS SELECTION

Table 6: Accumulator Specifications and Selection

Model	Vol. (Gal)	Weight (lb)	Weight (w/ oil)	Max PSI	Dimension	Energy / Weight	Energy storage capacity (lb-ft)
BA005B3T01A1	0.65	10	14.993	3000	15.5 x 4.5	2504	**37,538**
AD280B25T1A1	0.74	21	26.685	3600	9.5 x 6.75	1922	**51,282**
BA01B3T01A1	1.00	34	41.682	3000	17 x 6.5	1385	**57,750**
A230B230	1.00	30	37.682	3000	17.25 x 4.75	1533	**57,750**
TOBUL 4.5AL-20	1.08	20	28.297	3000	24 x 4	2204	**62,370**

Several accumulators from different companies were evaluated. The highest weighted factor was the energy to weight ratio. Since a big portion of the competition depends on efficiency, the ideal accumulator will be able to store high amounts of potential energy while not weighing the bike down. The amount of energy an accumulator can store is found by multiplying the volume of fluid it can handle by the pressure it can hold. The results of the highest rated accumulators are shown in Table 6. Overall, the accumulators TOBUL 4.5AL-20 and the Parker BA005B3T01A1 had the highest energy to weight ratios. Since the BA005B3T01A1 can only hold 0.65 gallons of fluid, the TOBUL 4.5AL-20 were a better choice at 1.08 gallons.

As shown above, the components chosen by the team have a very high efficiency on both the pump and the motor. The figures below (Figure 3) show how the pump has a far greater efficiency range, and with the use of the internal gear hubs selected for our vehicle, we could manipulate the gear train RPM to keep the motor RPM in its highest efficiency zone.

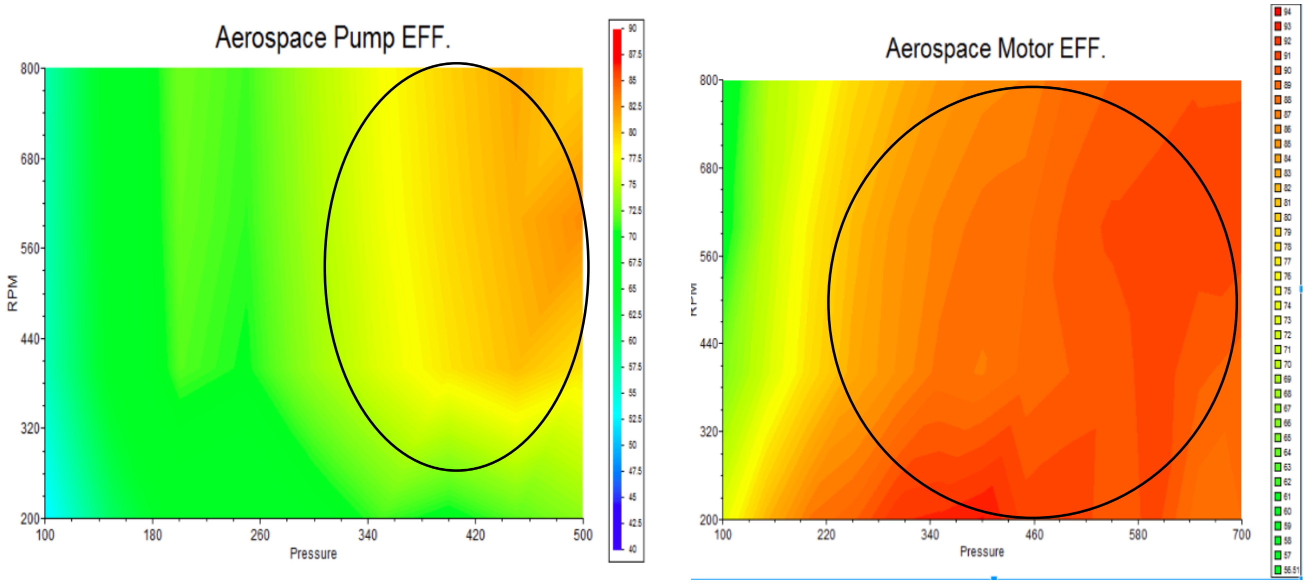


Figure 4: Aerospace Parker Pump/Motor Efficiency Graphs

4.4 HUBS SELECTION

Table 7: Hub Selection Specifications

Hub	# of Gears	Low Gear	High Gear	Cost
Shimano Alfine 11 Speed	11	0.527	2.153	$300
Shimano Alfine 8 Speed	8	0.527	1.615	$198
Shimano Nexus	7	0.632	1.54	$167
Sram I-3	3	0.73	1.36	$89
Sturmey Archer S3X	3	0.625	1	$189
Sturmey Archer SRF3	3	0.75	1.33	$99

Table 8: Front & Rear Hubs Pugh Matrix

Pugh Matrix										
Front Hubs						Rear Hubs				
Criteria	Weight	Shimano 11 speed	Shimano 8 Speed	Shimano Nexus		Criteria	Weight	Sram I-3	Sturney Archer S3X	Sturney Archer SRF3
Desired Gear Ratio	9	7	9	8		Desired Gear Ratio	9	10	7	9
Cost	6	5	7	9		Cost	6	9	5	8
Number of Gears	8	9	7	5		Number of Gears	8	9	9	9
Total Score		165	179	166		Total Score		216	165	201

The criteria used in the two tables was to have the desired gear ratio for the RPM, cost, while having the maximum number of gears to make the experience easier. In table 8, the Shimano 8 speed was the best choice because at his highest gearing it allows the rider to pedal at 35 rpm to run the pump at 600 rpm for maximum pump efficiency. The 11-speed version would have the rider pedaling a lot slower than what was intended. For the Shimano Nexus, the performance would be similar to the 8 speed, but it was one gear short, which in turn reduces ability to get the bike up to speed. In terms of cost, the Shimano 8 speed ranked alright, but it performed so well in the other two categories, so the hub was finally chosen.

While selecting hubs, our team had to focus on two things, such as the desired gear ratio for RPM and the cost. The three hubs that were assessed were the Scram I-3, STURNEY Archer S3X, and SRF3 as shown in table 8. The SRAM had the lowest cost and got a reasonable speed for wheel RPM. The other two options didn't give enough variation to spend more money for those hubs. The S3X would lower the wheel RPM in the lowest gear and SRF3 was just $10 more than the SRAM I-3 while having similar ratios. The SRAM I-3 was chosen because it performed the best and had a lower cost.

Image 9: Front Hub

Image 10: Front Hub

The team needed higher RPMs for the Aerospace pump/motor to work efficiently. It was decided that SRAM I-Motion 3 and the Shimano Alfine were the components to be selected. The I-Motion 3 gave the team the ability to have a transition of 186%, or could move the gear ratio from 1:1 to 1:1.36 or move it down from 1:0.76. The Shimano Alfine with its 8-internal speed could move the gear ratio from 1:1 to 1.615 or down from 1:0.527.

Since these hubs are originally made and design for bicycles with sprockets and chains in mind through a conventional drive-train system, we had to modified the hubs to accommodate our gears design. For the front hub, we utilized a 4" gear and a 6" gear both of which were modified and placed on the hub. The rear hub had a 3" gear and 2.5" gear which were modified and adjusted as desired.

4.5 GEARS SELECTION

The gears selected were deemed the best for our application. The spur gears that defined the drivetrain. To utilize the output of the mechanical power, a system of gears was installed between the pedal and the pump, and from the motor to the shaft of the rear axle. Various diameters ad configurations were considered, with multiple factors determining the basis of the team dynamic design. Some of these factors being: the resulting rotations per minute that would be exerted on the shaft, the wheel speed that would be a result from the number of revolutions per minute, the torque acting on the axle, as well as the diameters of the gears and how the spacing and component configuration would be affected by them. The team decided that it would be best to have five gears from the pedal to the pump and four gears from the motor to the axle. After calculating various gear ratios and comparing the benefits and drawbacks of each configuration, it was decided that from the motor a 2.5" pinion gear would drive a 3" gear on the hub, to which a 2.5" gear would transmit the resulting output power of the hub to a 5" gear located in the rear axle

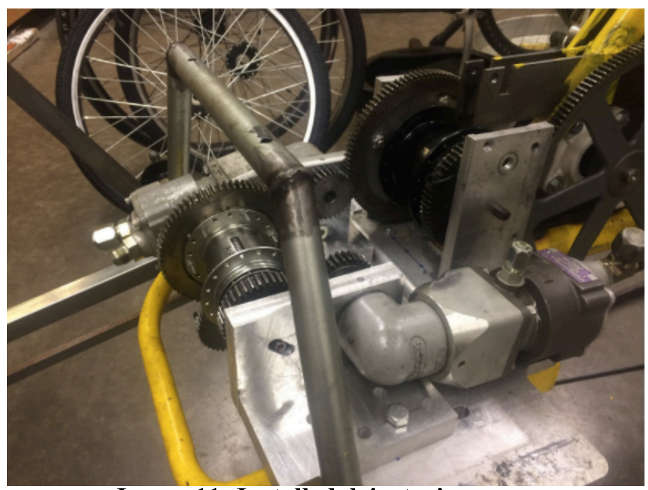


Image 11: Installed drivetrain

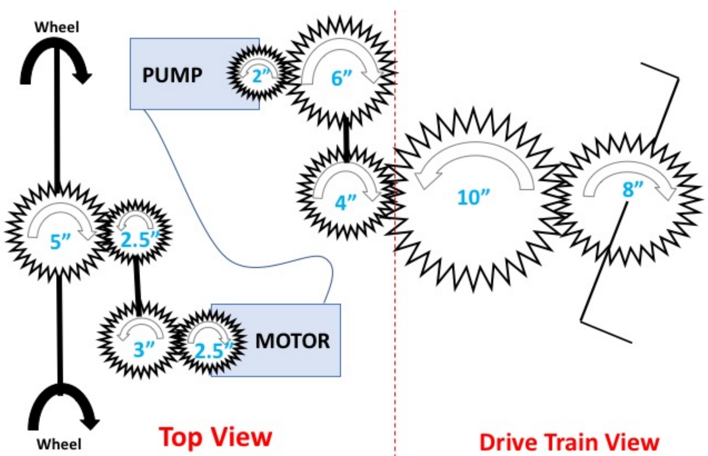


Figure 5: Drivetrain diagram

4.6 CALCULATIONS

Prior our testing and simulation process, our group decided to create various calculations that were made in Excel in order be sure that our system was going to work effectively. This section of our paper is was made in order to identify the pull of the vehicle in different inclined angles, torque of the drive wheel, determination of the system pressure, sizing the motor, the wheel RPM, GPM, horsepower, hydraulic lines, the size of the pump among others.

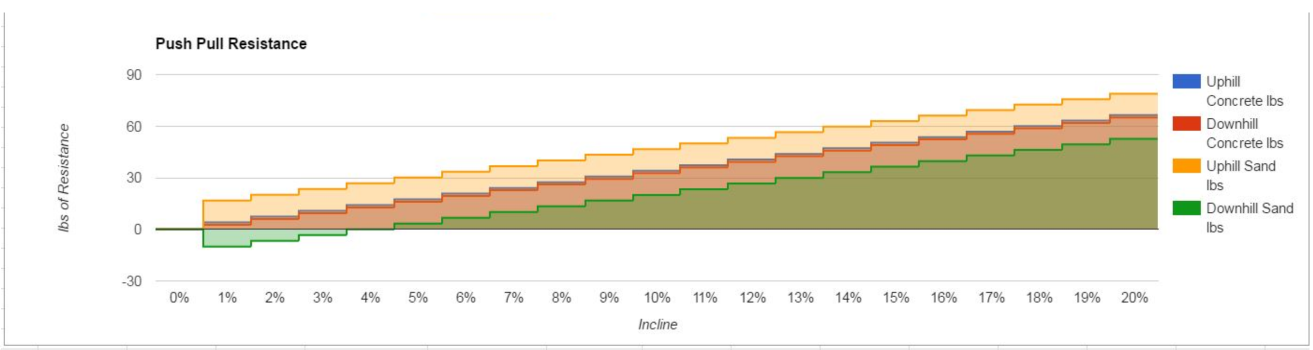
4.6.1 PUSH/PULL OF THE VEHICLE

Table 9: Pull & Push of the Vehicle

PUSH-PULL	
Vehicle weight in lbs =	185
Weight if rider in lbs=	150
Total weight=	335

Rolling Resistance	
Concrete	0.002
Sand	0.04

Incline	Degrees	Pull lbs	Push Concrete lbs	Push Sand lbs	Uphill Concrete lbs	Downhill Concrete lbs	Uphill Sand lbs	Downhill Sand lbs
0%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1%	0.5729	3.3498	0.6700	13.3993	4.0198	2.6799	16.7492	-10.0495
2%	1.1458	6.6987	0.6699	13.3973	7.3685	6.0288	20.0960	-6.6987
3%	1.7184	10.0455	0.6697	13.3940	10.7152	9.3758	23.4395	-3.3485
4%	2.2906	13.3893	0.6695	13.3893	14.0588	12.7198	26.7786	0.0000
5%	2.8624	16.7291	0.6692	13.3833	17.3983	16.0599	30.1124	3.3458
6%	3.4336	20.0639	0.6688	13.3759	20.7327	19.3951	33.4399	6.6880
7%	4.0042	23.3928	0.6684	13.3673	24.0611	22.7244	36.7600	10.0255
8%	4.5739	26.7146	0.6679	13.3573	27.3825	26.0468	40.0720	13.3573
9%	5.1428	30.0286	0.6673	13.3461	30.6959	29.3613	43.3747	16.6826
10%	5.7106	33.3337	0.6667	13.3335	34.0004	32.6671	46.6672	20.0002
11%	6.2773	36.6291	0.6660	13.3197	37.2950	35.9631	49.9487	23.3094
12%	6.8428	39.9136	0.6652	13.3045	40.5789	39.2484	53.2182	26.6091
13%	7.4069	43.1866	0.6644	13.2882	43.8510	42.5222	56.4748	29.8984
14%	7.9696	46.4470	0.6635	13.2706	47.1106	45.7835	59.7176	33.1764
15%	8.5308	49.6941	0.6626	13.2517	50.3566	49.0315	62.9458	36.4423
16%	9.0903	52.9268	0.6616	13.2317	53.5884	52.2652	66.1585	39.6951
17%	9.6480	56.1445	0.6605	13.2105	56.8050	55.4840	69.3550	42.9340
18%	10.2040	59.3463	0.6594	13.1881	60.0057	58.6869	72.5343	46.1582
19%	10.7580	62.5313	0.6582	13.1645	63.1895	61.8731	75.6958	49.3668
20%	11.3099	65.6989	0.6570	13.1398	66.3559	65.0419	78.8387	52.5591



In table 9, you can see that amount of force that is required to move the vehicle in both, uphill and downhill, while in different stages such as sand or concrete. Our team assumed to have a weight combination of 335 lbs. in the system. We also applied the rolling resistance while rolling over the sand and rolling over concrete. The highlighted 3% of inclined is supposed to be the average or steepest incline in the competition due to the flat surface in Ames. Our resultants tell us that we will need to apply 10.7 lbf to go uphill in an incline of 3% in concrete and 9.3 lbf while down hilling. 23.4 lbf to go uphill in sand and a -3.3 lbf to go downhill in sand. The negative resultant in this case is due to the rolling resistance meaning that the bicycle will have high friction while going down at that inclined angle. The graph of each stage is below the table 9.

4.6.2 TORQUE

Table 10: Torque of system during inclines

Torque uphill concrete	Torque downhill concrete	Torque uphill sand	Torque downhill sand
0.0000	0.0000	0.0000	0.0000
48.2376	32.1584	200.9900	-120.5940
88.4223	72.3455	241.1518	-80.3839
128.5822	112.5094	281.2735	-40.1819
168.7051	152.6379	321.3430	0.0000
208.7792	192.7193	361.3486	40.1498
248.7926	232.7414	401.2783	80.2557
288.7335	272.6927	441.1206	120.3056
328.5902	312.5614	480.8637	160.2879
368.3512	352.3359	520.4962	200.1909
408.0050	392.0049	560.0069	240.0030
447.5405	431.5569	599.3846	279.7128
486.9465	470.9811	638.6184	319.3092
526.2121	510.2663	677.6974	358.7810
565.3267	549.4020	716.6113	398.1174
604.2797	588.3776	755.3496	437.3077
643.0608	627.1828	793.9023	476.3414
681.6602	665.8076	832.2595	515.2083
720.0679	704.2422	870.4117	553.8984
758.2745	742.4771	908.3496	592.4019
796.2707	780.5030	946.0642	630.7095

Following the data from the inclines pull/push resistance force, we calculated the torque during those angles in both going uphill and downhill in concrete and sand. The highlighted cells are the ones at 3%, same as before.

We also calculated the torque at different pressures of the system during various RPM (from 0 to 100) shown in table 11. These calculations were to find and certify the output torque at different pump RPM's. The light blue cells are identified as "tested data" and the light green as "ideal data". The torque was calculated at pressures that the system should run from the minimum (250 psi), then average (500 psi) and finally top peak (750 psi).

Displ:	0.311	in^3
Front Hub Ratio:	1.615	:1
Torque:	273	lb in
Total gear ratio:	9.69	:1

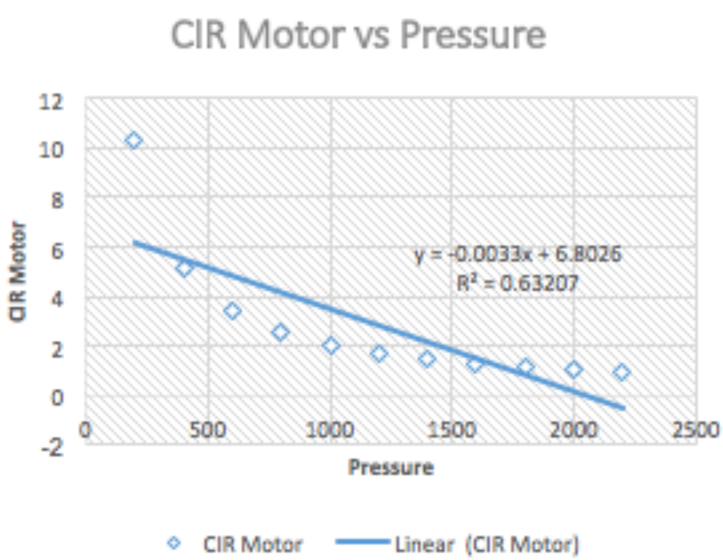
Table 11: Torque at different pressures

Pedal Rpm	Pump Rpm	Calculate Pedal Torque @ 250 psi	Calculate Pedal Torque @ 500 psi	Calculate Pedal Torque @ 750 psi
0	0.0000	0.0000	0.0000	0.0000
1	9.6900	157.1831	157.1831	153.5697
2	19.3800	78.5915	78.5915	76.7848
3	29.0700	52.3944	52.3944	51.1899
4	38.7600	39.2958	39.2958	38.3924
5	48.4500	31.4366	31.4366	30.7139
6	58.1400	26.1972	26.1972	25.5949
7	67.8300	22.4547	22.4547	21.9385
8	77.5200	19.6479	19.6479	19.1962
9	87.2100	17.4648	17.4648	17.0633
10	96.9000	15.7183	15.7183	15.3570
11	106.5900	14.2894	14.2894	13.9609
12	116.2800	13.0986	13.0986	12.7975
13	125.9700	12.0910	12.0910	11.8131
14	135.6600	11.2274	11.2274	10.9693
15	145.3500	10.4789	10.4789	10.2380
16	155.0400	9.8239	9.8239	9.5981
17	164.7300	9.2461	9.2461	9.0335
18	174.4200	8.7324	8.7324	8.5316
19	184.1100	8.2728	8.2728	8.0826
20	193.8000	7.8592	7.8592	7.6785
21	203.4900	7.4849	7.4849	7.3128
22	213.1800	7.1447	7.1447	6.9804
23	222.8700	6.3627	6.8340	6.6769
24	232.5600	6.0976	6.5493	6.3987
25	242.2500	5.8537	6.2873	6.1428
26	251.9400	5.6286	6.0455	5.9065
27	261.6300	5.4201	5.8216	5.6878
28	271.3200	5.2265	5.6137	5.4846
29	281.0100	5.0463	5.4201	5.2955
30	290.7000	4.8781	5.2394	5.1190
31	300.3900	4.7207	5.0704	4.9539
32	310.0800	4.5732	4.9120	4.7991
33	319.7700	4.4346	4.7631	4.9274
34	329.4600	4.3042	4.6230	4.7824
35	339.1500	4.1812	4.4909	4.6458
36	348.8400	4.0651	4.3662	4.5168
37	358.5300	4.2482	4.2482	4.3947
38	368.2200	4.1364	4.1364	4.2790
39	377.9100	4.0303	4.0303	4.1693
40	387.6000	3.9296	3.9296	4.0651
41	397.2900	3.8337	3.8337	3.9659
42	406.9800	3.7425	3.7425	3.8715
43	416.6700	3.6554	3.6554	3.7815
44	426.3600	3.5723	3.5723	3.6955
45	436.0500	3.4930	3.4930	3.6134
46	445.7400	3.4170	3.4170	3.5349
47	455.4300	3.3443	3.3443	3.4596
48	465.1200	3.2746	3.2746	3.3876
49	474.8100	3.2078	3.2078	3.3184
50	484.5000	3.1437	3.1437	3.2521
51	494.1900	3.0820	3.0820	3.1883
52	503.8800	3.0228	3.0228	3.1270
53	513.5700	2.9657	2.9657	3.0680
54	523.2600	2.9108	2.9108	3.0112
55	532.9500	2.8579	2.8579	2.9564
56	542.6400	2.8068	2.8068	2.9036
57	552.3300	2.7576	2.7576	2.8527
58	562.0200	2.7101	2.7101	2.8035
59	571.7100	2.6641	2.6641	2.7560
60	581.4000	2.6197	2.6197	2.7101
61	591.0900	2.5768	2.5768	2.6656
62	600.7800	2.5352	2.5352	2.6226
63	610.4700	2.4950	2.4950	2.5810
64	620.1600	2.4560	2.4560	2.5407
65	629.8500	2.4182	2.4182	2.5016
66	639.5400	2.3816	2.3816	2.4637
67	649.2300	2.3460	2.3460	2.4269
68	658.9200	2.3115	2.3115	2.3912
69	668.6100	2.2780	2.2780	2.3566
70	678.3000	2.2455	2.2455	2.3229
71	687.9900	2.2138	2.2138	2.2902
72	697.6800	2.1831	2.1831	2.2584
73	707.3700	2.1532	2.1532	2.2274
74	717.0600	2.1241	2.1241	2.1973
75	726.7500	2.0958	2.0958	2.1680
76	736.4400	2.0682	2.0682	2.1395
77	746.1300	2.0413	2.0413	2.1117
78	755.8200	2.0152	2.0152	2.0847
79	765.5100	1.9897	1.9897	2.0583
80	775.2000	1.9648	1.9648	2.0325
81	784.8900	1.9405	1.9405	2.0074
82	794.5800	1.9169	1.9169	1.9830
83	804.2700	1.8938	1.8938	1.9591
84	813.9600	1.8712	1.8712	1.9358
85	823.6500	1.8492	1.8492	1.9130
86	833.3400	1.8277	1.8277	1.8907
87	843.0300	1.8067	1.8067	1.8690
88	852.7200	1.7862	1.7862	1.8478
89	862.4100	1.7661	1.7661	1.8270
90	872.1000	1.7465	1.7465	1.8067
91	881.7900	1.7273	1.7273	1.7868
92	891.4800	1.7085	1.7085	1.7674
93	901.1700	1.6901	1.6901	1.7484
94	910.8600	1.6722	1.6722	1.7298
95	920.5500	1.6546	1.6546	1.7116
96	930.2400	1.6373	1.6373	1.6938
97	939.9300	1.6204	1.6204	1.6763
98	949.6200	1.6039	1.6039	1.6592
99	959.3100	1.5877	1.5877	1.6425
100	969.0000	1.5718	1.5718	1.6260

4.6.3 SIZING THE DRIVE MOTOR

Table 12: CIR of the system

PSI in the system	1000	psi
Motor Efficiency	90%	
Torque Given	294	lb in
CIR Motor needed	2.05	in^3



Pressure	CIR Motor
200	10.2625
400	5.1313
600	3.4208
800	2.5656
1000	2.0525
1200	1.7104
1400	1.4661
1600	1.2828
1800	1.1403
2000	1.0263
2200	0.9330

When we chose our drive motor for the system, being the AM1C-31 the selected, we looked at what CIR we needed in order to perform 90% efficiently with a 1.85in^3 of oil per revolution. With this motor having a size of 38.25 in^3 and a displ of 5.1 cc/rev. The graph and table 12 above, show how the motor behaves at different pressures of our system having a minimum of 200 psi with a 10.26 CIR motor and a maximum of 2200 psi with a 0.93 CIR motor. The graph above shows how the system behaves correlated to the information established.

4.6.4 WHEEL RPM & GPM

Table 13: Wheel RPM & GPM

Wheel diameter		24	inches
Bike Speed	RPM	Pedal RPM	GPM
0.0000	0.0000	0.0000	0.0000
1.0000	14.0000	6.0870	0.3091
2.0000	28.0000	12.1739	0.6182
3.0000	42.0000	18.2609	0.9273
4.0000	56.0000	24.3478	1.2364
5.0000	70.0000	30.4348	1.5455
6.0000	84.0000	36.5217	1.8545
7.0000	98.0000	42.6087	2.1636
8.0000	112.0000	48.6957	2.4727
9.0000	126.0000	54.7826	2.7818
10.0000	140.0000	60.8696	3.0909
11.0000	154.0000	66.9565	3.4000
12.0000	168.0000	73.0435	3.7091
13.0000	182.0000	79.1304	4.0182
14.0000	196.0000	85.2174	4.3273
15.0000	210.0000	91.3043	4.6364
16.0000	224.0000	97.3913	4.9455
17.0000	238.0000	103.4783	5.2545
18.0000	252.0000	109.5652	5.5636
19.0000	266.0000	115.6522	5.8727
20.0000	280.0000	121.7391	6.1818

The following data specified in table 13, shows the results of various RPM and pedal RPM at different bike speeds with a wheel diameter of 24 inches. The calculations for the RPM was as follows:

- RPM= 336* mph/ diameter

The GPM was then calculated by multiplying the CIR times the resultant RPM.

4.6.5 HORSE POWER

The Horse Power was identified by calculating it. We first multiply the GPM times the pressure, and then divided by 1714 which is 1/1714 GPM in one horse power. Our values are also calculated in terms of the speed.

Table 14: HP

Bike Speed	HP
0	0
1	0.028395
2	0.056789
3	0.085184
4	0.113578
5	0.141973
6	0.170367
7	0.198762
8	0.227156
9	0.255551
10	0.283945
11	0.31234
12	0.340734
13	0.369129
14	0.397523
15	0.425918
16	0.454312
17	0.482707
18	0.511102
19	0.539496
20	0.567891

4.6.6 LINE SIZING

Under sizing causes excess pressure drop and heat. In the industry there are few standards, such as 16 ft/s for ISO and 20 ft/s for ANSI. There are no restrictions within the last 10 diameters at pump inlet. In the table below, you will see the different velocity in ft/s of the oil at different diameter, such as 3/8" high and low and at ½ "high and low at different RPM. We decided to choose 3/8

Table 15: Line sizing at speeds

Pedal Rpm	velocity 3/8" ft/s High	velocity 3/8" ft/s Low	velocity 1/2" ft/s High	velocity 1/2" ft/s Low
0	0	0	0	0
1	0.0279302	0.0091141	0.0166773	0.0054421
2	0.0558604	0.0182281	0.0333546	0.0108841
3	0.0837905	0.0273422	0.050032	0.0163262
4	0.1117207	0.0364562	0.0667093	0.0217683
5	0.1396509	0.0455703	0.0833866	0.0272104
6	0.1675811	0.0546844	0.1000639	0.0326524
7	0.1955113	0.0637984	0.1167412	0.0380945
8	0.2234414	0.0729125	0.1334185	0.0435366
9	0.2513716	0.0820265	0.1500959	0.0489787
10	0.2793018	0.0911406	0.1667732	0.0544207
11	0.307232	0.1002546	0.1834505	0.0598628
12	0.3351622	0.1093687	0.2001278	0.0653049
13	0.3630923	0.1184828	0.2168051	0.0707469
14	0.3910225	0.1275968	0.2334825	0.076189
15	0.4189527	0.1367109	0.2501598	0.0816311
16	0.4468829	0.1458249	0.2668371	0.0870732
17	0.4748131	0.154939	0.2835144	0.0925152
18	0.5027432	0.1640531	0.3001917	0.0979573
19	0.5306734	0.1731671	0.3168691	0.1033994
20	0.5586036	0.1822812	0.3335464	0.1088414
21	0.5865338	0.1913952	0.3502237	0.1142835
22	0.614464	0.2005093	0.366901	0.1197256
23	0.6423941	0.2096234	0.3835783	0.1251677
24	0.6703243	0.2187374	0.4002556	0.1306097
25	0.6982545	0.2278515	0.416933	0.1360518
26	0.7261847	0.2369655	0.4336103	0.1414939
27	0.7541149	0.2460796	0.4502876	0.146936
28	0.782045	0.2551936	0.4669649	0.152378
29	0.8099752	0.2643077	0.4836422	0.1578201
30	0.8379054	0.2734218	0.5003196	0.1632622
31	0.8658356	0.2825358	0.5169969	0.1687042
32	0.8937658	0.2916499	0.5336742	0.1741463
33	0.921696	0.3007639	0.5503515	0.1795884
34	0.9496261	0.309878	0.5670288	0.1850305
35	0.9775563	0.3189921	0.5837061	0.1904725
36	1.0054865	0.3281061	0.6003835	0.1959146
37	1.0334167	0.3372202	0.6170608	0.2013567
38	1.0613469	0.3463342	0.6337381	0.2067987
39	1.089277	0.3554483	0.6504154	0.2122408
40	[illegible]	[illegible]	[illegible]	[illegible]

4.6.7 SIZING THE PUMP

Table 16: Sizing the Pump

Size of the Pump		
CIR	4.1	cir
Wheel speed	60	rpm
flow rate	1.0649351	GPM
Flow rate	1.065	GPM
Speed	60	RPM
CIR	4.10025	CIR
Add Vol. Eff.	4.5432133	CIR

The way we did our calculations to find out the actual CIR needed of the pump was thanks to the GPM formula:

$$GPM = \frac{CIR\ X\ RPM}{231}$$

Since we knew our GPM already, we solved for CIR having a resultant of 4.1 CIR. After finding the CIR needed, we could calculate the volumetric efficiency by diving the CIR by the pump and then divide the resultant by the motor. With this being said, we have a final volumetric efficiency of 4.54 CIR needed for our system.

The overall efficiency was calculated by multiplying the volumetric efficiency times the mechanical efficiency, which gives us a result of 18.61 CIR. After getting the 100% efficiency we would have to divide it by the overall system efficiency. A good note to have is that the pump CIR is always theoretically twice the motor with a ratio of 2:1.

4.7 *CONTROL SYSTEM SPECIFICATIONS*

The Specifications for the 2017 Fluid Powered Vehicle Control System are listed in Table 18.

Category	Requirement Goal Preference	Specification
Physical	**G**	1. Be smaller than last year's control system (~6.55 dm^3)
	G	2. System to run off a single 12V rail
	R	3. Directional Solenoids need 12V drive circuit with on/off control
	G	4. Proportional solenoid needs 12V drive circuit with varying current
	R	5. Solenoid drive circuits must be able to handle a 19W solenoid
	R	6. Input for a hall-effect sensor pulse to monitor speed
	R	7. Input for a 4 mA to 20mA (0psi to 3000psi) signal coming from the pressure sensor for pressure monitoring
	G	8. Serial communication circuitry for 5V serial ttl @ 250000 Baud
	G	9. Be modular
Circuit	**R**	10. Implement circuitry protection i.e. fuses/buffers
	G	11. SD card interface for logging data
	R	12. User input for mode toggle
	R	13. Vehicle status feedback
Software	**R**	14. Process input from the rider
	R	15. Control drive mode by toggling valves
	G	16. Record essential data for analysis
	G	17. Automate proportional flow
	R	18. Automate Pressure Regeneration
	G	19. Maintain a 40 Hz screen refresh rate
	R	20. Process feedback for the rider

Table 18: Specifications

5 DESIGN and FEA ANALYSIS

5.1 FRAME

After selecting our bike frame, a CAD model was created using CREO Parametric which was then used to simulate the overall stress distribution across the bike's frame. The results are displayed below in Figure 6. The maximum Von Mises stress was shown to be 8446.37 psi and a maximum displacement of 0.038 inches, which is within acceptable parameters. The force distribution included a rider weight of 160 lbf, as well as 100 lbf for various components.

Additional FEA tests were performed on individual components and sub-assemblies, including the top frame bracket (Figure 7), the pump and motor braces (Figure 8 and Figure 9), the rear and front left vertical supports (Figure 10 and Figure 11) and the reservoir assembly (Figure 12). The test results for these components were also acceptable. All simulations were done using CREO Simulate.

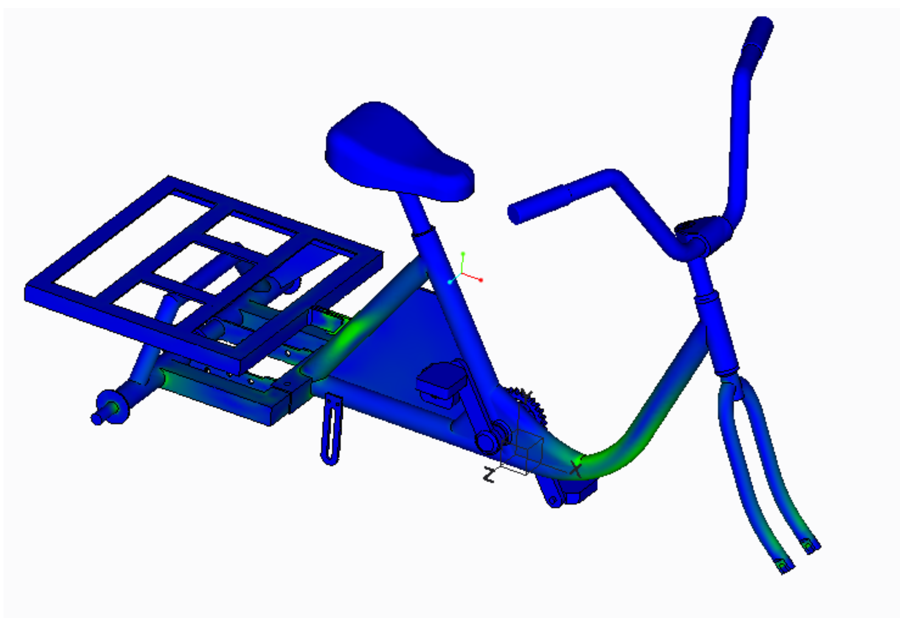


Figure 6: Von Mises stress plot of the frame CAD model

5.2 *BRACKETS & SUPPORT*

Max VM stress= 25,409.9 psi
Max displacement= 0.03019 in

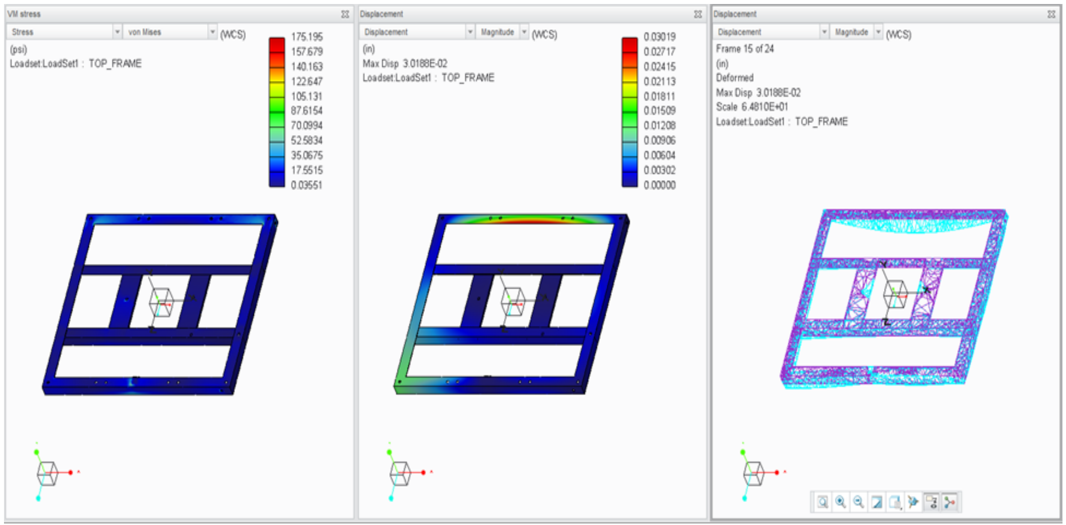
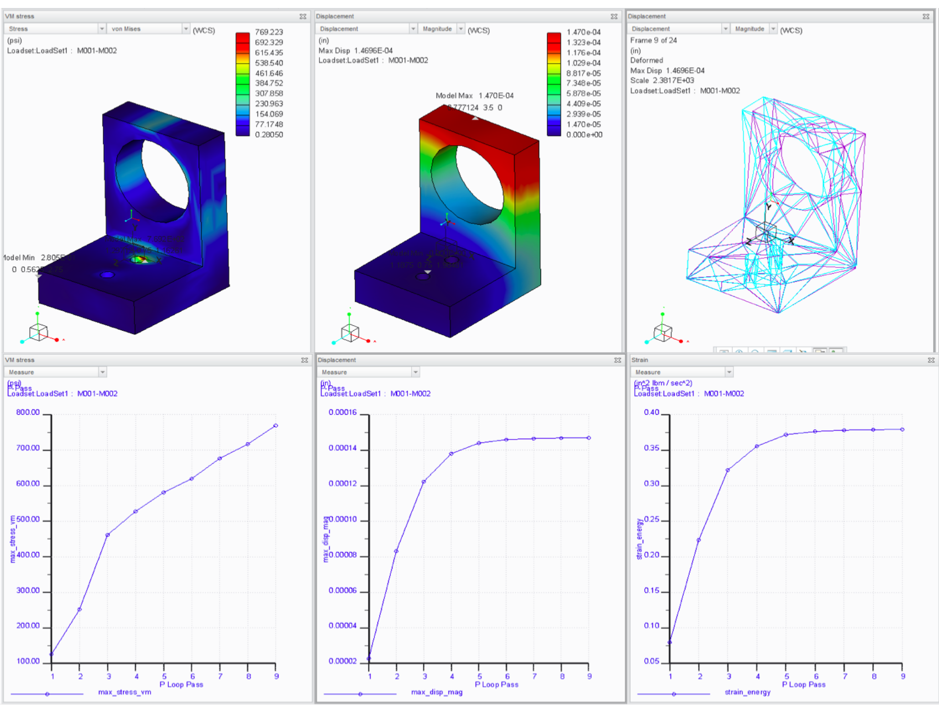


Figure 7: FEA results for the top frame bracket



Max VM stress = 769.223 psi
Max displacement = 1.4696*e-04 in

Figure 8: FEA results for the pump brace sub-assembly

Max VM stress = 464.492 psi
Max displacement = 1.162*e-04 in

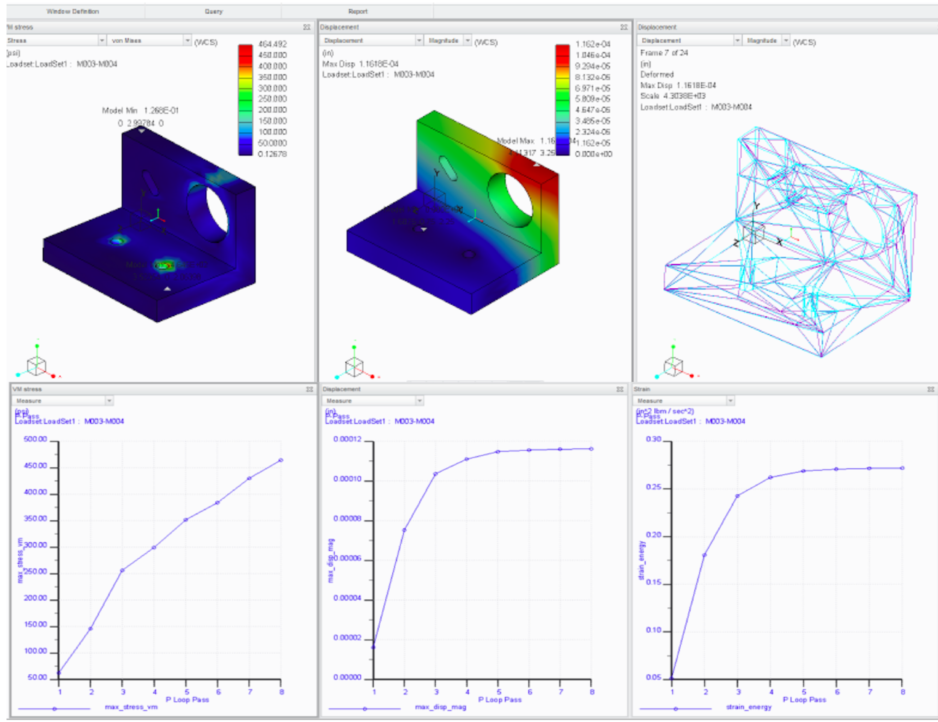
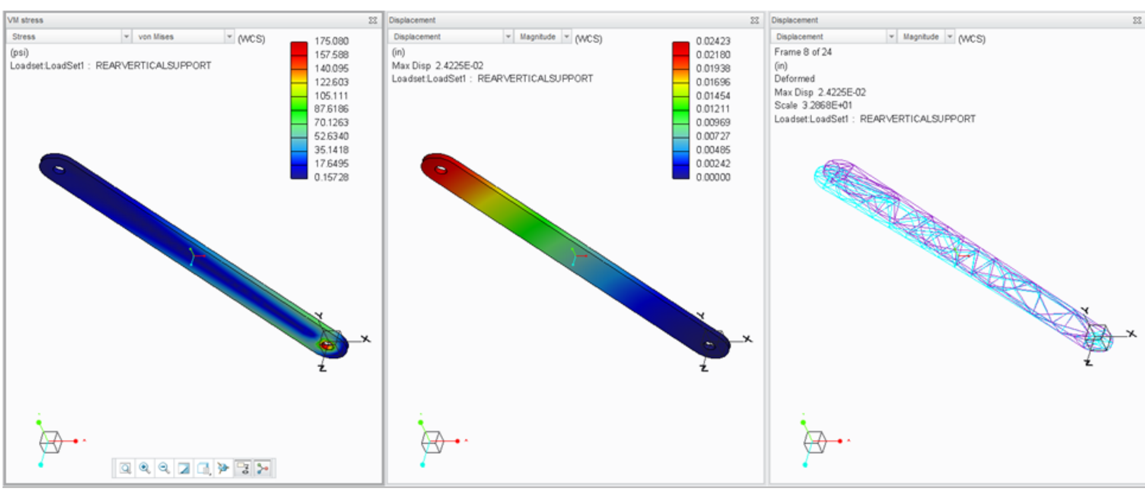


Figure 9: FEA results for the motor brace sub-assembly



Max VM stress = 175.080 psi
Max displacement = 0.02423 in

Figure 10: FEA results for the side frame supports

Max VM stress = 339.207 psi
Max displacement = 0.05668 in

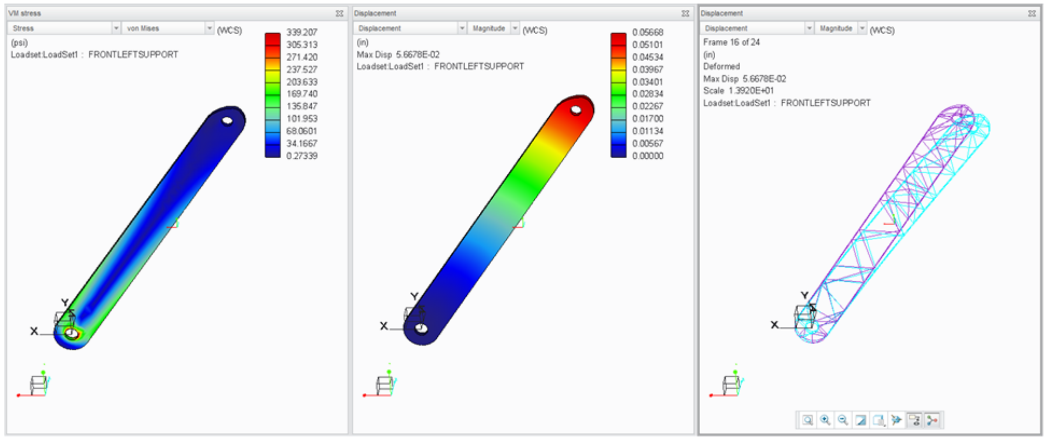
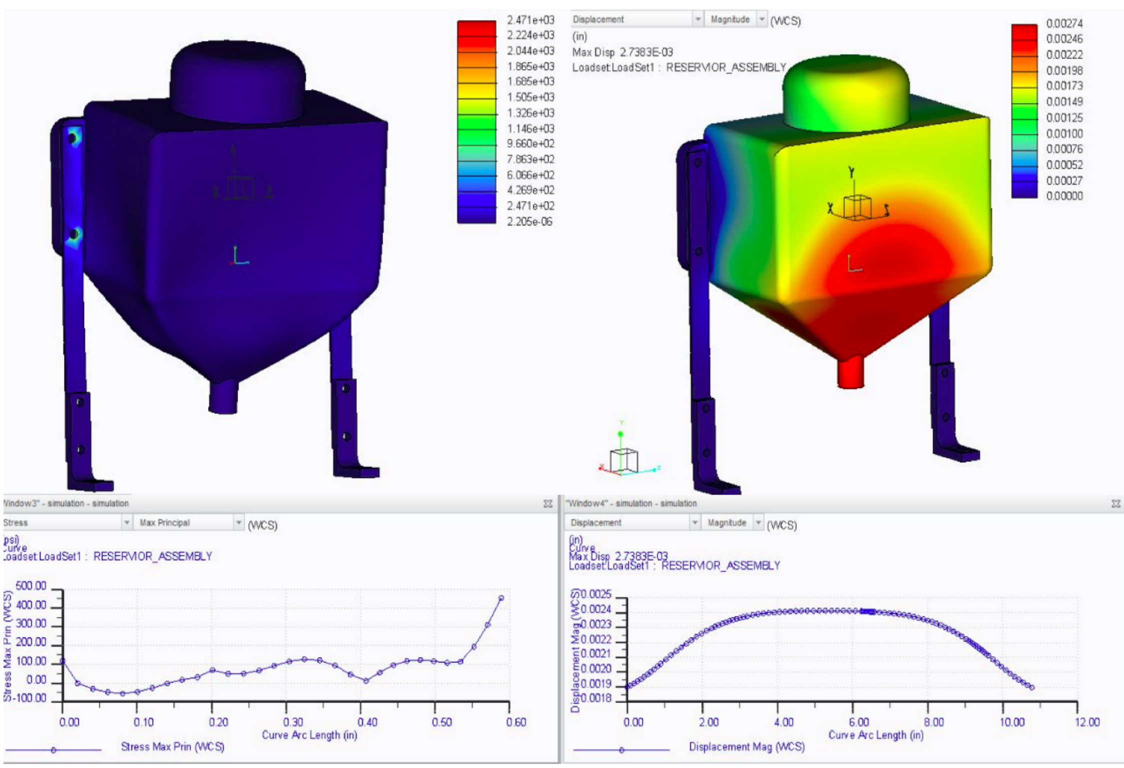


Figure 11: FEA results for the side frame supports

5.3 RESERVOIR



Max VM stress = 2.471*e03 psi
Max displacement= 2.740*e-03 in

Figure 12: FEA results for the reservoir sub-assembly

5.4 HYDRAULIC DIAGRAM

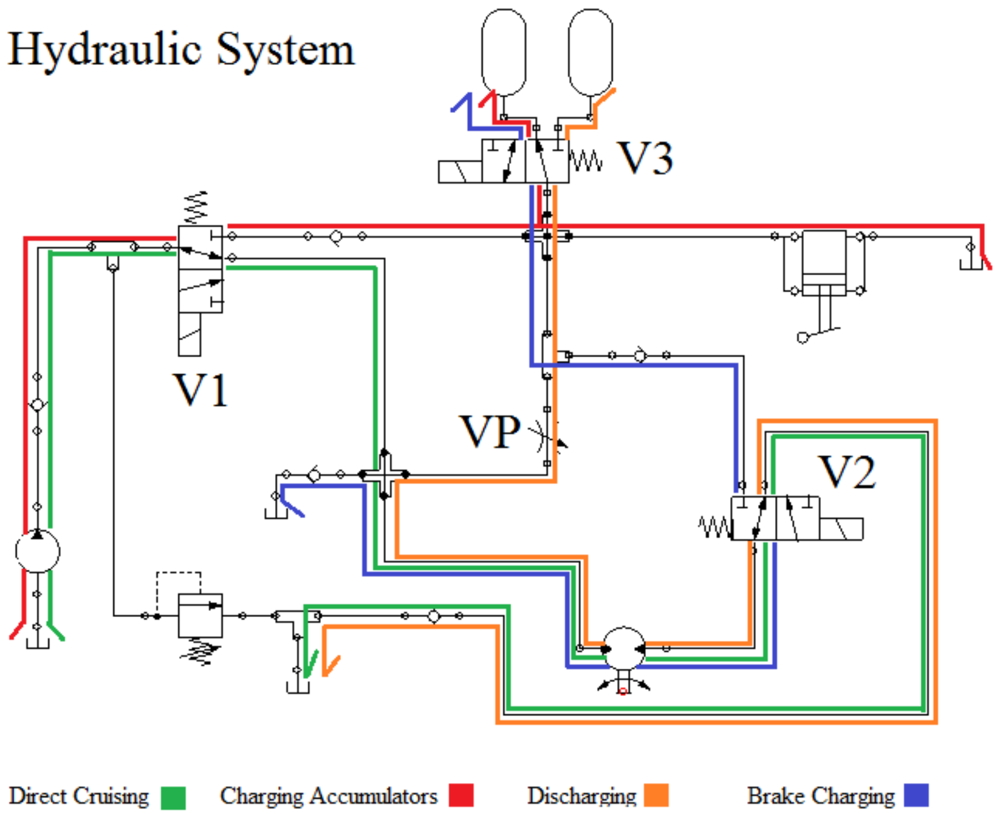


Figure 13: Circuit Diagram

The hydraulic system will consist of four functions, as displayed in the Figure 13 above. The default function will be direct cruising, where the flow will go directly from the pedal pump to the wheel motor. The second function will be to charge the accumulators. The accumulators can be charged by either the pedal pump or the manual hand pump. The hand pump will be used when the accumulator pressure gets too high for the rider to charge using the pedals. The third function is to discharge the accumulators to the wheel motor. This function mainly relies on a proportion valve controlling the flow between the two components. The final function is to charge the accumulators by capturing the momentum of the bike and turning it into potential energy. For this function, the wheel motor, used as a pump, is spun by the wheels and the flow is directed back to the accumulators.

5.5 CONTROL SYSTEM DESIGN

To meet the specifications listed in Table 19, the design effort focused on 8 components: the primary controller; secondary controllers; user interface; data logging; directional solenoid valve drive circuitry; proportional valve drive circuitry; pressure sensor circuitry; and speed sensor circuitry. Figure 14 below illustrates a block diagram showing how this new system is designed to work. The table shows how each specification is accounted for in the block diagram. In the sections following, the different components and their design will be discussed.

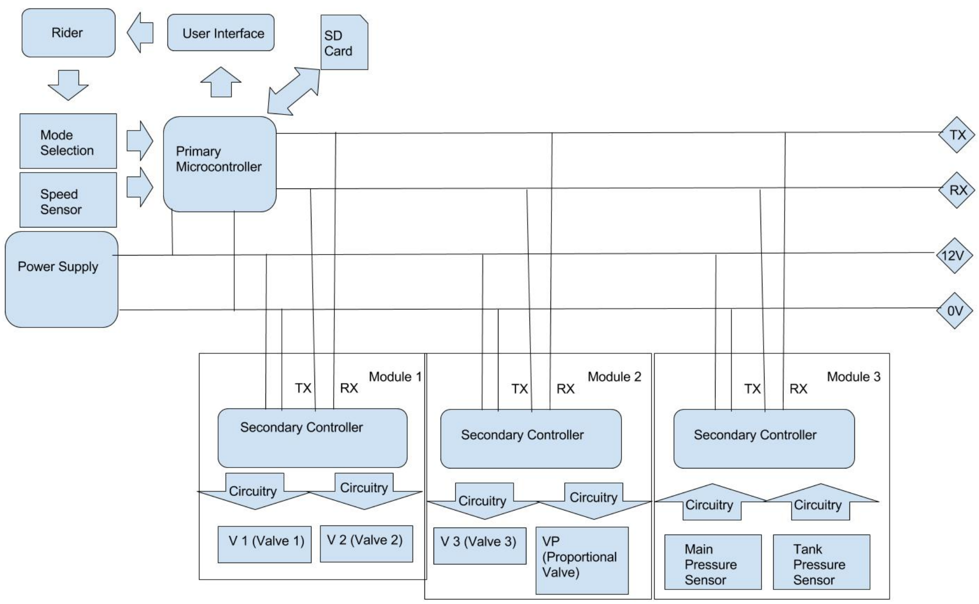


Figure 14: 2017 Proposed Fluid Power Vehicle Control Block Diagram

Specification	Addressed by
2	The power supply provides a 12V rail to each module and the primary controller enclosure.
3	Modules 1 and 2 handle the logic control for the 3 directional valves. The integrated drive circuitry converts the logic level to 12V control.
4	Module 2 provides the variable output to control the proportional valve. The same drive circuitry as the directional valves converts the logic level to 12V control.
5	All components selected allow for proper current flows.
6	The primary controller will read the pulse from the speed sensor. The drive circuitry is entirely in the speed sensor enclosure
7	Module 3 handles the input for the pressure sensors. The integrated circuitry converts the variable current to variable voltage
8	Not shown, but the Logic Level Shifting occur in the primary controller enclosure which ensures 5V is the standard for all TX and RX lines.
9	Using the network of controllers and integrated drive circuitry allows hot swapping of controllers and drive circuitry in the event of failure.
10	All circuitry uses 1 MΩ resistors to buffer controller inputs/outputs; and where appropriate, Positive Temperature Coefficient Fuses to protect other components. Diodes also play a role in the valve drive circuitry stopping back current
11	A micro SD card interface was purchased and attached.
12	Mode Selections is made through E-Bike Controls
13	The display provides the status of the vehicle
14-20	The primary controller performs most of the processing for these specifications
15	Based on commands from the primary controller, the secondary controllers in Modules 1 and 2 toggle the necessary valves.
16	The secondary controllers provide readings related to the status of their devices for the primary controller to record
17 & 18	Module 2 alters the flow rate of the proportional valve based on the primary controller's commands.

Table 19: Proposed Block Diagram Connection to Specifications

5.5.1 Primary Controller

The most important component of this project is the primary controller. This device is where all the automation occurs, all of the user interface is processed, and also chose the development environment for the project. The controllers being considered were the STM32F4 Discovery used last year, the Arduino Mega 2560, and the Arduino Due. The primary factors considered were usability, number of external interrupts available to the chip, processing speed, cost, shape and size of the controller, as well as the weight of the device. Table 20 gives each device a score after factoring in the importance of each factor and the score in that category.

Table 20: Microcontroller Decision Chart

Weight	Characteristic	STM32F4	Mega 2560	Due
10	Usability	3	5	5
9	Interrupts	5	3	4
8	Speed	5	1	4
7	Cost	5	3	3
6	Form	3	5	5
5	Weight	3	5	5
Totals		183	161	194

Based on the evaluation criteria, the Due was the best option. The Arduino platform is very easy and user friendly allowing more time to be spent analyzing data than setting up the controller which gave the Mega and the Due an edge over the STM32F4. Both the STM32F4 and the Due are ARM based architectures giving them both lots of external interrupts, similarly they both have higher clock speeds. While the STM32F4 is almost half the price of the Due and Mega, $40 for the primary microcontroller is still reasonable when compared to its importance. Another advantage for the Arduino platforms is there are many screens that are designed to just connect to the headers of the microcontrollers and work. In addition, these screens are generally in the same development environment as the microcontrollers stopping the group from having to learn another development language. Due to weight of the system being a concern, the weight of each board was assessed. Both the Due and the Mega are approximately half the weight of the STM32F4, which is already very light, still pushed the team to picking the Arduino Due.

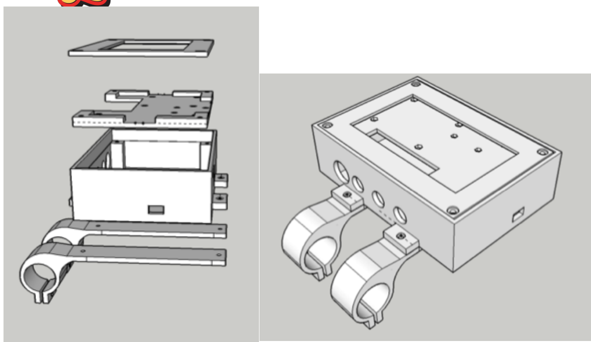


Figure 15: 2017 Primary Control Enclosure Model

5.5.2 Secondary Controller

To improve reparability and making the system more modular, the design created a network with one primary controller and several secondary controllers. The selection of the secondary controller came down to one factor: what was the smallest controller in the selected development environment? The answer was the Arduino Pro Mini. The problem with using these two controllers is that they do not have the same logic levels. To address this a logic level shifter circuit was considered using mosfets and pull up resistors but was going to be large and take up more space. So, a simple voltage divider using two resistors was used on the Mini TX and a buffing resistor was used on the Due TX. Figure 16 shows this circuit. Figure 17 is the response of the circuit verifying phase and levels, note that TXD, RXD, TXM, and RXM correspond to TX on the Due, RX on the Due, TX on the Mini(s), and RX on the Mini(s) respectively. This circuitry is in the primary controller enclosure to help keep the secondary enclosures as small as possible.

However, even though the secondary controllers were initially designed to utilize the Arduino Pro-Mini controllers, the designs were required to change. In December, a pack of Arduino Pro-Minis was ordered which never arrived. In order to progress, the Pro-Minis or a similar substitute was needed. Since Pro-Minis were not available from a distributor who could ship them in a timely fashion, the Arduino Nano microcontroller was ordered instead. Because both the Nano and the Mini are based on the Arduino Uno's architecture, this was a very logical step to make. The key differences between the two microcontrollers are their size (the Nano is a rectangular 0.73" by 1.70", while the Mini is a bit smaller 0.7" by 1.3") and the fact that the Nano has a USB port while the Mini does not.

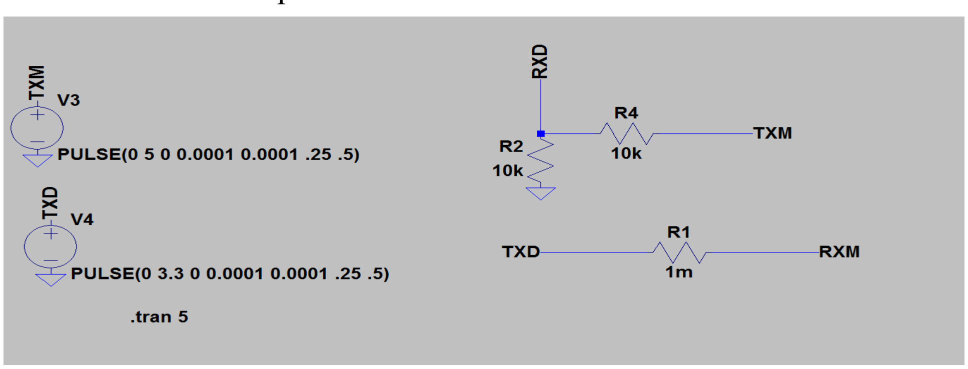


Figure 16: Logic Level Shifter Circuit

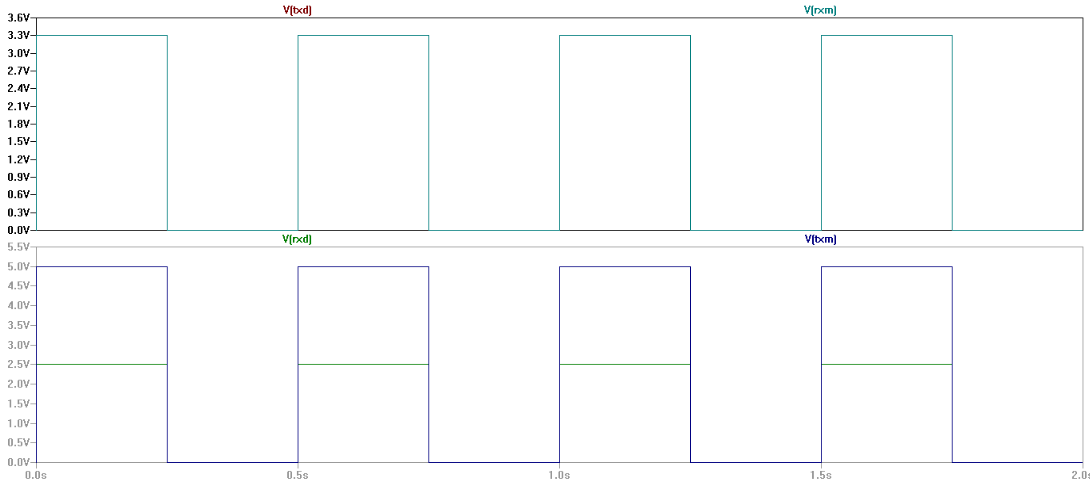


Figure 17: Logic Level Shifter Circuit Response

5.5.3 User Interference

A user should be able to operate a vehicle without having to think about where the controls are or find themselves guessing what a button will do, especially in an emergency. This year the design will implement e-bike controls which will aide in the ergonomic and intuition factors of the controls to help reduce the reaction time of the user as well as reduce the amount of time the user needs to look away from their path of travel. These e-bike controls are how the design meets specification 12. Like last year, the UI still includes a screen for detailed readouts, but the graphics have been dropped for simplicity. For comparison, the controls for the 2016 vehicle are pictured in Image 12.

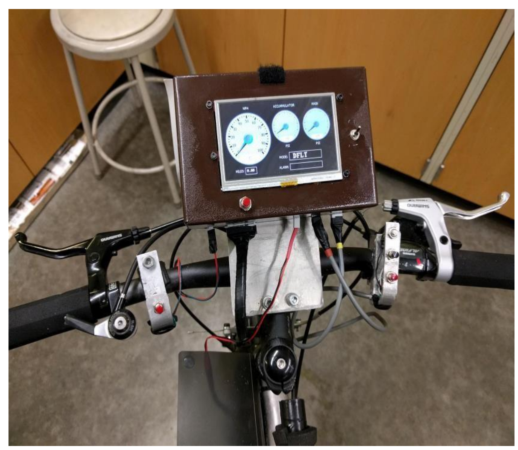


Image 12: 2016 User Interface

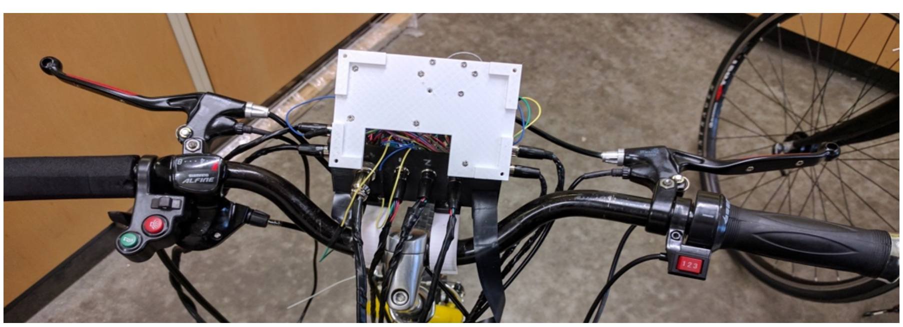


Image 13: 2017 User Interface Design

5.5.4 Data Logging

To better analyze the performance of the vehicle this year, the design implemented an SD card interface. The hardware design implemented and tested this but the software side was unable to accomplish this in the allotted time.

5.5.5 Directional Solenoid Valve Drive Circuit

To control the directional solenoid valves, the 5-volt logic of the Arduino Mini will need to energize and de-energize 12V across the solenoid. The easiest way to do this is to use a MOSFET to float and connect the ground. According to the datasheet, the S520N-H12-4W valve uses the C16 solenoid which is a 19 Watt solenoid. To find the resistance and the inductance of the solenoid the steady state must be analyzed:

$$I = \frac{P}{V} = \frac{19Watts}{12V} = 0.6315789\,A$$

$$R = \frac{V}{I} = \frac{12V}{0.6315789A} = 19.00000\,\Omega$$

The time constant was not listed on the specifications for the directional valve however, the proportional valve selected for this project (PFR21H-N-6-H-12-3W) uses the same solenoid and has a response time of 80ms. For simulation purposes the transient time was assumed to be 80ms which can be used to find the time constant and then the inductance of the solenoid.

$$\tau = \frac{.08s}{5} = 0.016s$$

$$L = \tau * R = 0.016s \, * \, 19.00000\,\Omega \, = \, 304mH$$

A baseline transient simulation for the solenoid was obtained using the parameters calculated. The result can be seen in Figures 18 and Figure 19.

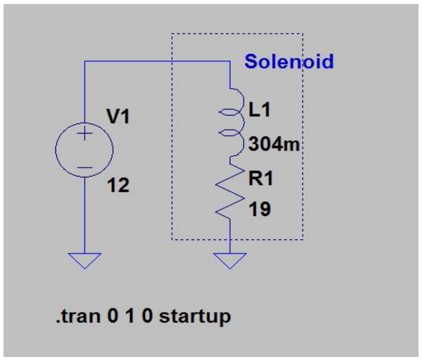


Figure 18: Simple Solenoid Coil Based on Specs

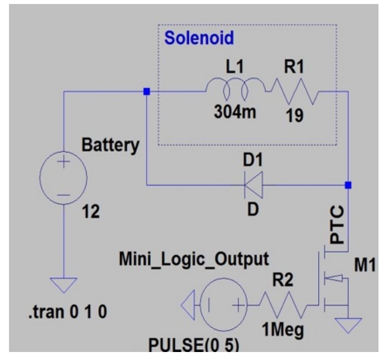


Figure 19: Proposed Solenoid Valve Circuit

To control the circuit, a MOSFET was added to the ground node on the solenoid side, a fly back diode was paralleled with the solenoid, a Positive Temperature Coefficient (PTC) fuse will be added between the solenoid and the MOSFET, and a 1 M*Ω* resistor was added to buffer the simulated Mini logic output as illustrated in Figure 19 with the resulting step response current in Figure 20 and on/off/on/off cycle in Figure 21.

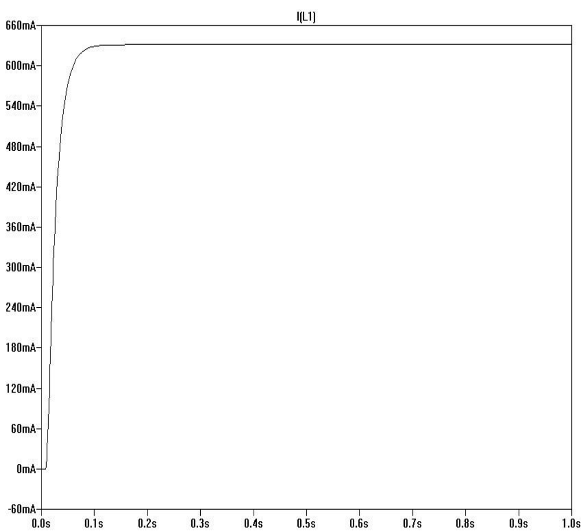


Figure 20: Step Response of Solenoid Drive Circuit

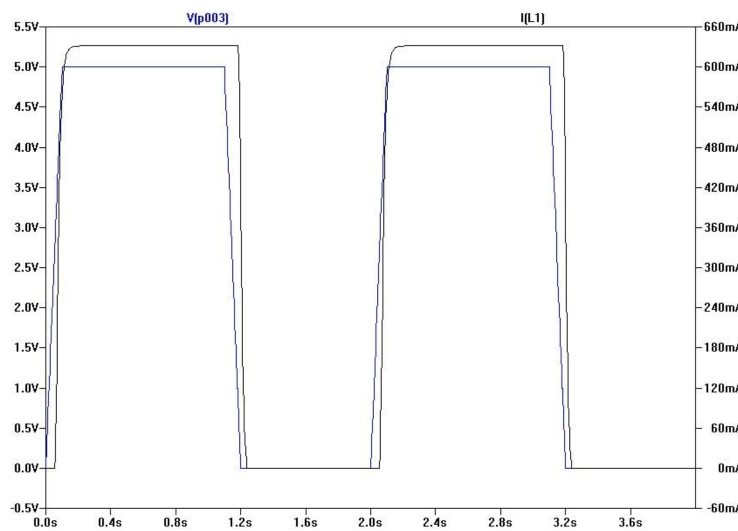


Figure 21: Dual Pulse Response Solenoid

The drive circuitry responds to the logic signal in simulation as expected. The on/off drive meets specification 3 while implementing the PTC fuse protects the MOSFET and the 1 MΩ resistor protects the output of the Mini which meets specification 10. Specification 5, while related, will not be assessed until the components are selected and tested. Modules 2 and 3 will both have this circuit integrated into them.

5.5.6 Proportional Solenoid Drive Circuit

The same circuit will be implemented in proportional control due to the solenoid coil being the exact same model. For this circuit, a Pulse Width Modulation (PWM) with varying duty cycles will be introduced. Figure 22 shows the current through the solenoid between 37.5% and 40% duty cycles with .5% intervals at 200 Hz (the recommended operational frequency).

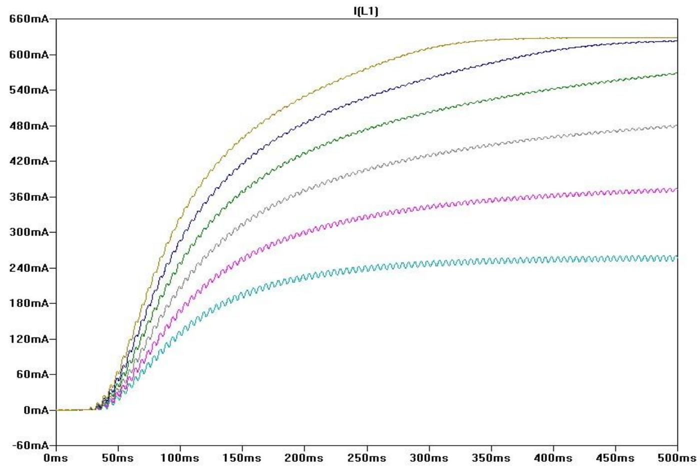


Figure 22: 200 Hz PWM Response of Solenoid Drive Circuit

While the signal still has some oscillations, the average current for each duty cycle increases as the percentage increases. This may need to be damped, but without the devices available, it is uncertain if this will be stable enough for smooth performance. The high end of the recommended operating frequency was 400 Hz and the result of the circuit excitation at 400 Hz can be found in Figure 23. It was found that the duty same duty cycles gave approximately the same current range through the proportional valve, only with less oscillation.

In addition to controlling a proportional valve, running a PWM and adjusting the duty cycle of the directional valves could reduce their current demand and save on battery life.

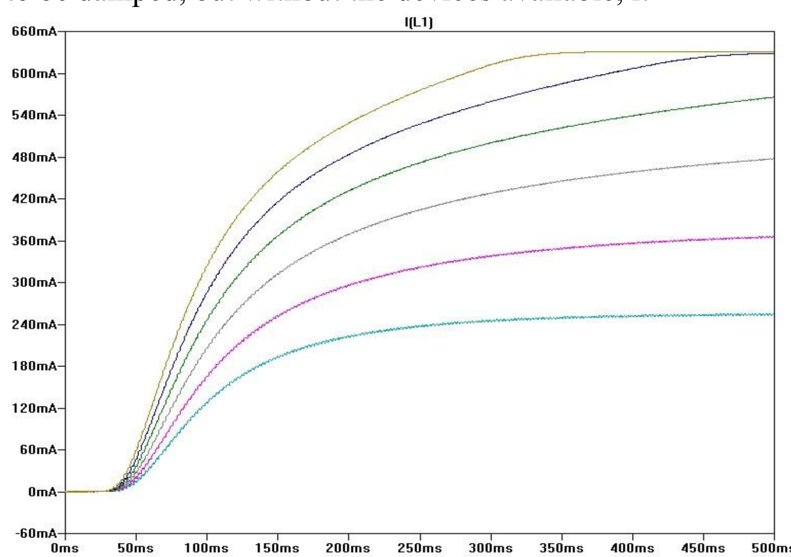


Figure 23: 400 Hz PWM Response of Solenoid Circuit

5.5.7 Pressure Sensors

To monitor the pressure of the system and meet specification 7, a series of SCP01-3000p-25-07 pressure sensors were to be tied into the hydraulic lines. These pressure sensors output a current from 4mA to 20mA indicating 0-3000 psi. In Figure 24, the sensor was modeled as a current source that varied from 0.4mA to 20mA to see the response of the system. The controller input was to be buffered with a 1 MΩ resistor and a diode was to help set a maximum safe voltage. Since the Arduino Pro Mini operated in the 0-5V range, R1 needed to be a resistance that when multiplied by the maximum current does not exceed 5V.

$$\frac{5V}{20mA} = 250\Omega$$

Since this is not a standard resistance, 240Ω is close enough and keeps the signal voltage below 5V. Figure 24 shows the circuit and Figure 25 shows the response. According to the sponsors, last year's vehicle did not use more than ~1500 psi. Because of this, a potentiometer was used for R1 which allowed the option of a higher resolution to be used on the analog read function vs pressure.

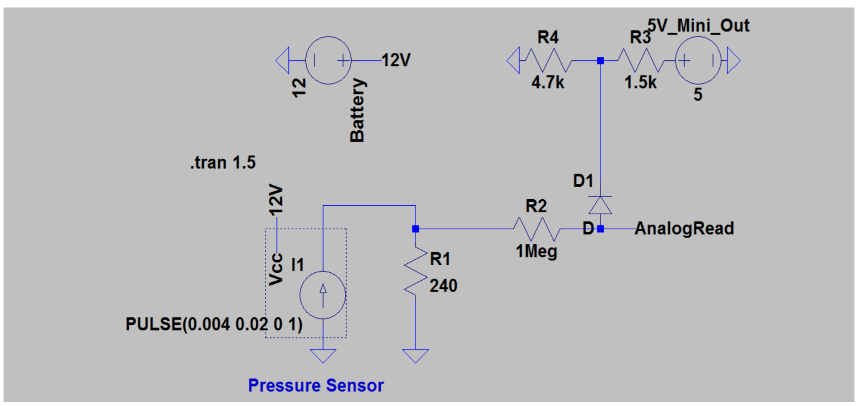


Figure 24: Pressure Sensor Circuit

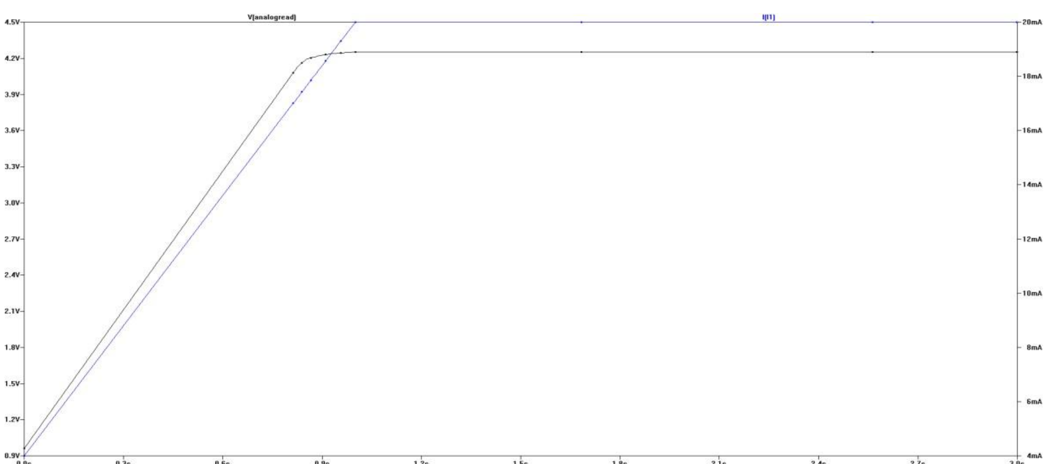


Figure 25: Pressure Sensor Circuit Response to Varied Current

Each secondary controller has the capability of monitoring six analog voltages and currently the design only calls for two sensors, but the goal is to monitor three (drive, accumulator 1, and accumulator 2). According to the sponsors, last year's vehicle did not use more than ~1500 psi, because of this, a potentiometer will be used for R1 which will allow a higher resolution to be gained on the analog read function vs pressure.

5.5.8 Speed Sensors

The hall-effect sensor being used to detect wheel rotation/speed will output a high voltage (12V) when no magnetic field is present and low when a magnet passes in front of it. Because the speed sensor will be connected to the Due, the high voltage cannot exceed 3V3. To do this, a voltage divider will be added to the recommended circuit from the A1469 hall-effect sensor datasheet. Figure 26 depicts the circuit to feeding the Due.

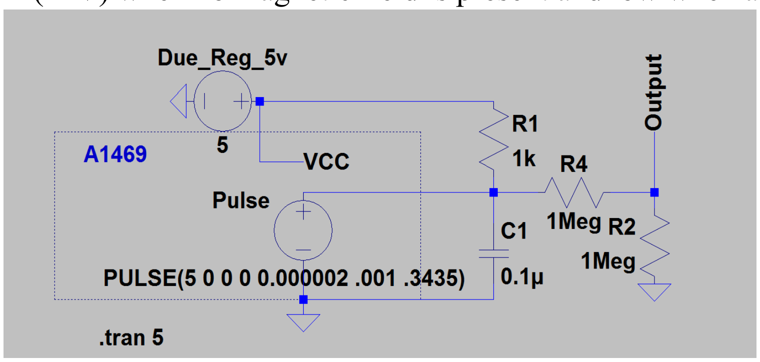


Figure 26: Hall-Effect Sensor Circuit

When no field is present the output node is: $5\ V * \frac{1{,}000{,}000\ \Omega}{2{,}000{,}000\ \Omega} = 2.5\ V$

The simulated results can be seen in Figure 27, they can be viewed as 2 magnets on a 24" wheel at 15 mph or 1 magnet on a 24" wheel at 30 mph.

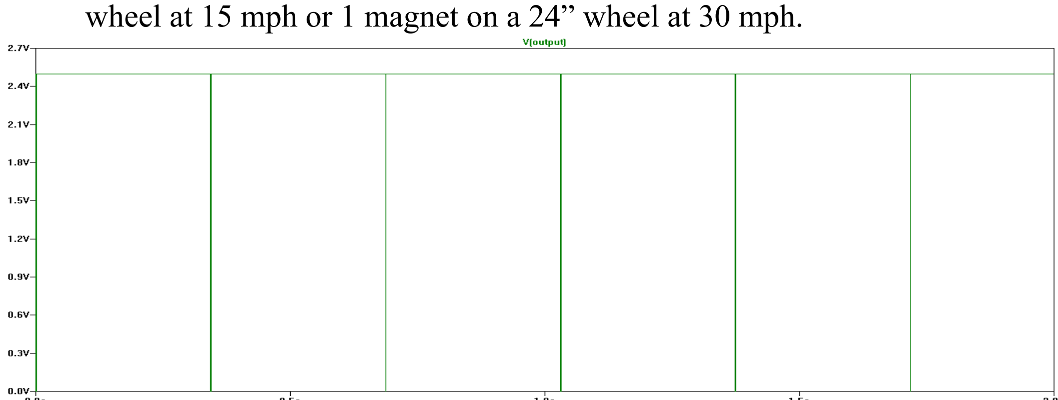


Figure 27: Simulated Hall-Effect Circuit Response

This sensor circuitry allows the design to meet specification 6.

6 DESIGN DRAWINGS

This year, our team built several mounts, brackets, and supports for the placement of our system components. The parts were created in house in our Student Shop at the College of Engineering & Applied Sciences with material donated by advisors and other local companies. Most the brackets were created on aluminum to create a high resistance and light weight to our vehicle.

One our team members fabricated the majority of the fabrication process, but another member was in charge of the CAD modeling of the entire bike including brackets, hoses, and other components. In this manner, the CAD designer had to create every single drawing or documentation of the part that was going to be fabricated so that the fabricator could build the requested parts without interrupting any other process.

The following are some design drawings of brackets and supports designed and fabricated by our team.

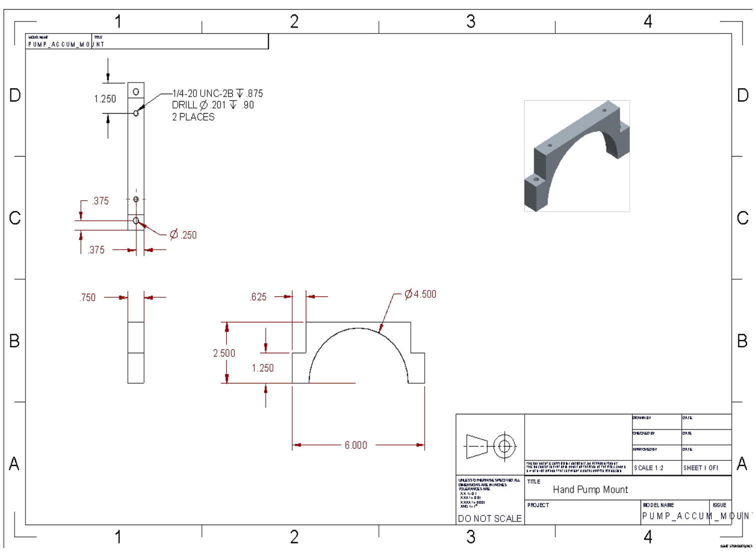


Figure 28: Pump mount drawing (Top)

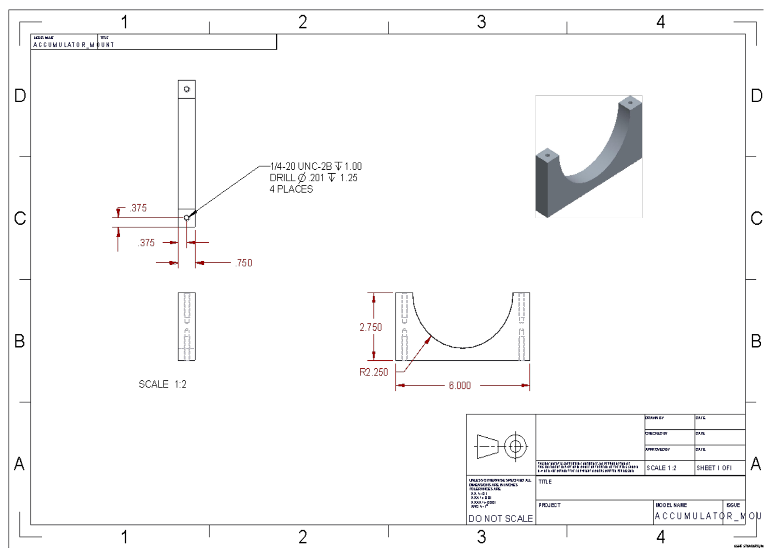


Figure 29: Pump mount drawing (Bottom)

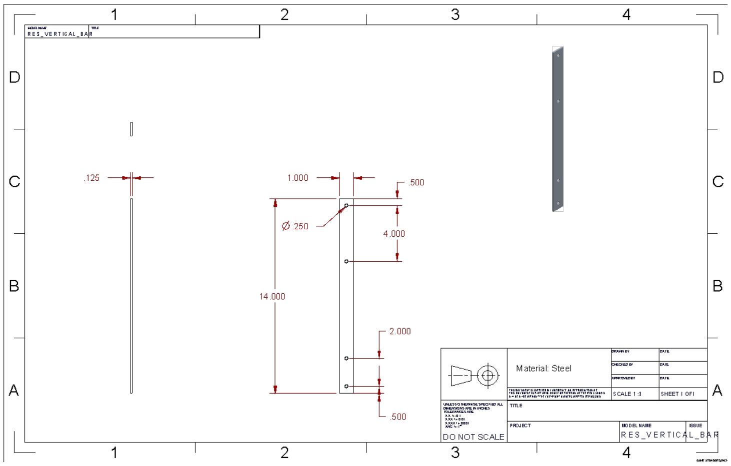


Figure 30: Reservoir vertical bracket

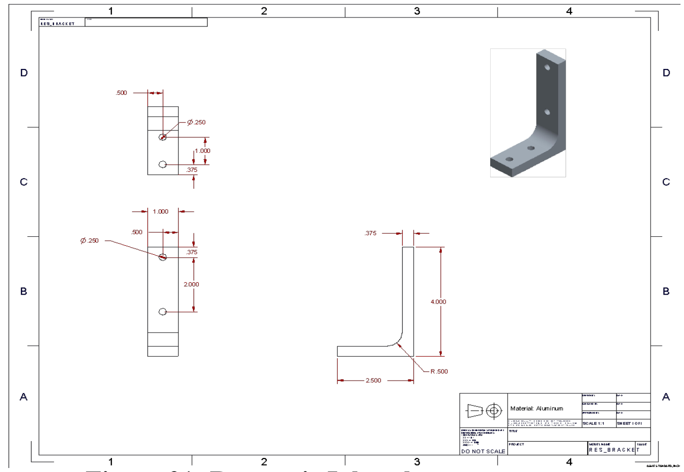


Figure 31: Reservoir L bracket connector

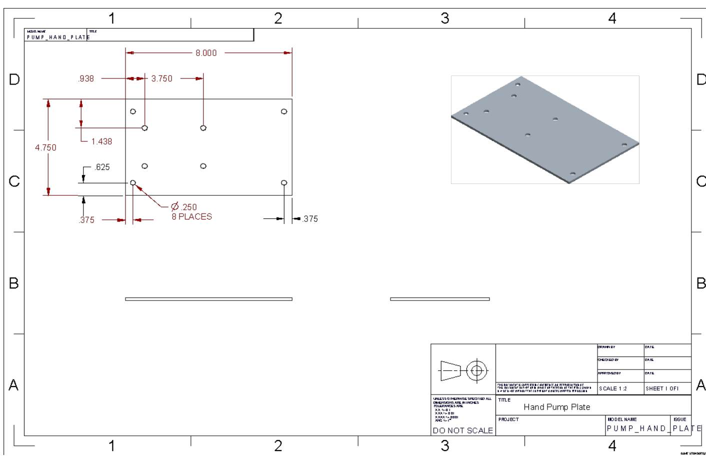


Figure 32: Bottom support for hydraulic system

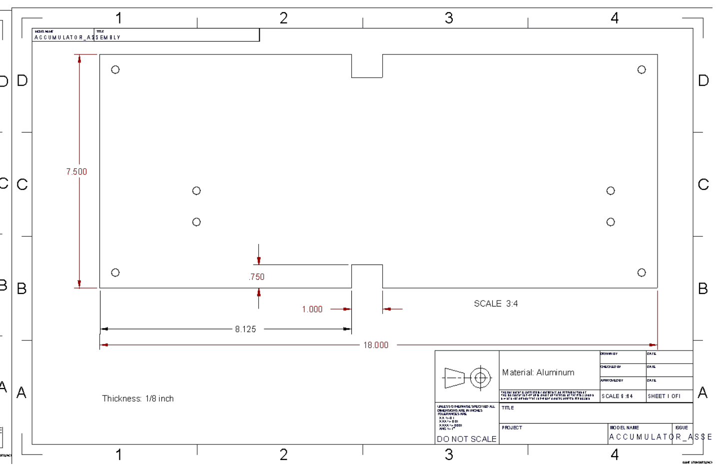


Figure 33: Bottom support for mechanical system

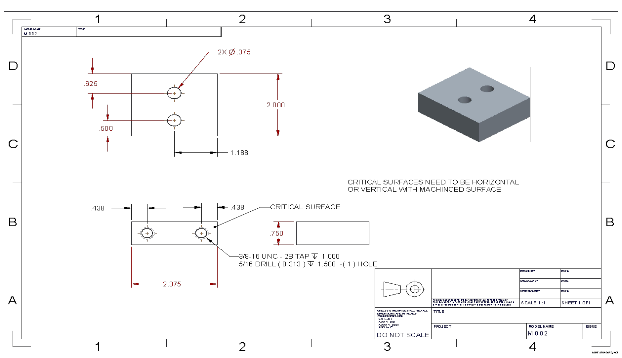


Figure 34: Horizontal support for hub

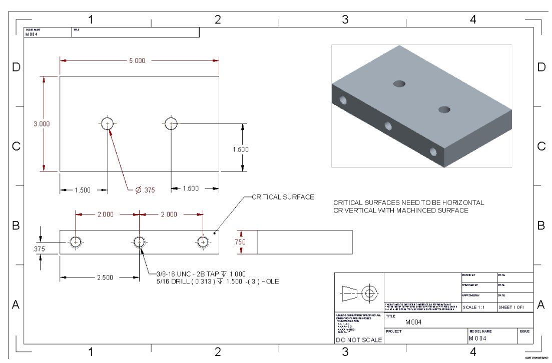


Figure 35: Horizontal support for gears

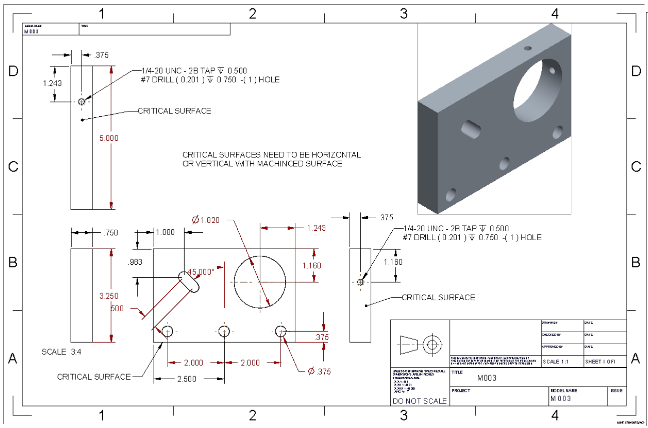


Figure 36: Vertical support for hub and motor

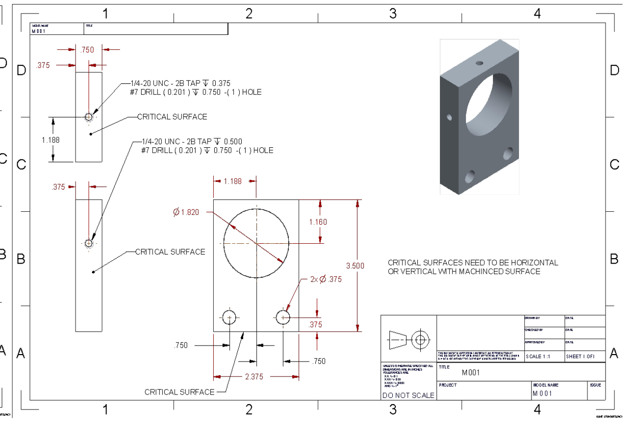


Figure 37: Vertical support for pump

6.1 FABRICATION

Image 14: Bottom Support

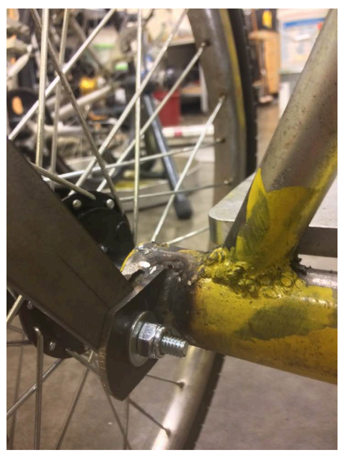


Image 15: Welded piece

Image 16: Connection bracket

Image 17: Vertical connection

Image 18: Accumulator support

7 IMPLEMENTATION OF MANIFOLD

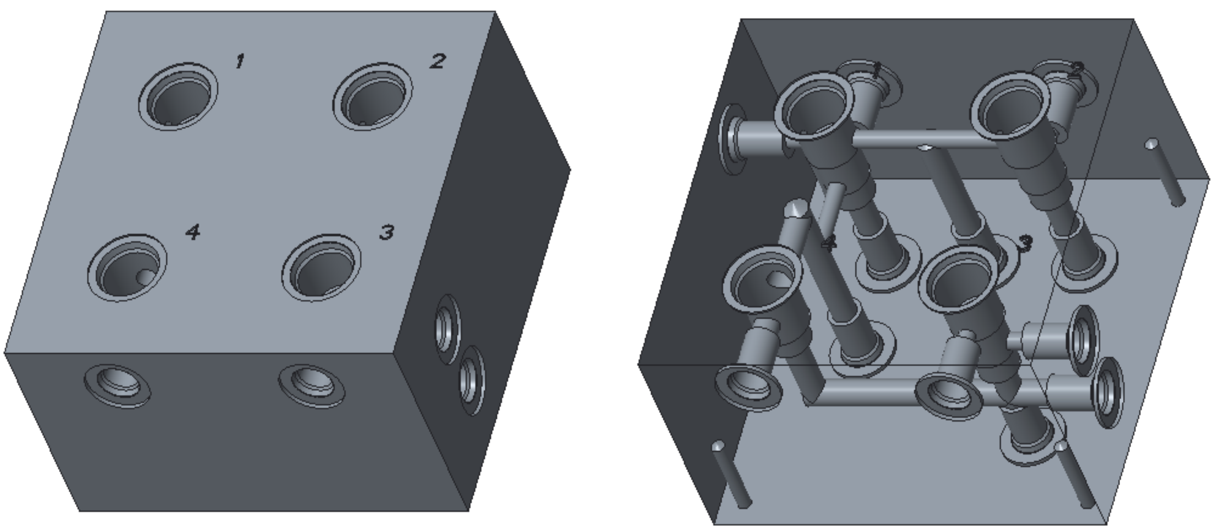


Figure 38: Exterior & Interior of Manifold Design

Due to the number of valves required to control the hydraulic system, excessive amounts of fittings and hoses would be required. Given our limited space, it would have been very difficult to connect all of the valves neatly with the large C-10 bodies they came with. This would also have made the wiring more cluttered because the wires would have to spread to disperse locations. To solve this issue, a custom manifold was implemented to condense and centralize all flow control devices.

The manifold's primary design focus is to cover the direct connections between the valves. Since the internal construction holes require an entry point, it is best to place the holes so that they coincide with fitting connection ports. Any construction hole made that doesn't coincide with a fitting port would have to be plugged and would cause dead space in the manifold. Due to many interconnections between the valves, a linear 4x1 design was deemed not feasible due to excessive amounts of construction holes and plugged ports required. A square 2x2 configuration proved to be more direct with less machining operations required. The final manifold has 12 ports total; 8 for fitting connections, 1 for a pressure sensor, leaving only 3 ports plugged.

The manifold is place in the back of the upper frame, between the two accumulators and above the open space behind the drive train. The ports on the manifold are specifically place so that they face the general direction of the component that they are connected too. All ports related to the pump and motor below are on the bottom of the manifold. The accumulator ports are towards the rear so that to correspond with the accumulator connections. The reservoir return port faces forward and connects with the line from the relief valve; meaning only one hose is required to reach the top of the reservoir.

7.1 FINITE ELEMENT ANALYSIS

As shown in figure 37, the areas shaded in yellow are the sections of the system that are covered or connected to the manifold.

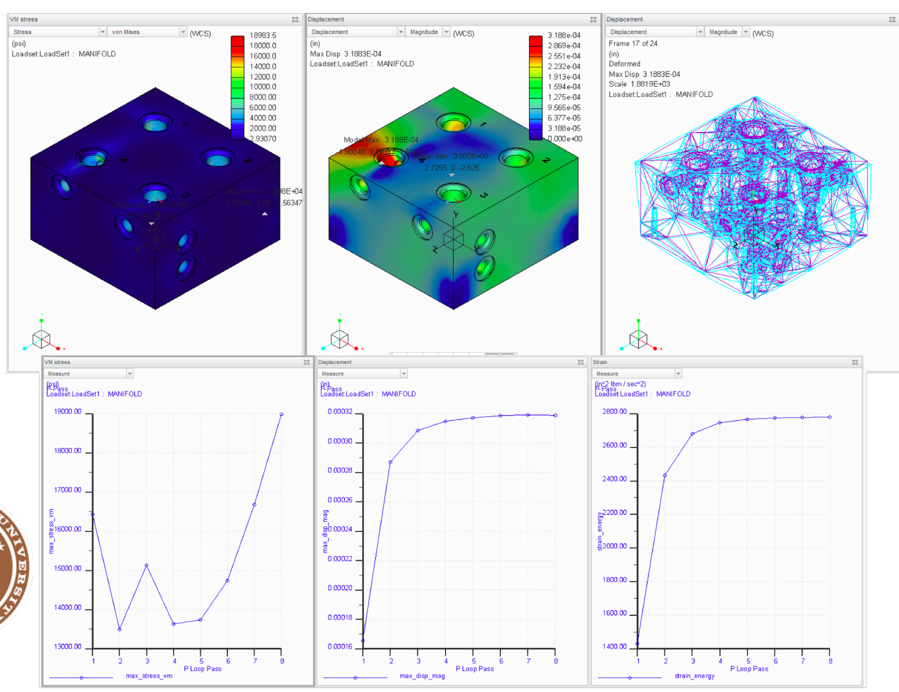


Figure 39: FEA results of manifold

Max VM stress = 18983.5 psi
Max displacement = 3.188*e04 in

7.2 DESIGN DRAWINGS

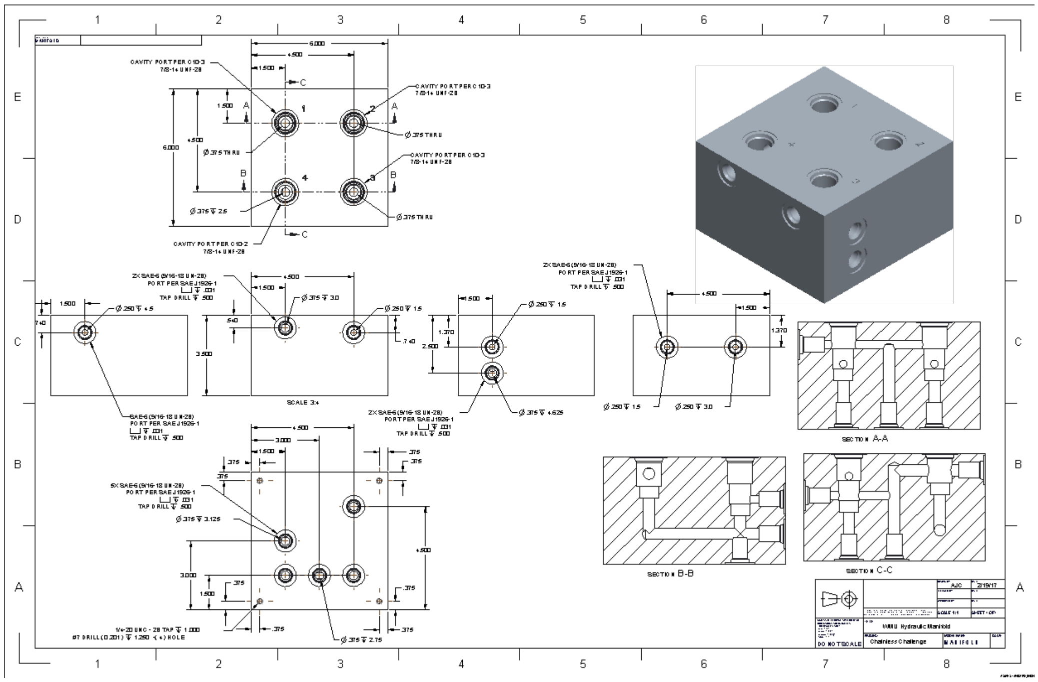


Figure 40: Manifold design drawing pre-production

8 COMPONENT LIST

The following Table is a comprehensive list of all the components used in building the 2017 bicycle. A total of 266 parts were counted, and it is a very good estimate from the design process. A higher count is very likely because several adjustments were required once initial testing was performed. At that point there were several modifications, mostly in the hydraulic and electric circuits.

Table 21: List of Components

Item #	Component name	Description	Qty.
Hydraulic Components			
1	AM1C-31	Hydraulic Pump	1
2	AM1C-31	Hydraulic Motor	1
3	915-8D27	Manual Pump	1
4	Eaton Vickers SV1-10	Directional Valves	3
5	JEM Technical SP10	Proportional Valves	1
6	FPR3/8-0.5	Check Valves	5
7	TOBUL4.5AL-20	Accumulators	2
8	2.5 Gal Polypropylene Tank	Reservoir	1
9	RDH081	Pressure Release Valve	1
10		Pressure Sensor	2
11	915-8D27	Auxiliary hand pump	1
12	C51130	Manifold (6"x6"x3.5")	1
		System Total	**20**
Mechanical Components			
13	Shimano Alfine 8 Speed	Front Gear Hub	1
14	Sram I-3	Rear Gear Hub	1
15		8" Spur Gear	1
16		10" Spur Gear	1
17		5" Spur Gear	1
18		3" Spur Gear	1
19		2" Spur Gear	1
20		30" rear axle	1
21		Tricycle Frame	1
		System Total	**9**
Electrical Components			
22		Arduino Due	1
23		1M Resistor	20
24		Diode	10
25		NMOS	10
26		Mini XLR 2pack	10
27		Large Connector	1
28		Brakes	1
29		Mode Switch	1
30		Toggle/momentary switch	1
31		PTC fuse	10
32		Potentiometer	2
33		4.7K Resistor	2
34		1.5K	2
35		10k Resistor	1

36		1K Resistor	1
37		0.1uF Capacitor	1
38		3.3K Resistor	1
39		3 Color LED	5
40		10K Resistor Bar	2
41		Hall-effect Sensor	1
42		M3 Screws	1
43		M1.6 Screws	1
44		Arduino Nano	2
45		Rubber inserts	1
46		Battery	1
47		Screen	1
48		RA8875 Interface	1
49		Micro SD interface	1
50		PCB	1
		System Total	**93**
Fabricated Parts			
51	Pump Mount (top)	1/2" Aluminum mount	1
52	Pump Mount (bottom)	1/2" Aluminum mount	1
53	Reservoir Vertical Bracket	1/4" x 14"	2
54	Reservoir L bracket	4" x 2.5"	1
55	Bottom Support hydraulics	8" x 4.5"	1
56	Front Gear Support	1/4" thick	1
57	Rear Gear Support	1/4" thick	1
58	Hub & Motor Support	3.250" x 5"	1
59	Pump Support	3.5" x 2.375"	1
		System Total	**10**
Hardware			
60		1/4" bolts	10
61		1/4" hex nuts	30
62		1/4" washers	30
63		1/4" zinc washers	4
64		3/8" zinc washers	10
65		3/8" Zinc bolts	12
66		1" bolts (10-24x)	8
67		1" bolts (6-32x)	6
68		5/16" washers	10
69		1/4" x 1" set screw	4
70		1/4" x 3/4" zinc bolts	4
71		1/4" x 1 1/2" bolts	6
		System Total	**134**

8.1 COST ANALYSIS

This section presents the cost analysis of our vehicle, as regards to the prototype fabricated for the competition, and as production of 500 units. This new product could be launched in the market as a human assisted green energy vehicle based on hydraulic power and motion controls capable of performing well while sprinting, stop-go, and regular riding conditions.

Table 22: Cost of Components and Labor

Item #	Component name	Description	Qty.	Unit Price	Subtotal	Labor Hours	Labor Cost
Hydraulic Components							
1	AM1C-31	Hydraulic Pump	1	$ 800	$ 800	0.00	$ -
2	AM1C-31	Hydraulic Motor	1	$ 800	$ 800	0.00	$ -
3	915-8D27	Manual Pump	1	$ 250	$ 250	0.00	$ -
4	Eaton Vickers SV1-10	Directional Valves	3	$ 160	$ 480	0.00	$ -
5	JEM Technical SP10	Proportional Valves	1	$ 160	$ 160	0.00	$ -
6	FPR3/8-0.5	Check Valves	5	$ 60	$ 300	0.00	$ -
7	TOBUL4.5AL-20	Accumulators	2	$ 850	$ 1,700	0.00	$ -
8	2.5 Gal Polypropylene Tank	Reservoir	1	$ 23	$ 23	0.00	$ -
9	RDH081	Pressure Release Valve	1	$ 63	$ 63	0.00	$ -
10		Pressure Sensor	2	$ 75	$ 150	0.00	$ -
11	915-8D27	Auxiliary hand pump	1	$ 258	$ 258	0.00	$ -
12	C-51130	Manifold (6"x6"x3.5")	1	$ 300	$ 300	0.00	$ -
		System Total	20		$ 5,284		$ -
Mechanical Components							
13	Shimano Alfine 8 Speed	Front Gear Hub	1	$ 189	$ 189	0.30	$ 18
14	Sram I-3	Rear Gear Hub	1	$ 99	$ 99	0.30	$ 18
15		8" Spur Gear	1	$ 102	$ 102	0.25	$ 15
16		10" Spur Gear	1	$ 110	$ 110	0.45	$ 27
17		5" Spur Gear	1	$ 85	$ 85	0.25	$ 15
18		3" Spur Gear	1	$ 55	$ 55	0.25	$ 15
19		2" Spur Gear	1	$ 20	$ 20	0.15	$ 9
20		30" rear axle	1	$ 40	$ 40	0.05	$ 3
21		Tricycle Frame	1	$ 288	$ 288	0.00	$ -
		System Total	9		$988		$ 120.00
Electrical Components							
22		Arduino Due	1	$ 32.13	$ 32.13	0.25	$ 15
23		1M Resistor	20	$ 0.10	$ 2.00	0.00	$ -
24		Diode	10	$ 0.36	$ 3.60	0.00	$ -
25		NMOS	10	$ 0.63	$ 6.30	0.00	$ -
26		Mini XLR 2pack	10	$ 8.87	$ 88.70	0.00	$ -
27		Large Connector	1	$ 17.99	$ 17.99	0.00	$ -
28		Brakes	1	$ 16.49	$ 16.49	0.25	$ 15
29		Mode Switch	1	$ 3.82	$ 3.82	0.00	$ -
30		Toggle/momentary switch	1	$ 7.99	$ 7.99	0.00	$ -
31		PTC fuse	10	$ 0.48	$ 4.80	0.00	$ -
32		Potentiometer	2	$ 0.52	$ 1.04	0.00	$ -
33		4.7K Resistor	2	$ 0.10	$ 0.20	0.00	$ -
34		1.5K	2	$ 0.10	$ 0.20	0.00	$ -
35		10k Resistor	1	$ 0.10	$ 0.10	0.00	$ -
36		1K Resistor	1	$ 0.10	$ 0.10	0.00	$ -
37		0.1uF Capacitor	1	$ 0.21	$ 0.21	0.00	$ -
38		3.3K Resistor	1	$ 0.10	$ 0.10	0.00	$ -
39		3 Color LED	5	$ 0.98	$ 4.90	0.00	$ -
40		10K Resistor Bar	2	$ 0.76	$ 1.52	0.00	$ -
41		Hall-effect Sensor	1	$ 2.63	$ 2.63	0.00	$ -
42		M3 Screws	1	$ 21.99	$ 21.99	0.00	$ -
43		M1.6 Screws	1	$ 12.99	$ 12.99	0.00	$ -
44		Arduino Nano	2	$ 11.98	$ 23.96	0.00	$ -
45		Rubber inserts	1	$ 9.99	$ 9.99	0.00	$ -
46		Battery	1	$ 41.32	$ 41.32	0.15	$ 9
47		Screen	1	$ 29.95	$ 29.95	0.00	$ -
48		RA8875 Interface	1	$ 34.95	$ 34.95	0.00	$ -
49		Micro SD interface	1	$ 7.50	$ 7.50	0.00	$ -
50		PCB	1	$ 9.99	$ 9.99	0.00	$ -
		System Total	93		$ 387.46		$ 39.00
Fabricated Parts							
51	Pump Mount (top)	1/2" Aluminum mount	1	$ 11.14	$ 11.14	2.50	$ 150
52	Pump Mount (bottom)	1/2" Aluminum mount	1	$ 11.14	$ 11.14	2.50	$ 150
53	Reservoir Vertical Bracket	1/4" x 14"	2	$ 7.86	$ 15.72	1.00	$ 60
54	Reservoir L bracket	4" x 2.5"	1	$ 9.86	$ 9.86	3.00	$ 180
55	Bottom Support hydraulics	8" x 4.5"	1	$ 9.56	$ 9.56	3.00	$ 180
56	Front Gear Support	1/4" thick	1	$ 12.46	$ 12.46	2.00	$ 120
57	Rear Gear Support	1/4" thick	1	$ 12.46	$ 12.46	4.00	$ 240
58	Hub & Motor Support	3.250" x 5"	1	$ 14.20	$ 14.20	4.50	$ 270
59	Pump Support	3.5" x 2.375"	1	$ 14.00	$ 14.00	1.50	$ 90
		System Total	10		$ 110.54		$ 1,440.00
Hardware							
60		1/4" bolts	10	$ 0.61	$ 6.10	0.00	$ -
61		1/4" hex nuts	30	$ 0.26	$ 7.80	0.00	$ -
62		1/4" washers	30	$ 0.20	$ 6.00	0.00	$ -
63		1/4" zinc washers	4	$ 0.15	$ 0.60	0.00	$ -
64		3/8" zinc washers	10	$ 0.02	$ 0.20	0.00	$ -
65		3/8" Zinc bolts	12	$ 0.10	$ 1.20	0.00	$ -
66		1" bolts (10-24x)	8	$ 0.15	$ 1.20	0.00	$ -
67		1" bolts (6-32x)	6	$ 0.98	$ 5.88	0.00	$ -
68		5/16" washers	10	$ 0.28	$ 2.80	0.00	$ -
69		1/4" x 1" set screw	4	$ 0.96	$ 3.84	0.00	$ -
70		1/4" x 3/4" zinc bolts	4	$ 0.56	$ 2.24	0.00	$ -
71		1/4" x 1 1/2" bolts	6	$ 0.75	$ 4.50	0.00	$ -
		System Total	134		$ 42.36		$ -

Table 23: Summary or Costs

Summary	
Total number of items	266
Total Worth of Parts & Materials	$ 6,811.96
Total Spend by 2017 Team	$ 618.21
Cost of Labor & Preparation	$ 1,599.00
Cost of Assembly	$360
TOTAL COST	**$ 8,770.96**

In the summary table, we can find the total number of items, total cost of material, total labor cost with preparation and with assembly. Our team also included the amount that we have spent with this project. The reason behind the low amount is due to the re usage of components from previous years. Our team thought that the best components were already in house due to their energy capacity. Other components, such as valves, fluid, and fittings were donated by our sponsors.

From the $618.21, only $230.75 was spent by the mechanical team, which contributes to few items such as hardware, tires, tubes, wheels, a rear axle and brake pads. The electrical team bought most of their items online with a total of $387.46.

The cost of producing a single prototype is presented in Table 23, and it is based on the Bill of Material presented in Table 22. In this table, there are two cost calculated: total cost of components and materials, and total cost of labor highlighted in yellow. In the case of parts & materials, for each component listed, there is a Unit Price. This Unit Price, together with the Quantity for each item, determines the Total Cost of that item in the prototype. For the calculation of labor, there is labor included in all the subsystems that are not stock or standard parts, i.e., where some fabrication took place, and when some adjustments needed to be made to the standard, purchased parts. Most of the brackets and frame modifications fall under the Fabrication subsystem, and in the Mechanical subsystem there was need to create keyways and holes (for set screws) in the hubs of several of the gears (purchased without those features to realize some savings). The labor hours are estimated values based on the time that was required to do the machining by semi-experienced students in the team, which is different from the time – and cost – that took team members to get the part(s) right. The cost per hour used for the calculations was the provided one of $60/hr.

The total cost of parts/materials for the prototype is $6,811.96 with the total cost of labor being $1959, for a total cost of $8,770.96. It is interesting to note that a large portion of this cost is related to the hydraulic circuit (Core, Valves, Connectors accounts for $5,284–77.57%).

For the scenario of planning for a production of 500 units, the results are presented in Table 24. In this table, the 5 major sub-categories from the BOM are listed with their respective Part/Material Cost and Labor Cost. For each one of these sub-categories there is an estimate of what reduction (and increase, if appropriate) in cost will be incurred as the prototype is taken to a 500-units production. There are two main factors that will influence the costs: a) bulk purchasing, and b) use of automated fabrication equipment during fabrication. Under these premises, the following changes are estimated:

- For Hydraulic Components, it is estimated that a 25% reduction in unit price is possible. This percentage is considered a happy medium for components that include out of a catalogue, but manufactured as requested.
- For Mechanical Components, there is an estimate of 20% savings for bulk purchasing. The percentage is lower than others, because the items to be ordered will include features, such as keyways, holes for mounting gears on the hubs. So, with smaller discount, we'll have the elimination of labor cost.
- For Electrical Components, there is an estimate of 40% discount which is more in line with bulk purchasing of quality electronic components. Higher savings can be realized by purchasing performance-like components of unknown brands.
- For Fabricated Parts, it is considered that CNC equipment will be used, this automating the process and having better accuracy and repeatability within tolerances. A 35% saving in cost of materials, a 66% savings in labor of fabrication, but a small increase in labor (prorated) due to the setting and programming of the equipment.
- For Hardware equipment, such as bolts, nuts, screws, and spacers, a conservative estimate of 90% savings by bulk purchasing.
- For Assembly Cost (Labor), on one hand there are savings (estimation of 70%) to be realized by using jigs and fixtures – extremely useful to place motor/pump and gears, but there is a cost involve in fabricating the fixtures, which is prorated

Table 24: Cost Analysis for the Production of500 units of the Tricycle

Cost Analysis of 500 units						
Subsystem	Parts Cost	Labor Cost	Economy of Scales (parts)	New Parts Cost	Economy of Scale - Labor	New Labor Cost
Hydraulic System						
Total	$ 5,284	$ -	Bulk Purchase - 25% discount	$ 3,963.00		$ -
Mechanical System						
Total	$ 987.60	$ 120.00	Bulk Purchase - 20% discount	$ 790.00	Include In Purchase Order	$ -
Electrical System						
Total	$ 387.46	$ 39.00	Bulk Purchase - 40% discount	$ 232.48		$ -
Fabricated Parts					Use of CAM (CNC)	$ 160.00
Total	$ 110.54	$ 1,440.00	Bulk Purchase - 35% discount	$ 73.51	Programer time (prorated)	$ 3.60
Hardware						
Total	$ 42.36	$ -	Bulk Purchase - 90% discount	$ 4.24		$ -
Cost of Materials	$ 6,811.96			$ 5,063.22		
Labor Cost	Preparation	$ 1,599.00				$ 163.60
Labor Cost	Assembly	$ 360.00			Jig/Fixture Assembly & set up	$ 120.00
Total Cost		$ 8,770.96				$ 5,346.82
Percent Reduction						35.00%
Total Cost (500 Units)						$ 2,850,562.00

9 ACTUAL TEST DATA COMPARED TO ANALYSIS

9.1 PUMP & MOTOR TESTING

Pump and motor manual testing was done at the Parker lab at Western Michigan University. The diligence for testing our components manually was to make sure that there was no leakage and to make sure that the pressure was not dropping due to any inconvenience or failure in the component since we are reusing those components from a year ago. The pump and motor are designed to be a fixed directional but, for our application, the pump/motor has the ability to flow bi-directional and maintain the same level of performance. Also, we were able to identify and alter the pump/motor configuration to eliminate the case drain. This drain purpose is to remove heat and debris from the pump/motor. Again, in our application our pressures and flow rates cannot create enough heat for this case vent to be necessary. By testing the pump/motor we were able to identify and eliminate the trivial vent creating unnecessary loss in the system.

Image 19: Pump/Motor manual test

Image 20: Rider testing competition simulation

9.2 PHYSICAL TESTING

After fabrication of the components and assembly of hydraulic circuit and development of the control system, it was tested for performance. First test was operation of the hydraulic circuit for each of the four functions out in the field:

- **Direct Cruising:** In this operation, the rider operates the vehicle by pedaling while valve 1 is in default position. Rear axle will move the driving wheel and the bike will move forward.
- **Charging Accumulators:** Solenoid valve 1 is activated and flow from pump charges accumulator 1 and 2 based on solenoid valve 2 position. A Bourdon gage indicated pressure of up to 3,000 psi in the accumulator.
- **Discharging:** After the accumulators are charged to 3,000 psi pressure, flow control valve is opened gradually and driving wheel started to spin at a slow rpm.
- **Brake Charging:** Solenoid valve 3 is activated and bike is moved forward. Accumulator pressure increased slightly, indicating the motor is acting as a pump and charging accumulator.

Design process requires acquisition of operational data and comparison of this data with the theoretical and Automation Studio simulation data. Analysis of the operational data can lead to improvement of system efficiency and reliability.

9.2.1 Test runs with Accumulator

Among the tests that were run with our bike upon completion were trial runs to test the functionality of our accumulators. The primary focus of these runs was to ensure that we could have consistency in our accumulators. Giving that the accumulators have such an advantage on others like the density and volume rate, we thought that the bike was going to move faster. Due to the trials and the low speed at an efficiency level, we came up with the idea that our accumulators might need be pre-charge with nitrogen before the final competition. We ran these tests with a maximum distance reached of about 130 ft.

Table 25: Test runs for accumulator discharge

Accumulator #1		Accumulator #2	
RUN #1		RUN #2	
Distance (ft.)	Pressure (psi)	Distance (ft.)	Pressure (psi)
0	3,000	0	3,000
25	2,500	25	1,500
50	1,000	50	500
75	250	75	3,000
100	3,000	100	2,000
125	1,500	125	500
130	0	135	125
		140	0

During testing this configuration and due to the inefficiency on the system, we found out that if we gradually press to discharge the accumulators was more efficient than realizing the pressure at once. In table 25, you can see that run test #2 goes longer than test #1 due to the operation of the discharge operation.

Also from the trial accumulator runs, we attempted riding our bike with both the direct drive mode and the regeneration mode. Both worked almost exactly as we expected they would. Shifting gears with both hubs worked well, and we were able to travel in a manner similar to that of a regular bicycle, other than feeling the extra work required to move the extra weight, with balancing again being a non-issue. The regeneration mode didn't recover as much energy as we had hoped on flat ground, though. Moving at 12 mph, we found that slowing the bike down with the regeneration mode would only gain us 15-20 psi of pressure in the accumulators before having to switch back to direct drive mode to keep moving.

Due to the uncertainty of our team not know why the accumulators where dropping the pressure so fast in such a short distance, we assumed it was because of the low amount nitrogen pre-charge. Due to this inconvenient, our team calculated the amount of pressure needed to be in our accumulators, so that we could accurately ask for the amount when inserting the nitrogen before the final competition. If our calculations are right, then we would need a minimum of 675 psi of pre charged pressure in order to operate at 750 psi at least.

Table 26: Nitrogen quantity needed for competition

Equations used	
PV=RT	
User inputs	
Temperature (F)	70
Volume (gal)	1.08
Nitrogen Density (g/L)	1.25
Gas constant of nitrogen	0.30
Outputs	
Temp. Kelvin	294.26
Nitrogen Density (kg/m^3)	1.25
Pressure needed (kPa)	10682.57
Pressure needed in psi	1549.32

9.3 VIRTUAL TESTING

A duty cycle with five different scenarios including coasting was created in order to simulate the various modes of operation of the hydraulic circuit implemented in tour vehicle. The circuit was implemented in Automation Studio.

The bike runs in several modes such as Direct drive, Charging Accumulators, Discharging, Brake Charging and Coasting shown in the figures below. In direct cruising the pump directly drives the motor as shown in figure 41. The directional valves below make sure that the fluid goes directly to the pump.

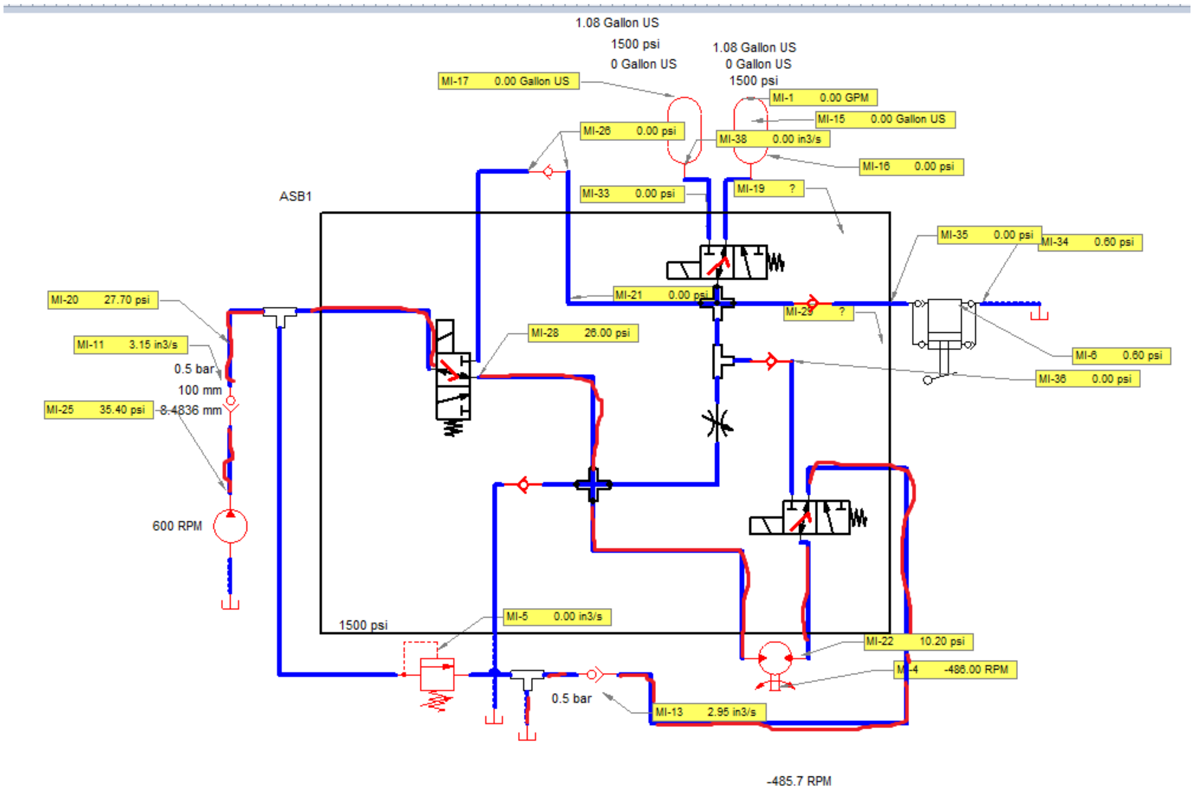


Figure 41: Direct cruising virtual analysis

The second mode that the bike has is charging the accumulator as shown in figure 42. It takes about 2 minutes and 51 seconds to charge both accumulators to a pressure of 1500 psi each. The purpose of charging the accumulator is to give the rider a method to store energy so it can be used to propel the bike later. In figure 43 explains how when the accumulators are discharge it would be able propel the bike for a couple minutes.

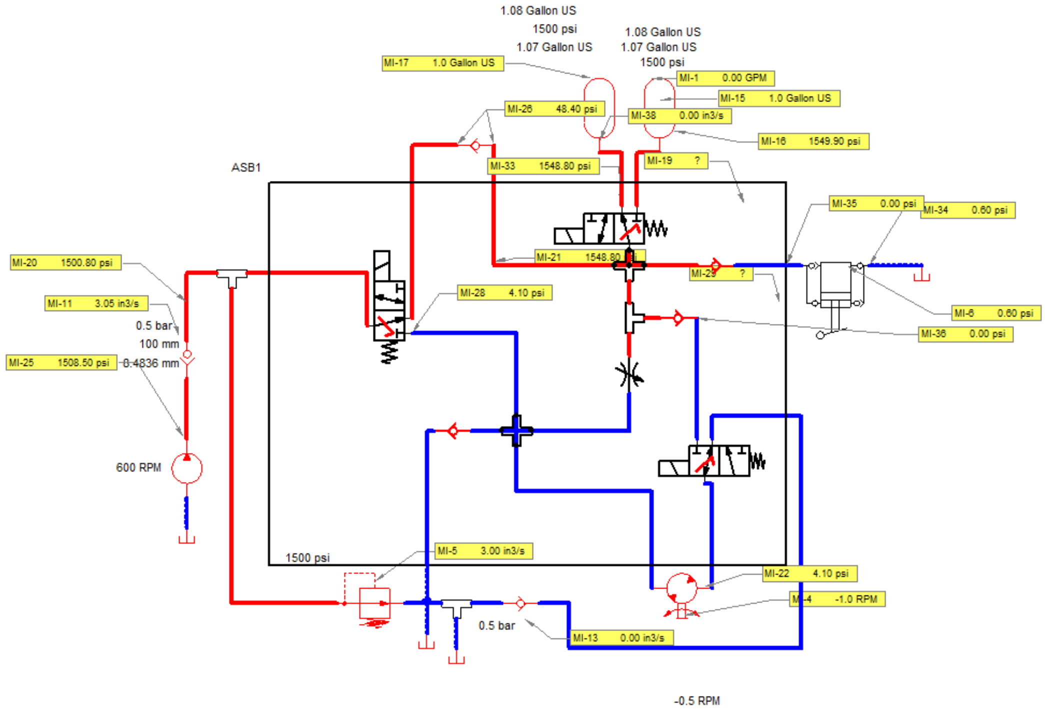


Figure 42: Charging Accumulators virtual analysis

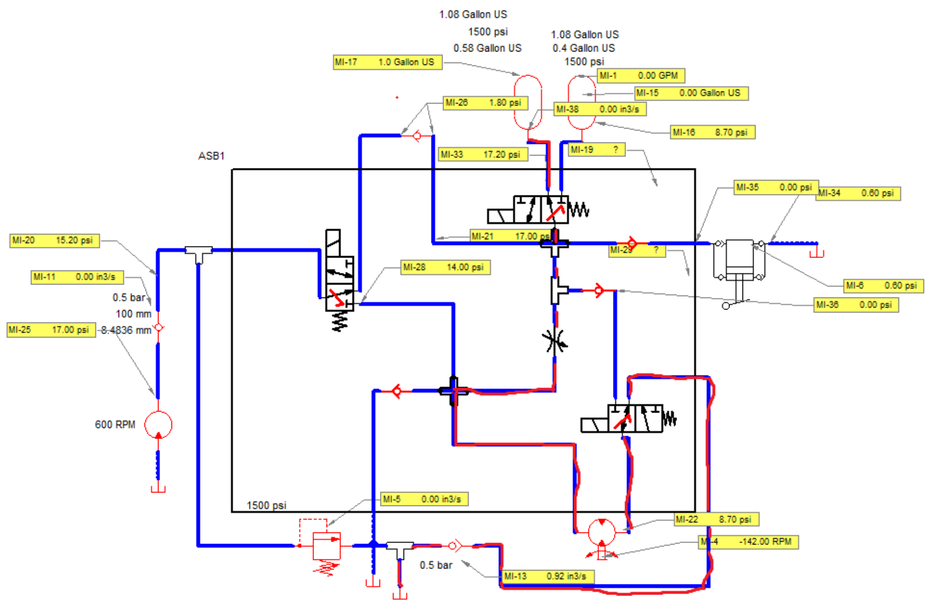


Figure 43: Discharging Accumulators virtual analysis

The final mode is the brake recharging mode is once the bike is in motion it can be switched to this mode and the rider can use the bikes momentum to recharge the accumulators, which can be released to help get the bike up the hill or to just increase overall speed. In figure 44 the motor swapped out for a pump to simulate how brake recharging could work. In the simulation, the motor will run for 489 rpm for 2 min to simulate coasting in brake recharge mode.

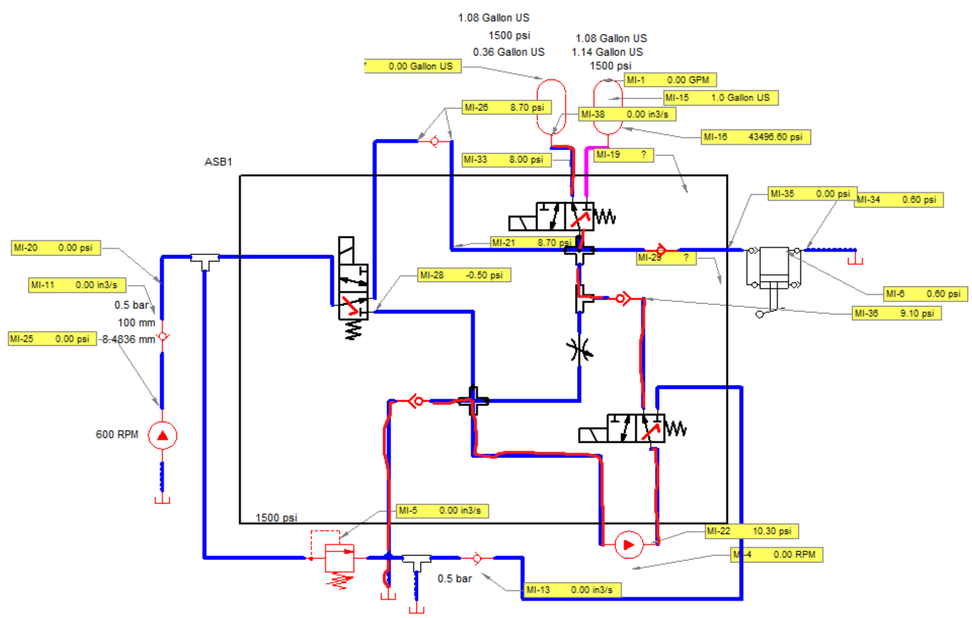


Figure 44: Brake Charging virtual analysis

In the coasting mode in Automation Studio, the variable throttle valve will open to 4 mm and the tanks and the motor pressure would be rated at 1500 psi. When both tanks have released their pressure as in figure 45 the bike will coast for about 3 minutes

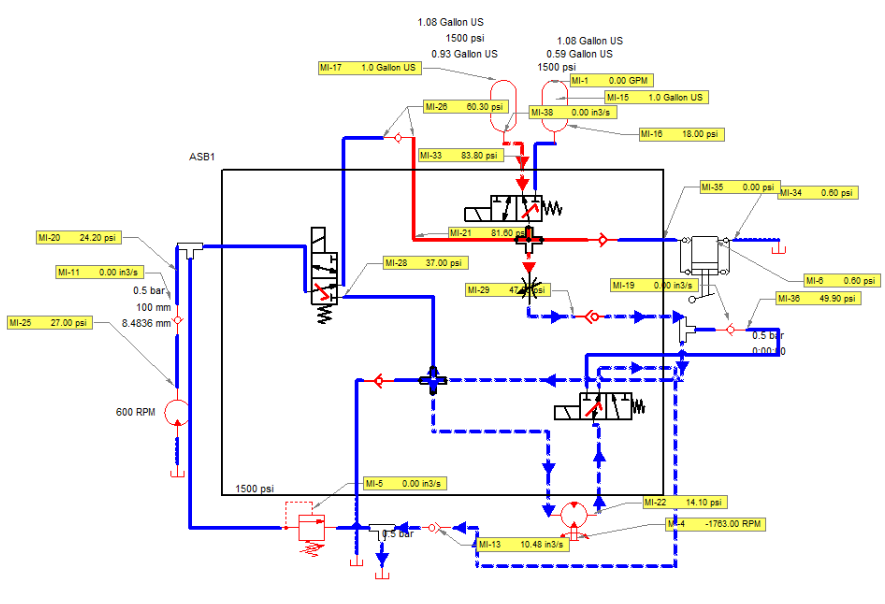


Figure 45: Coasting mode virtual analysis

When the pressure is released the motor rpm spikes to about 1100 rpm and the tanks are switched when the motor rpm reaches 30 rpm. By approaching it this way it allows for the longest distance with the coasting mode.

9.3.1 Relation Between Automation Studio & Excel Calculations

The Automation Studio and Excel calculations will differ because automation studio considers losses in the lines and excel only factors in the losses in the pump. In figure 46 when the pump spins at 600 rpm the motor will operate at 305 rpm, which is different only because head loss is factored into the equation

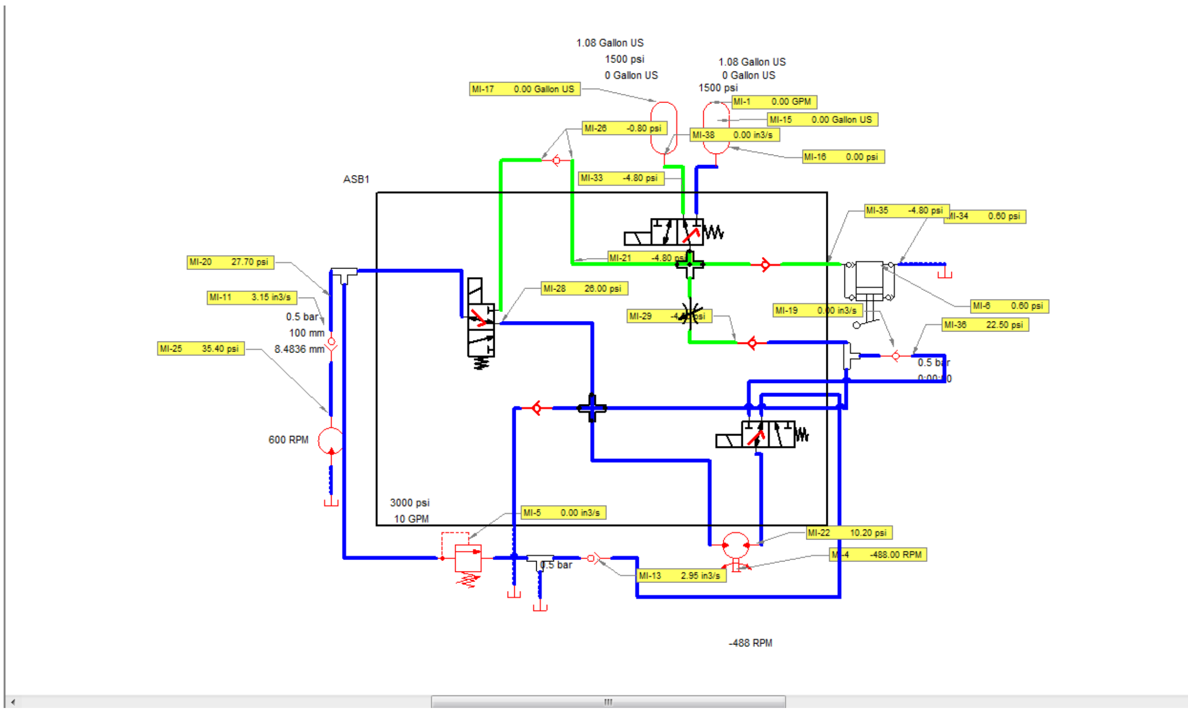


Figure 46: Automation Studio Analysis

Also, in the program the tubing that we used are NPS 1/2 83/DN 15-2.1 Stainless steel. In our actual project, we used threaded tubing from the previous year's bike which would make the results vary a little bit.

10 CONTINGENCY PLAN

There is always a risk that the product can fail in some ways which might lead to failure in performing its function or danger to the user. It´s therefore important to know how the system can fail and what can be done to minimize the risk of failure. A good way of doing this is to perform a *Failure Modes and Critical Effects Analysis* (FMECA). In an FMECA, the possible failure modes of all the functions and components that are analysed are identified with use of brainstorming and experience from use of similar products or functions. The potential impact of the failure modes is assessed. The possible causes of the failures are identified. Corrective actions are suggested for each of the failures and their causes. The severity of the potential impact of the failures are rated on a scale of 1 through 10, see table 27

Table 27: Severity of Failure

Rating	Description	Severity Description
1	None	The effect is not noticed
2	Very minor	Some variation noticed and correctible
3	Minor	Slight effect that causes confusion and irritation (still not problematic)
4	Very low	Slight Effect that causes to seek for assistance or service
5	Low	Effect that requires immediate service
6	Moderate	Continuous effect that create problems
7	High	Major effect. Repair may not be reparable
8	Very high	Not worth to repair, system should be of out of service or unrepairable
9	Extreme	Advance warning. Might affect operators and others safety, safety risk
10	Critical/Hazardous	Is a dangerous critical point. Affects safety of operator and others without any preview warning

The likelihood of occurrence of each of the causes are assessed and given a rating from 1 to 10 according to table 28

Table 28: Probability of Failure

Rating	Approx. Probability of failure	Description of occurrence
1	< 1 x 10^-6	Extremely remote
2	1 x 10^-5	Remote, very unlikely
3	1 x 10^-5	Very slight chance of occurrence
4	4 x 10^-4	Slight chance of occurrence
5	2 x 10^-3	Occasional occurrence
6	0.01	Moderate occurrence
7	0.04	Frequent occurrence
8	0.20	High occurrence
9	0.33	Very high occurrence
10	> 0.50	Extremely high occurrence

Each of the potential failures is then given a *Risk Priority Number* (RPN), which is the product of the severity rating and likelihood rating of the failure. The risk of the potential failure is assessed with the RPN as shown in table 29.

Table 29: Risk Priority Number

Risk Priority Number (RPN)

Occurrence \ Severity	1	2	3	4	5	6	7	8	9	10
10	10	20	30	40	50	60	70	80	90	100
9	9	18	27	36	45	54	63	72	81	90
8	8	16	24	32	40	49	56	64	72	80
7	7	14	21	28	35	42	49	56	63	70
6	6	12	18	24	30	36	42	48	54	60
5	5	10	15	20	25	30	35	40	45	50
4	4	8	12	16	20	24	28	32	36	40
3	3	6	9	12	15	18	21	24	27	30
2	2	4	6	8	10	12	14	16	18	20
1	1	2	3	4	5	6	7	8	9	10

Risk
Failure
Critical
High
Medium
Low

The corrective actions are then prioritized by the value of the RPN of the potential failures. The ones with the highest RPN are considered first.

10.1 HYDRAULIC PLAN

Table 30: Hydraulic Plan

System	Component Failure	Possible Cause	Effect on System	Primary Solution	Secondary Solution	Severity Score	Occurrence Likelyhood	Risk Priority	Failure Severity
Hydraulic	Manifold Valve 1 Failure to shift.	1. Contamination 2. Solenoid Failure 3. Bent Valve Stem	Mode 2 Pedal Charging would not function. Mode 2 Hand Pump should still function. Modes 1, 3, 4 unaffected.	1. Remove contamination 2. Replace solenoid 3. Replace valve	Use Hand Pump for charging	5	5	25	Medium (Reduced Functionality)
Hydraulic	Manifold Valve 2 Failure to shift.	1. Solenoid Failure 2. Bent Valve Stem	Mode 4 Braking Recharge would not function. Modes 1-3 unaffected.	1. Remove contamination 2. Replace solenoid 3. Replace valve	Continue without Mode 4	2	3	6	Low (Non-important function)
Hydraulic	Manifold Valve 3 Failure to shift.	1. Solenoid Failure 2. Bent Valve Stem	Accumulator 2 would not be usable. Mode 3 energy storage reduced. Mode 1, 2, 4 unaffected.	1. Remove contamination 2. Replace solenoid 3. Replace valve	Continue with Accumulator 1	5	8	40	High (Reduced Performance)
Hydraulic	Manifold Valve 4 Failure to shift.	1. Solenoid Failure 2. Bent Valve Stem	Mode 3 Discharge would not function. Modes 1, 2, 4 unaffected.	1. Remove contamination 2. Replace solenoid 3. Replace valve	Use valve manual override	10	8	80	Critical (Function Failure)
Hydraulic	Pedal Pump Failure	1. Contamination 2. Internal Part Damage	Mode 1 would not function. Mode 2 Pedal Charging would not function. Mode 3, 4 unaffected.	Replace pump with spare.	None	10	7	70	Critical (Function Failure)
Hydraulic	Motor Failure	1. Internal Part Damage 2. Contamination	All modes would not function.	Replace pump with spare.	None	10	10	100	System Failure
Hydraulic	Hand Pump Failure	1. Lever broken 2. Internal damage	Mode 2 Hand Pump would not function. Pedal Pump would still function. Mode 1, 3, 4 unaffected.	None	None	9	6	54	High (Reduced Performance)
Hydraulic	Accumulator 1 or 2 Failure	1. Nitrogen leak	Affected Accumulator would lose pressure. Mode 3 energy storage reduced. Mode 1, 2, 4 unaffected.	Refill Nitrogen	Use other Accumulator	8	7	56	High (Reduced Performance)
Hydraulic	Reservoir Leak	1. Bottom fitting loose 2. Reservoir	Fluid loss. All modes would not function.	1. Tighten/Seal fitting 2. Replace Reservoir with spare	None	10	9	90	System Failure
Hydraulic	Check Valve 1 Failure	1. Contamination 2. Internal Part Damage	Reversed flow through pedal pump. Peddles will rotate in reverse. Mode 1 still functional. Mode 2, 3, 4 unaffected.	1. Replace check valve 2. Remove contamination	Continue use of Mode 1	4	7	28	Medium (Reduced Functionality)
Hydraulic	Check Valve 2 Failure	1. Contamination 2. Internal Part Damage	Reversed flow through motor. Motor will rotate in reverse in Mode 4. Mode 1, 2, 3	1. Replace check valve 2. Remove contamination	Continue without Mode 4	2	7	14	Low (Non-important function)
Hydraulic	Check Valve 3 Failure	1. Contamination 2. Internal Part Damage	Reverse flow possiblethrough motor. All Modes unaffected.	1. Replace check valve 2. Remove contamination	Continue use	2	7	14	Low (Non-important function)
Hydraulic	Check Valve 4 Failure	1. Contamination 2. Internal Part Damage	Continuous loop in system. Modes 1, 3 would not function. All propulsion lost Modes 2, 4 unaffected.	1. Replace check valve 2. Remove contamination	None	10	7	70	System Failure

10.2 MECHANICAL PLAN

Table 31: Mechanical Plan

System	Component Failure	Possible Cause	Effect on System	Primary Solution	Secondary Solution	Severity Score	Occurrence Likelyhood	Risk Priority	Failure Severity
Mechanical	Tires get flat	1. Flat tire 2. Lack of air	Low Speed. Less efficient. Damadge rim.	Re-inflate	Replace tube	5	2	10	Low (Non-important function)
Mechanical	Pedal/ Crank falls off	High Stress	Pedal falls off	1. Tighten pedal 2. Replace pedal	Replace pedal/crank	5	5	25	Medium (Reduced Functionality)
Mechanical	Gear-pinion mesh	Gear disalignment	Gears will spin freely . The Bike won't run.	1. Re-align gears. 2. Tighten locking bolts	none	6	4	24	Medium (Reduced Functionality)
Mechanical	Gear-pinion teeth	Gears teeth brake due to high torque or exhaust	Gear will slip and won't allow effiency on the bike	1. Find gear with broken tooth 2. Replace gear	File the edges of the tooth until functional	7	8	56	High (Reduced Performance)
Mechanical	Gear Hub won't shift	Cable shifter snaps	Won't allow the bike to shift to the lower gear	1. Reconnect cable 2. Replace cable	Keep pedaling without a shifting system	3	9	27	Medium (Reduced Functionality)
Mechanical	Wheel Axle shears	High stress under high torque.	Fatality. The wheels won't rotate.	Replace axle if we have a spare	none	10	9	90	System Failure
Mechanical	Key moves out of place	Gears moves out of place	Axle gear or Gear hub will be out of place	Remove components and place the key back in	Raplace key	7	10	70	Critical (Function Failure)

11 CAD FINAL RESULTS

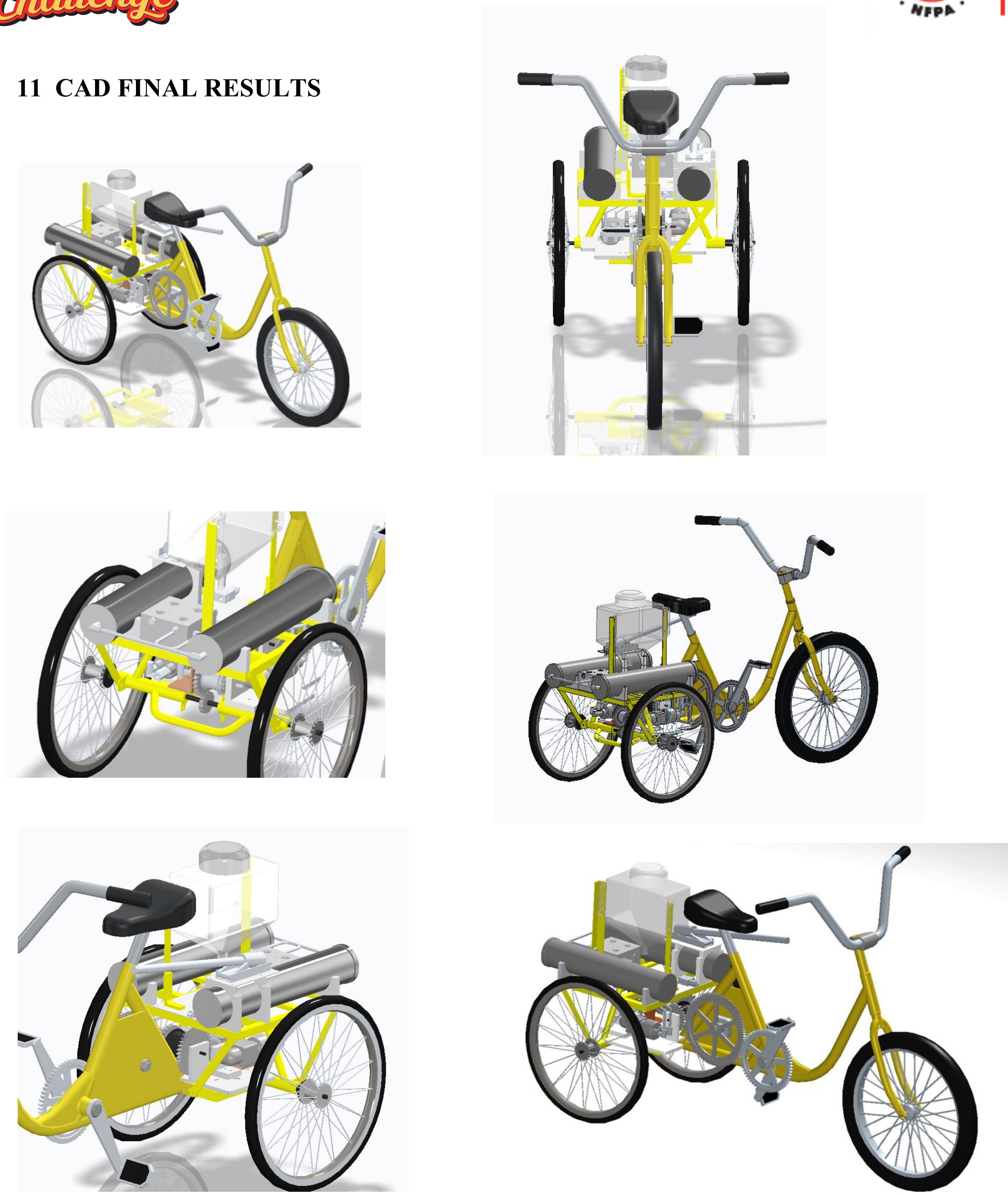
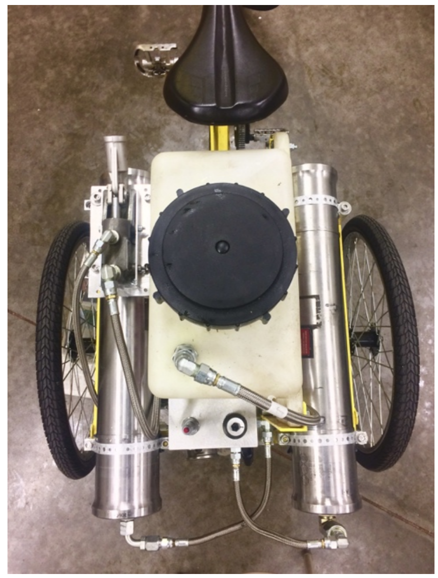


Figure 47, 48, 49, 50, 51, & 51: Final CAD Models

12 FINAL RESULTS



Images 21, 22, 23, & 24: Final CAD Models

13 LESSONS LEARNED

While the manifold condensed a decent portion of the hydraulic system, the manifold itself could have been a little more compact. The manifold was made slightly larger so that there was enough space between the cavities and the outer walls for fitting ports. There was also some uncertainty earlier on about how far apart the cavities needed to be each other, so spacing was kept on the safe side. After the manifold was fabricated and the valves inserted, it was found that the cavities could have been closer together. The valves used in the system were the larger C-10 size, which required larger cavities in the manifold. The smaller C-08 valves would have likely been adequate. Were the manifold to be redesigned with these changes in mind, it could be reduced in overall size and weight.

The trike frame was selected primarily for its stability, which was one of the recommendations from the previous year. However, as the drive train was being fabricated, issues with spacing began to make assembly and modifications difficult. Since the drive train had to turn an axle instead of a hub built into the rear wheel, extra gearing and mounts had to be used. These mounts had to be precise for the gears to mesh properly. Also, implementing a rear hub proved to be even more difficult since the hubs that were selected were not designed to have gear mounted on both sides. If a stable frame is desired in the future, it is recommended that a recumbent frame with a single rear wheel would likely have less implementation issues.

Due to the electronic system, not being fully functional in time, the bike was unable to go through full testing. Without the speedometer, pressure sensors, and computer data collection, the bike could only be tested in general. Were the bike able to record specific testing data, the system could have been optimized more for efficiency.

14 CONCLUSIONS

In order to compete in the Fluid Powered Vehicle Challenge, Western Michigan assembled two student design teams. The mechanical team was responsible for the hydraulic circuit and the frame. The electrical team was responsible for the vehicle control system. The mechanical team was able to assemble a vehicle in the last week leading up to presentations while the electrical team was unable to complete the control system due to parts not being delivered on time, some errors in assembly, and some still uncertain issues, the ultimate outcome of the control system was a failure. A few goal specifications were able to be met but not all of the required specifications were met in the allotted time. The major failed specifications were 4. Proportional Valve Control, 7. Pressure Sensor Circuitry, and 20 Feedback for the Rider. t is still uncertain whether the circuitry failed for the proportional valve or the design was incompatible due to a lack of remaining time. There is still some question as to whether the pressure sensor failed or the circuitry failed in the proportional valve controls and because of this, Whether or not the rider feedback was working properly could not be assessed. A few remaining issues are the speed sensor not functioning as expected which was probably attributable to the internal pullup resistor being active in the microcontroller, and the display screen failing due to excessive handling while troubleshooting other components.

For next year, the electrical team should find a way to verify the pressure sensor in the fall semester. This would have allowed for another system to function on this vehicle and be one step closer to competing. While a spare screen could have been ordered, it would have been better to find a way to not have to alter the screen when troubleshooting other components. This year's team was also not meeting weekly with the mechanical team which would have been more ideal, part of the problem on that front was conflicting schedules (i.e. one works 1st shift and another works 2nd). The best advice for solving this problem is to try to get group members that are on approximately the same schedule. Ultimately this project will also not get done by one person, it needs to be a group effort with everyone contributing ideally equal shares of the word.

15 ACKNOWLEDGEMENTS

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17 APPENDICES

Table 32: Frame Decision Sample

Pugh Matrix Frame Design Evaluations:

Area	#	Requirements	Weight Factor (1 - 10)	Frame Design Types (score of 1 to 5): *3-wheel (trike)*	*3wheel - delta recumbent*	*3wheel - long front (NSS)*	*3wheel - expanded back tricycle*	*2wheel - long back cargo*
Design	1	Reliability	10.0	4.5	4	3.5	4.5	3.5
Design	2	Safety	9.0	5	4.5	4.5	4	4
Design	3	Accuracy	8.0	5	5	5	4.5	4.5
Design	4	Quality	7.5	5	5	5	4.5	4.5
Design	5	Structural Integrity / Durability	10.0	5	2	4	5	4.5
Design	6	Creativity / Innovation	6.0	4.5	4.5	4.5	5	5
Design	7	Aesthetics	6.0	5	4	5	3	3
Manufacturing	8	Ease of Use & Control	8.0	5	4	4.5	5	4.5
Manufacturing	9	Material and parts cost (cheapest = 5)	7.5	4	3	2	5	5
Manufacturing	10	Technologically Advanced	5.0	4	4.5	5	4	4
Manufacturing	11	Level of repairability	9.0	5	3	4	4.5	4.5
Function	12	Weight (lightest = 5)	9.0	4	5	2.5	4	4
Function	13	Performance	10.0	5	4	3.5	5	4.5
Function	14	Aerodynamics	6.0	4	5	3	4	5
Function	15	Number of parts	3.0	5	4.5	3.5	4	4.5
Weight	16	Load Distribution	9.0	5	4.5	5	5	3
Weight	17	Available Space or Capacity	8.0	4.5	2	4	5	3.5
Weight	18	Customization	9.0	4	4	4	5	4.5
		Totals:		651.5	554	561	638.75	587.75

Average per area	*trike*	*delta recumbent*	*long front nSS*	*expanded back*	*cargo bike*
Design	4.86	4.14	4.50	4.36	4.14
Manufacturing	4.50	3.63	3.88	4.63	4.50
Function	4.50	4.63	3.13	4.25	4.50
Weight	4.50	3.50	4.33	5.00	3.67

Table 33: Criteria

Design

1	Reliability
2	Safety
3	Accuracy
4	Quality
5	Structural Integrity / Durability
6	Creativity / Innovation
7	Aesthetics

Manufacturability

8	Ease of Use & Control
9	Material and parts cost (cheapest = 5)
10	Technologically Advanced
11	Level of repairability

Functionality

12	Weight (lightest = 5)
13	Performance
14	Aerodynamics
15	Number of parts

Weight

16	Load Distribution
17	Available Space or Capacity
18	Customization

Table 34: Torque & pump calculations

Pressure (psi)	750	
HP	0.333	
RPM	Torque (lb in)	Displ.
0	0	0
10	2098.7325	17.58230028
20	1049.36625	8.791150138
30	699.5775	5.860766759
40	524.683125	4.395575069
50	419.7465	3.516460055
100	209.87325	1.758230028
150	139.9155	1.172153352
200	104.936625	0.879115014
250	83.9493	0.703292011
300	69.95775	0.586076676
350	59.96378571	0.502351436
400	52.4683125	0.439557507
450	46.6385	0.390717784
500	41.97465	0.351646006
550	38.15877273	0.319678187
600	34.978875	0.293038338
650	32.28819231	0.270496927
700	29.98189286	0.251175718
750	27.9831	0.23443067
800	26.23415625	0.219778753
850	24.69097059	0.206850591
900	23.31925	0.195358892
950	22.09192105	0.185076845
1000	20.987325	0.175823003

Pumps chosens:	25507	25508
Displacements:	3.12	3.37
Max. Pressure (psi)	3000	2750
Max. Int. Pressure (psi)	3400	3150
Rated Speed (RPM)	2500	2250
Dimension A (in)	4.29	4.43
Dimension B (in)	5.57	5.71

Table 35: Motor fluid displacement at different RPM

	Wheel GPM		
Bike RPM	120	rpm	
CIR	2.05	cir	
Flow rate	1.06	GPM	(D100*D101)/231

					Flow Rate					
Bike RPM	CIR (displ)	Motor 1 (5 in3)	Motor 2 (6 in3)	Motor 3 (7 in3)	Motor 4 (8 in3)	Motor 5 (9 in^3)	Motor 6 (10 in^3)	Motor 7 (11 in^3)	Motor 8 (12 in^3)	Motor 9 (13 in^3)
750	5	16.23	19.48	22.73	25.97	29.22	32.47	35.71	38.96	42.21
800	6	17.32	20.78	24.24	27.71	31.17	34.63	38.10	41.56	45.02
850	7	18.40	22.08	25.76	29.44	33.12	36.80	40.48	44.16	47.84
900	8	19.48	23.38	27.27	31.17	35.06	38.96	42.86	46.75	50.65
950	9	20.56	24.68	28.79	32.90	37.01	41.13	45.24	49.35	53.46
1000	10	21.65	25.97	30.30	34.63	38.96	43.29	47.62	51.95	56.28
1050	11	22.73	27.27	31.82	36.36	40.91	45.45	50.00	54.55	59.09
1100	12	23.81	28.57	33.33	38.10	42.86	47.62	52.38	57.14	61.90
1150	13	24.89	29.87	34.85	39.83	44.81	49.78	54.76	59.74	64.72

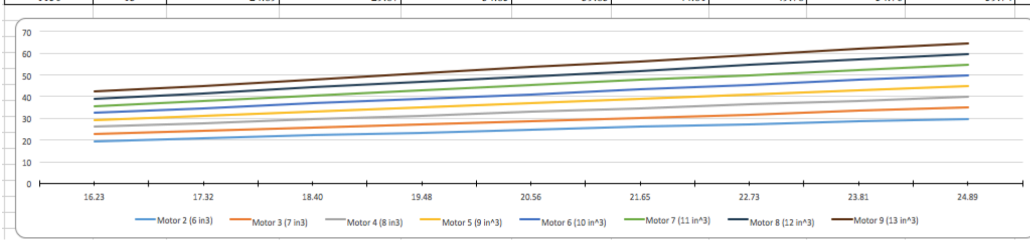

Table 36: Accumulator decision

ACCUMULATORS									
Parker	Gal	Flow Rate	Weight (lb)	Weight (w/ oil)	PSI	Dims.	**Energy/ Weight**	Energy storage capcity (lb-ft)	
BA02B5T01A1	2.5	220	120	139.2060965	5000	22.5 x 9.6	1729	**240,625**	1728.552
BA01B5T01A1	1	150	50	57.68243861	5000	17.25 x 7	1669	**96,250**	1668.619
BA02B3T01A1	2.5	220	80	99.20609653	3000	21" x 9"	1455	**144,375**	1455.304
BA01B3T01A1	1	150	34	41.68243861	3000	17"x6.75"	1385	**57,750**	1385.476
AD280A25T1A1	0.74	42	10	15.68500457	3600	10" x 7"	3269	**51,282**	3269.492
BA005B3T01A1	0.65	60	10	14.9935851	3000	15.5"x4.5"	2504	**37,538**	2503.571
HYDAC	Gal	FlowRate	Weight (lb)	Weight (w/ oil)	PSI	Dims.	**Energy/ Weight**		
SB 600-10	2.5	240	114	133.2060965	5000	22.4 x 9.5	1806	**240,625**	1806.411
SB 600-4	1	160	33	40.68243861	5000	16.3 x 6.8	2366	**96,250**	2365.886
SB 330-10	2.5	240	86	105.2060965	3000	22 x 9.1	1372	**144,375**	1372.306
SB 330-6	1.5	160	33	44.52365792	3000	20.5 x 6.6	1946	**86,625**	1945.595
SB 330-4	1	160	30	37.68243861	3000	16.3 x 6.6	1533	**57,750**	1532.544
SBO 330	0.92	40	30.6	37.66784352	4700	10.8 x 6.8	2210	**83,237**	2209.763
SBO 210	0.74	40	18	23.68500457	3000	9 x 6.6	1804	**42,735**	1804.306
SBO 250	0.92	40	24.6	31.66784352	3000	11.1 x 6.7	1678	**53,130**	1677.727
TOBUL 4.5AL-20	2.5		42	61.20609653	2500	49 x 4.6	1966	**120,313**	1965.695
Eaton	Gal	Flow Rate	Weight (lb)	Weight (w/ oil)	PSI	Dims.	**Energy/ Weight**	Energy storage capcity (lb-ft)	
A230B060	0.25	60	10	11.92060965	3000	22.5 x 9.6	1211	**14,438**	1211.138
A230B230	1	160	30	37.68243861	3000	17.25 x 7	1533	**57,750**	1532.544
A230B578	2.5	240	86	105.2060965	3000	21" x 9"	1372	**144,375**	1372.306
AP34C230	1	160	45	52.68243861	3000	17"x6.75"	1096	**57,750**	1096.191
AP34C346	1.5	160	55	66.52365792	3000	10" x 7"	1302	**86,625**	1302.168
AP34C460	2	160	68	83.36487722	3000	15.5"x4.5"	1385	**115,500**	1385.476
AP34C578	2.5	160	80	99.20609653	3000	15.5"x4.5"	1455	**144,375**	1455.304

	Gal	FlowRate	Weight (lb)	Weight (w/ oil)	PSI	Dims.	**Energy/ Weight**	Energy storage capcity (lb-ft)			
BA005B3T01A1	0.65	60	10	14.9935851	3000	15.5 x 4.5	2504	**37,538**			2503.571
AD280B25T1A1	0.74	42	21	26.68500457	3600	9.5 x 6.75	1922	**51,282**			1921.753
BA01B3T01A1	1	60	34	41.68243861	3000	17 x 6.5	1385	**57,750**			1385.476
A230B230	1	160	30	37.68243861	3000	17.25 x 4.75	1533	**57,750**			1532.544
TOBUL 4.5AL-20	1.08		20	28.2970337	3000	24 x 4	2204	**62,370**			2204.118

Table 37: Pump Decision

Pumps	Size(in^3)	Effiency (%)	Weight(lbs)	Disp. CC/rev	Cost
F11-5	83.66	90.4	11	4.9	$600
F11-10	118.13	88.4	16.5	9.8	$715
AM1C-31	38.25	84	4	5.1	$800

Factors	Weight Factors	F11-5	F11-10	AM1C-31
Efficiency	10	8.75	7.5	5.75
Disp. Volume	8	6.5	9.5	7.25
Size	6	5.5	4	8.5
Weight	4	5.5	3.5	8.5
Cost	2	8.5	4	3.5
	Total:	211.5	197	207.5

Factors	Weight Factors	F11-5	F11-10	AM1C-31
Efficiency	10	10	9	8.8
Disp. Volume	8	6	10	8
Size	6	8	6	10
Weight	4	7	5	10
Cost	2	10	8	6
	Total:	244	242	264

Factors	Weight Factors	F11-5	F11-10	AM1C-31
Efficiency	10	9.375	8.25	7.275
Disp. Volume	8	6.25	9.75	7.625
Size	6	6.75	5	9.25
Weight	4	6.25	4.25	9.25
Cost	2	9.25	6	4.75
	Total:	227.75	219.5	235.75

Image 25: Final Bike Assembly

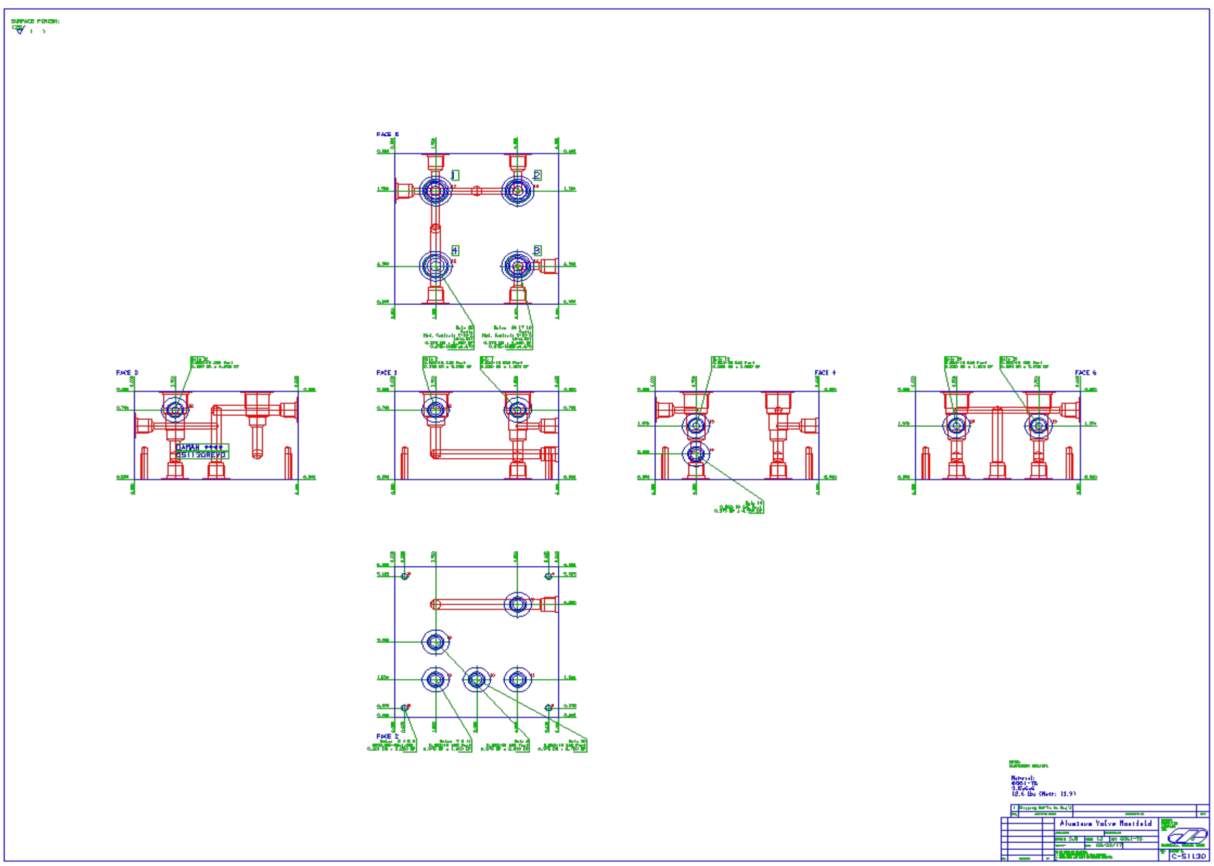

Figure 52: Manifold drawing for production

Table 38: Analysis & Calculations

Pump Rpm	Flow Rate (GPM) @ 750 psi	Calculate Pedal Torque @ 250 psi	Calculate Pedal Torque @ 500 psi	Calculate Pedal Torque @ 750 psi	HP @ 100 psi	HP @ 250 psi	HP @ 500 psi	HP @ 1500 psi	Line velocity 8mm (0.0262 ft) ft/s	Line velocity 1/2" ft/s	Reynolds number of 8mm line	Friction factor	head loss h_L ft	h_R ft	hp in fluid @ 750 psi	Torque from motor lb-ft	Motor rpm @ 750 psi	Low Gear (.417) @ 750 psi	Wheel speed (mph)
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
9.6900	0.0153	157.1831	157.1831	153.5697	0.0009	0.0022	0.0045	0.0134	0.0634	0.0027	4.1656	15.3641	0.2632	0.2632	0.0004	22.7500	0.0828	0.0377	0.0027
19.3800	0.0307	78.5915	78.5915	76.7848	0.0018	0.0045	0.0090	0.0269	0.1268	0.0054	8.3311	7.6820	0.5264	0.5264	0.0017	22.7500	0.3313	0.1509	0.0108
29.0700	0.0460	52.3944	52.3944	51.1899	0.0027	0.0067	0.0134	0.0403	0.1902	0.0081	12.4967	5.1214	0.7896	0.7896	0.0038	22.7500	0.7455	0.3396	0.0243
38.7600	0.0614	39.2958	39.2958	38.3924	0.0036	0.0090	0.0179	0.0537	0.2536	0.0108	16.6623	3.8410	1.0528	1.0528	0.0068	22.7500	1.3253	0.6037	0.0431
48.4500	0.0767	31.4366	31.4366	30.7139	0.0045	0.0112	0.0224	0.0672	0.3170	0.0135	20.8278	3.0728	1.3160	1.3160	0.0106	22.7500	2.0708	0.9433	0.0674
58.1400	0.0921	26.1972	26.1972	25.5949	0.0054	0.0134	0.0269	0.0806	0.3804	0.0162	24.9934	2.5607	1.5792	1.5792	0.0152	22.7500	2.9819	1.3584	0.0970
67.8300	0.1074	22.4547	22.4547	21.9385	0.0063	0.0157	0.0313	0.0940	0.4438	0.0188	29.1590	2.1949	1.8424	1.8424	0.0207	22.7500	4.0587	1.8489	0.1321
77.5200	0.1228	19.6479	19.6479	19.1962	0.0072	0.0179	0.0358	0.1075	0.5072	0.0215	33.3245	1.9205	2.1056	2.1056	0.0270	22.7500	5.3012	2.4149	0.1725
87.2100	0.1381	17.4648	17.4648	17.0633	0.0081	0.0201	0.0403	0.1209	0.5706	0.0242	37.4901	1.7071	2.3688	2.3688	0.0342	22.7500	6.7093	3.0564	0.2183
96.9000	0.1535	15.7183	15.7183	15.3570	0.0090	0.0224	0.0448	0.1343	0.6340	0.0269	41.6556	1.5364	2.6320	2.6320	0.0422	22.7500	8.2831	3.7733	0.2695
106.5900	0.1688	14.2894	14.2894	13.9609	0.0098	0.0246	0.0492	0.1477	0.6975	0.0296	45.8212	1.3967	2.8952	2.8952	0.0511	22.7500	10.0226	4.5657	0.3261
116.2800	0.1842	13.0986	13.0986	12.7975	0.0107	0.0269	0.0537	0.1612	0.7609	0.0323	49.9868	1.2803	3.1584	3.1585	0.0608	22.7500	11.9277	5.4336	0.3881
125.9700	0.1995	12.0910	12.0910	11.8131	0.0116	0.0291	0.0582	0.1746	0.8243	0.0350	54.1523	1.1819	3.4216	3.4217	0.0713	22.7500	13.9985	6.3770	0.4555
135.6600	0.2149	11.2274	11.2274	10.9693	0.0125	0.0313	0.0627	0.1880	0.8877	0.0377	58.3179	1.0974	3.6848	3.6849	0.0827	22.7500	16.2349	7.3958	0.5283
145.3500	0.2302	10.4789	10.4789	10.2380	0.0134	0.0336	0.0672	0.2015	0.9511	0.0404	62.4835	1.0243	3.9480	3.9481	0.0950	22.7500	18.6370	8.4900	0.6064
155.0400	0.2456	9.8239	9.8239	9.5981	0.0143	0.0358	0.0716	0.2149	1.0145	0.0431	66.6490	0.9603	4.2112	4.2113	0.1081	22.7500	21.2048	9.6598	0.6900
164.7300	0.2609	9.2461	9.2461	9.0335	0.0152	0.0381	0.0761	0.2283	1.0779	0.0458	70.8146	0.9038	4.4745	4.4745	0.1220	22.7500	23.9383	10.9050	0.7789
174.4200	0.2763	8.7324	8.7324	8.5316	0.0161	0.0403	0.0806	0.2418	1.1413	0.0485	74.9802	0.8536	4.7377	4.7377	0.1368	22.7500	26.8374	12.2257	0.8733
184.1100	0.2916	8.2728	8.2728	8.0826	0.0170	0.0425	0.0851	0.2552	1.2047	0.0511	79.1457	0.8086	5.0009	5.0009	0.1524	22.7500	29.9021	13.6218	0.9730
193.8000	0.3070	7.8592	7.8592	7.6785	0.0179	0.0448	0.0895	0.2686	1.2681	0.0538	83.3113	0.7682	5.2641	5.2641	0.1688	22.7500	33.1326	15.0934	1.0781
203.4900	0.3223	7.4849	7.4849	7.3128	0.0188	0.0470	0.0940	0.2821	1.3315	0.0565	87.4769	0.7316	5.5273	5.5273	0.1862	22.7500	36.5287	16.6405	1.1886
213.1800	0.3377	7.1447	7.1447	6.9804	0.0197	0.0492	0.0985	0.2955	1.3949	0.0592	91.6424	0.6984	5.7905	5.7905	0.2043	22.7500	40.0905	18.2631	1.3045
222.8700	0.3530	6.3627	6.8340	6.6769	0.0206	0.0515	0.1030	0.3089	1.4583	0.0619	95.8080	0.6680	6.0537	6.0537	0.2233	21.7275	45.8799	19.9611	1.4258
232.5600	0.3684	6.0976	6.5493	6.3987	0.0215	0.0537	0.1075	0.3224	1.5217	0.0646	99.9736	0.6402	6.3169	6.3169	0.2431	21.7275	49.9562	21.7346	1.5525
242.2500	0.3837	5.8537	6.2873	6.1428	0.0224	0.0560	0.1119	0.3358	1.5851	0.0673	104.1391	0.6146	6.5801	6.5801	0.2638	21.7275	54.2060	23.5835	1.6845