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Human-Assisted Fluid Power Vehicle

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WESTERN MICHIGAN UNIVERSITY
NFPA 2015/2016 Chainless Challenge
Project Report

"The Silver Bullet"

Western Michigan University
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1.0 Abstract/Executive Summary

The rising cost of energy has prompted industrial and technology companies to research and implement renewable or green energy sources in every aspect of their business. This green technology can consist of sources such as: solar, wind, fluid, or others to create energy from renewable sources. The use of these various sources reduces the pollution associated with standard methods of energy development, and it will ultimately drive costs down to benefit the general population. One of the largest benefactors to the use of renewable energy sources is the transportation industry. Billions of people rely on various modes of transportation every day, and the creation of renewable energy for transportation will help create a more sustainable society.

One innovative way to promote the research and development of renewable energy for transportation is through the Chainless Challenge competition hosted by Parker-Hannifin Corporation (Parker) and the National Fluid Power Association (NFPA). Established in 2004 the competition leads various students across the country to develop alternative transportation methods with the use of vehicles and fluid power. Western Michigan University (WMU) will be participating in this competition, and the team will consist of seven students (four mechanical and three electrical members) and two faculty advisors. The team represents the College of Engineering and Applied Sciences (CEAS) and this project is held as a senior capstone project.

The main objective for this project is to design and fabricate a unique energy-efficient fluid power system that is human-assisted. This system will be used to power an individual transportation device; it will also utilize green engineering concepts, and will go through extensive testing to ensure an optimal and efficient design. This project was approached through a typical engineering design process, which started with the definition of the need of the project, and the constraints that were required. Once those were established, the team defined specific goals/objectives for the project, and developed various criteria that would guide the project, and developed goals/objectives for the project. The next step was to brainstorm conceptual ideas for the project, and evaluate each alternative that was presented. Once the overall design was decided, the team began to design the details of the complete system, starting with the selection of the frame and the hydraulic components, then the system was modeled in CAD software and the hydraulic system was designed with simulation software tools.

The second part (i.e. spring semester) of this project was devoted to the fabrication, assembly, and testing of the system. The assembly of the various components was performed in steps, which started with frame modifications, then the mounting bracket fabrication and component placement, and finally the hydraulic system implementation. The hydraulic system is designed to operate at the most efficient levels possible for this application and features four modes of operation. The *direct drive mode* will move the bike through pedaling, the *charging mode* will pressurize the accumulators, the *discharging mode* releases the stored energy in the accumulators, and the *regeneration mode* will also store energy in the accumulators when the operator is braking or slowing down. This system is designed for the best performance during the various races at the competition, and our team is eager to see how well the system will perform against other competitors.

2.0 Problem Statement

2.1 Introduction

The most common transportation vehicle in the world today is the bicycle. There are over 1.4 billion bicycles worldwide, and approximately 130 million bicycles are being produced throughout the globe. Given that the global bicycle market is expected to exceed $77 billion this year, this is an industry that will continue to thrive. Since the basic design, in terms of the framework and the drive train, have remained the same over the past 100 years, this presents an opportunity to develop innovative modifications to the standard operating bicycle.

The challenge of innovation for this industry is to successfully combine two technologies – the bicycle and hydraulic power to produce a functioning transportation vehicle. The primary challenge is to utilize technologies that are not usually associated with each other to create an efficient design. Parker Hannifin, and now NFPA, sponsor this annual competition between various teams across the country to showcase innovative designs with hydraulics and bicycles. The goal of this competition is to support the education of engineering students in the use of fluid power and electronics for motion and control purposes. Another aspect that is added by this competition is the practical experience of working in an engineering team on a project with multiple components and timelines for various aspects of the vehicle.

Since a standard bicycle design has remained unchanged over the past century, new innovations in this field can spark increased interest in hydraulics and motion control. The ideal design of a human assisted fluid powered vehicle would optimize the performance of the vehicle for multiple conditions, while requiring minimal rider input. This chainless challenge competition has been performed by senior engineering students through the sponsorship of Parker and the NFPA. Fluid power and electronics applications will be researched to develop the necessary knowledge and skills to perform this project successfully. The engineering team will design, simulate, build, test, and compete with the proposed vehicle concept against other teams with the hopes of placing first in the Chainless Challenge competition.

2.2 Background

At Western Michigan University (WMU), the human assisted green energy vehicle concept has been conducted as a senior design project. The senior design project 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 Chainless Challenge are required to design and build the drive system for their vehicles, as well as participate in the final demonstration competition. Components for the hydraulic system such as the pumps/motors, accumulators, valves, hoses, fittings and fluid can be provided by Parker, up to a $2,000 limit. For the current hydraulic system design, our team decided to utilize multiple components from previous year's designs, thus supporting the concept of reuse/recycle, and only order the remaining needed components from Parker.

The final demonstration event is the final component of the Chainless Challenge, and is conducted over a two day period in California. The demonstration focuses on the head to head competition where teams face off with their vehicle designs, and includes a sprint race, efficiency challenge, and a time trial/endurance race. The presentation part is conducted on the second day of the event. Cash awards are also given to the top teams in each specified category for the competition.

Western Michigan University has participated in every Chainless Challenge competition. For each competition, a new design was implemented for use as a senior design project. For the Chainless Challenge this year, our group analyzed and researched previous WMU concepts to improve the hydraulic system design for this year. The 2012 and the 2015 Chainless Challenge designs from WMU are the primary focus for this year's engineering design process. Our team will analyze the hydraulic systems and the bicycle designs to promote ideas/innovations for the new hydraulic vehicle.

The 2012 WMU Chainless Challenge vehicle (Figure 1) was evaluated by the current team to determine if any improvements could be made to the overall design to be implemented in the current vehicle. The 2012 vehicle utilized an upright bicycle frame, which would provide the lowest weight and cost among other frames, but would also provide the smallest amount of mounting areas as well. The team utilized an aerospace pump/motor in its design, which provided a relatively high efficiency at low operating RPMs, and small size and weight. The team also utilized an aerospace accumulator with appropriate characteristics in terms of capacity, weight, and pressure. Finally, the hydraulic circuit used in this design is very simple; it incorporates few components, and is operated manually.


Figure 1: 2012 Chainless Challenge Bike

The most recent WMU vehicle in the Chainless Challenge, the 2015 entry (Figure 2) was also analyzed to provide input into the current design. The 2015 bike also utilized an upright frame, but it was used in a tricycle frame style, which increased weight, but also increased mounting area as well. The design utilized the Parker H3 pump/motor, which are larger and heavier components, but also variable displacement. For the 2015 design, the team also used two bladder style accumulators that used a lower capacity than the aerospace accumulator, but incorporates higher pressure. The hydraulic circuit for this design is quite different from the 2012 bike by incorporating more valves and hosing, but also a hand pump for charging the accumulator. This design also utilizes a gear train to change the operating velocity (i.e. rpm's) of the


Figure 2: 2015 Chainless Challenge Bike

pump for various conditions. Finally, the circuit is operated electronically, so the operator does not have to manually manipulate valves to change the fluid flow.

Based on the bike designs from previous WMU Chainless Challenge entries, the team for this year will focus on the improvement of multiple aspects of these designs. For the current challenge, the system will be designed for maximum efficiency, and minimum weight. The team will use a simple hydraulic circuit that utilizes few components to increase efficiency in the system. An electrical control system will also be used to control the valves to direct the flow of the fluid. A gearing system will also be used between the pedal and pump, and the motor and wheel to vary the rpm of the pump and motor. These components will be designed by incorporating input from evaluations of these components on previous designs.

2.3 Statement of Design Problem

The power production of a standard bicycle is limited to the capabilities of the rider to input energy. This limits the performance of the bicycle due to the physical abilities of the rider. A traditional bicycle lacks technical innovation since it has not been greatly modified for many years. Parker Hannifin and the NFPA recognize the need for innovations in this field, and have led them to host the 2016 Chainless Challenge 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 or pneumatics without any direct chain drive mechanism. The design style for the actual vehicle was not specified, and could include various options as long as it was limited to a single operator. The design and build of the system will be judged on factors such as ingenuity, safety, manufacturability, marketability, and others. The competition will be judged based on the performance of the vehicle in the three races: sprint, endurance, and efficiency. The combination of these factors will decide the best overall bicycle and will be part of the focus of the design objectives

3.0 Project Plan and Objectives

3.1 Objectives

The overall objective for this project is to design, fabricate, and test a unique energy-efficient fluid power system that is human-assisted. This system will be used to power an individual transportation device for the Chainless Challenge competition. The fluid power system is designed to deliver the optimal performance during the sprint, endurance, and efficiency races in the competition. The goals for our team is to create a unique vehicle compared to previous WMU entries, and meet all deadlines set forth by Parker Hannifin and the NFPA for the competition. Additional objectives for this project include:

- Maintain weight of vehicle under 210 pounds
- Implement electrical control of hydraulic circuit
- Include green engineering and sustainable processes
- Minimize cost of competition vehicle

In order to create a unique design for this project, it will be necessary to research existing systems and previous entries in this competition in order to decide on the type of vehicle to be used, and the configuration of the hydraulic circuit. To maximize the funds our team received from Parker Hannifin, previous components can be used, and affordable parts for the system will be researched based on their function. Lightweight Parker HD (Hydraulic Division) aerospace components were used to maintain a low weight for the vehicle.

There was also a team of three students from the Electrical and Computer Engineering (ECE) Department who worked on the development of an electronic control system to simplify the operation of the hydraulic circuit. This control system was designed according to the following guidelines:

- A system that must allow easy operation by the rider through a simple and intuitive user interface
- A system developed in a modular design
- A system capable of optimizing hydraulic operation parameters
- A system with high reliability and capable of promoting safety

Finally, both the mechanical and electrical teams had to be cautious to use the least amount of material possible and reduce the overall waste during the fabrication process. Each subsystem was constructed separately to ensure minimal rework and time for the assembly of the vehicle.

3.2 Project Planning

Since this project is conducted as an engineering project, it will follow a standard engineering design process from start to finish. The engineering design process starts with the definition of a need for the project, and typically ends with the delivery of the final product. Between these two steps, the project goes through conceptual designs, various analyses, tests and prototypes and final selection of a design. Figure 3 to the right shows a diagram of a typical engineering design process.

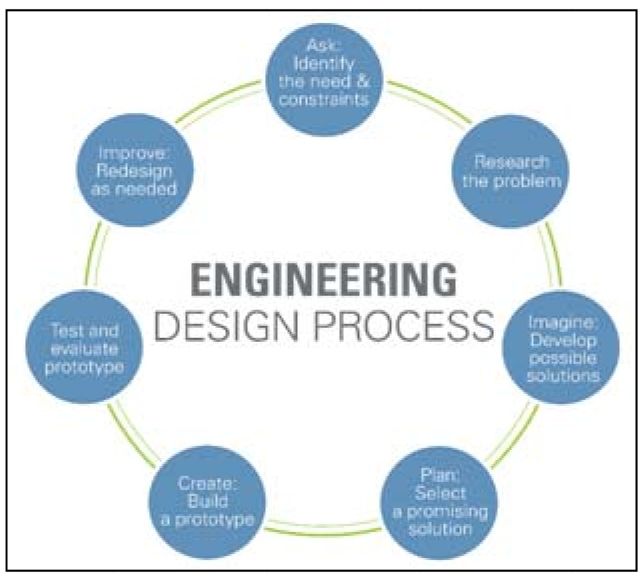


Figure 3: Design Process

The first step that was taken in this design process was to define the need for the project. As the sponsor for the Chainless Challenge, Parker Hannifin has already outlined the need for this project to be conducted. For this step, the criteria and the constraints for the project must also be identified. The second stage in this design process was to research the problem, and that was accomplished by the evaluation of previous designs and vehicles. The purpose of this step was to see what components were used in the past, and determine if any improvements could be made to the existing systems. The evaluation of the frame design, hydraulic system and components, and the electrical system would be used as input into the current design. The next step that our team conducted was to develop/brainstorm possible ideas for the overall design to satisfy our objectives. Some ideas that were incorporated in this step included:

- Selection of frame to be used
- Modifications needed for the frame
- Ease of manufacturing
- Component selection
- Component placement

After these ideas and many others were considered, an overall design for the vehicle can be created to evaluate further. Once our team developed options for the vehicle, we could begin to select a solution that best met the criteria outlined for the competition. Some evaluations for each design option included:

- Rider position
- Center of gravity
- Hydraulic system configuration/simulation
- Strength analyses (Finite Element Analysis)
- Safety and reliability
- System functional analysis

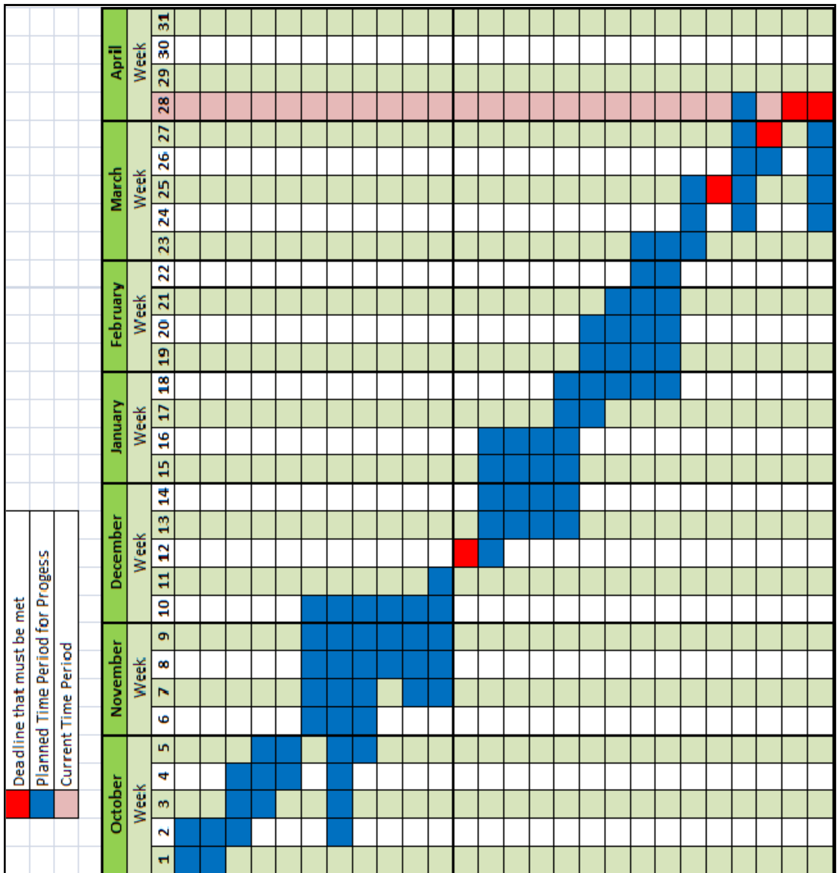
The implementation of the evaluations listed above would assist our team in the development of an ideal design to be used for the competition. Once an ideal design is selected, a prototype can be built to replicate the hydraulic circuit. The next step for our team is to build a prototype of the hydraulic circuit and use simple hydraulic components such as pump/motor, accumulator and reservoir. Once a prototype is built, it can be tested to ensure that it functions correctly. This test would validate the design of the circuit, and would show that the fluid could travel to the motor, turn the wheel, and that it could be stored in the accumulator, and finally released into the motor to also turn the wheel. After the hydraulic circuit is mounted, the entire vehicle could be field tested for successful operation. The final step in this process is to improve or redesign the prototype as needed for the competition. For this vehicle, the analysis from the field tests will be used to improve aspects of the design, such as component placement, hydraulic line placement, electrical system functionality, gear system, etc. Once all these systems function together properly, a final design can be agreed upon to use in the Chainless Challenge competition.

In order to ensure successful completion of this project, our group established milestone dates and other critical deadlines to ensure that we are completing tasks on time and progressing towards the completion of the final design. The milestones for our project also include those that are established by Parker Hannifin, which are focused on the three phases of participation verification, the midway review, and the final demonstration event. There are also milestones established by our group that include: background research, brainstorming ideas and design, building and fabrication, testing and modification, and the final demonstration. Each team, mechanical and electrical, established its own timeline, with the intention that development would be basically independent of each other, and in the last steps the integration of the two will take place. The figures below show the corresponding Gantt charts.

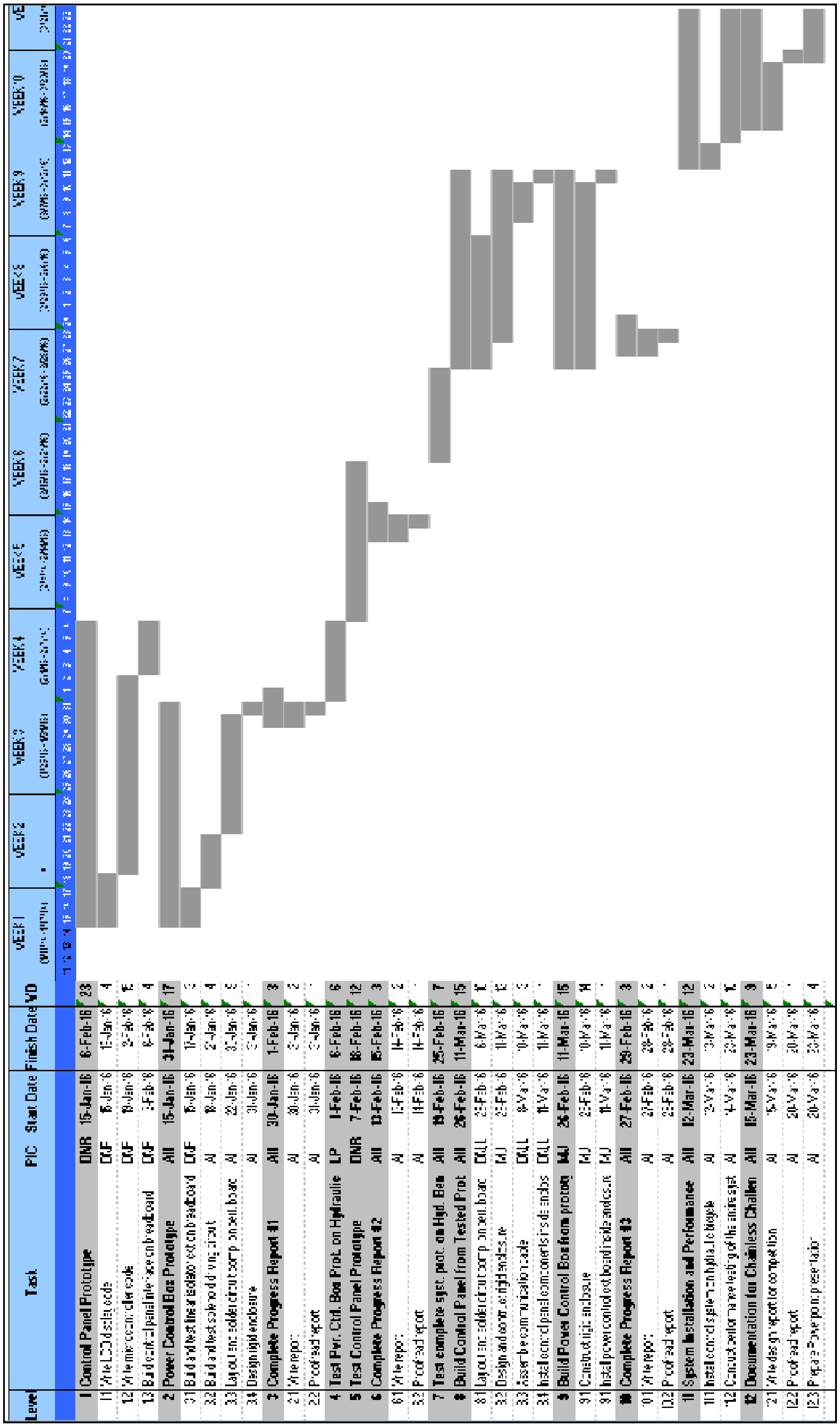
3.2.1 Mechanical Team Gantt Chart

Chainless Challenge 2015-2016

Activity	Plan Start	Plan Finish	Plan Duration	Actual Start	Actual Finish	Actual Duration	Precent Completion
Project Objectives	1	2	2	2	3	2	100%
Project Scope	1	2	2	2	3	2	100%
Bike Frame Research	1	3	3	2	4	3	100%
Frame Comparisons	3	5	3	3	5	3	100%
Bike Frame Selection	4	5	2	4	5	2	100%
Design Bike Frame Modifications	5	10	6	6	10	5	100%
Hydraulic Circuit Research	2	10	9	6	10	5	100%
Hydraulic Circuit Design	5	10	6	5	10	6	100%
Hydraulic Circuit Comparisons	8	10	3	7	10	4	100%
Create 3D CAD Model	7	10	4	6	10	5	100%
Midway Report & Presentation	7	11	5	8	11	4	100%
Order Components	12	12	1	12	12	1	100%
Analysis of Hydraulic Circuit	12	16	5	21	26	6	100%
Prototype Hydraulic Circuit	13	16	4	21	23	3	100%
Test & Analyze Prototype	13	16	4	21	23	3	100%
Vehicle Assembly & Fabrication	13	18	6	16	24	9	100%
Initial Testing/Troubleshooting	17	20	4	25	26	2	100%
Analysis of Data From Testing	18	21	4	25	26	2	100%
Improve Hydraulic Circuit	18	23	6	26	26	1	100%
Vehicle Improvements	18	23	6	20	26	7	100%
Final Vehicle Testing & Analysis	23	25	3	25	26	2	100%
Parker Vehicle Varification Demo	25	25	1	25	25	1	100%
Design Report/Presentation	24	28	5	25	28	4	100%
Shipment of Bike	26	26	1	26	26	1	100%
Chainless Challenge Competition	28	28	1	28	28	1	100%
Chainless Challenge Presentation	24	28	5	27	28	2	100%



3.2.2 Electrical Team Gantt Chart



4.0 Design Analysis

The design analysis is one of the most important aspects in an engineering project. The design analysis involves analyzing and evaluating every design factor of the project and making informed decisions in order to meet or exceed the design criteria. The following section shows how decisions were reached with the results from various tests and analyses that were performed. In order to be successful in this project, it was necessary to gather/compare data and make decisions based on these results, and advice from our advisors and various industry professionals. The design for the vehicle is limited by the constraints that are set for the competition, and the goal is to meet all of the project objectives while adhering to the required specifications and constraints.

4.1 Original Design Concepts

4.1.1 Power Transmission System

The first item decided upon for this project was the type of power transmission medium that would be implemented in our design. The rules state that either hydraulic or pneumatic power can be used with electronic sub systems. The decision to use hydraulics as the power transmission medium for the drive system was based on the resources available at WMU, personal experience involved with the use of hydraulic components, and knowledge available from our advisors and industry professionals. Among the many resources available at WMU, the most prominent is the Parker motion and control laboratory used for the testing of hydraulic components and systems. The knowledge and skills to use the laboratory effectively were acquired in the Fluid Mechanics and Hydraulics course here at Western Michigan University. This course gave an introduction to the functions and capabilities of hydraulics as well as the theoretical calculations associated with the use of hydraulics. Every previous Chainless Challenge team from Western Michigan has used hydraulics for their drive systems, and the decision to implement a hydraulic system rather than a pneumatic system provided a starting point and basis for this year’s project.

4.1.2 Vehicle Type

The following decision made towards defining the finished product was the type of vehicle the hydraulic system would be powering. Research was conducted on our past designs as well as those from other competing universities in past competitions. In the past, WMU has used three different types of bikes, those being the tricycle, upright, and recumbent, with the latter two being successful. There were other options available including vehicles with four or more wheels, but none of them were viable contenders due to their need for a more complex drive train to achieve satisfactory propulsion and control. The increase in complexity would cause in increase in power loss in the system, therefore decreasing efficiency, and since the input from the rider powers it the less power that is lost in the system the better. The decision between a tricycle, upright, and recumbent vehicle was made by taking the information on the vehicles, races, and awards given in the rules for the competition and creating a set of criteria ranked in order of importance to the design. These criteria were then used in a Pugh matrix where scores were given for each of the design types and then tallied up for comparison. The type of bike with the highest score, which was the upright bicycle in this case, was the one that was chosen as shown in Table 1.

Table 1: Frame Selection Pugh Matrix

		Upright	Tricycle	Recumbent
Factors	Weight Factor	Average	Average	Average
Safety	14	6	7	7
Weight	13	9	3	5
Adaptability	12	5	8	5
Mounting Area	11	5	8	5
Maintenance	10	8	6	5
Operability	9	7	7	3
Cost	8	8	5	3
Stability	7	6	8	9
Load Limit	6	5	8	7
Drag	5	7	3	7
Maneuverability	4	8	5	5
Climbing	3	4	7	6
Rider Comfort	2	7	6	9
Aesthetics	1	9	3	6
	Total Score:	668	630	577

4.1.3 Research and Brainstorming Ideas

After the decision on the frame, the next phase was to conduct research and brainstorm ideas. Research into previous designs, particularly those from WMU and past winners from other universities, was conducted to learn both from their successes as well as what could have been done better. We also looked into new ideas that had yet to be implemented in the Chainless Challenge.

1. **Reservoir Placement Optimization**

   The first concept that our group developed for the upright bicycle frame was the incorporation of the reservoir into the middle portion of the frame. The primary rationale behind this concept was to reduce the cross section of the bike, which would lower the aerodynamic drag, and increase the stability of the bike through the lower weight placement of the reservoir and the fluid. This concept was modeled in CAD software, and a very simple system was integrated on the frame to simulate how the custom reservoir would affect the placement of components. This concept was not further pursued because it did not place all of the hydraulic fluid above the pump/motor for successful operation, and it limited the placement of other components in the system.

2. **Frame Extension/Alteration**
A second concept that our group developed for the upright bicycle frame was the extension and the alteration of the shape of the frame itself. The upper and lower beams would be extended by five or six inches to accommodate additional components used in the gearing system. The extension on the frame would also provide easier mounting capabilities to other components. Since the frame would be longer than the standard frame length, it would give the bike a longer wheelbase, which would add stability to the vehicle. This modification would add additional space beneath the rider to mount components, and it also provides a unique look for aesthetic value. Another motivation for this frame alteration is the placement of electrical components. The electrical system incorporates multiple assemblies that need to be mounted within close proximity of the display screen on the front handlebars. The modified frame provides additional spacing to mount the electrical components in their needed locations.

3. **Aerodynamic Shell**
Another consideration to utilize in the final design of the bike is the incorporation of aerodynamic shells to shield the hydraulic components. The purpose of the shells is to reduce the aerodynamic drag on the bike when traveling at fast speeds. Reducing the drag would allow our design to use less energy to keep the bike traveling at a constant velocity. Since these shells can be fabricated from a variety of materials, it would give our team a lot of flexibility in terms of the design. The shells could also function as a safety feature for the rider in shielding them from moving parts such as the gear system. These shells can be produced from a variety of materials, and lightweight plastic can be used from a 3D printer, which would add minimal weight.

4. **Electrical Control System**
The electrical control system implemented in this design will be an improvement from previous entries from WMU. The electrical system on the bike will control all of the valves in the system to direct the fluid flow from one component to the other. A display will also be located between the handlebars to show important data to the rider. Control buttons will be located on the handlebars, so the rider doesn't have to move their hands to operate the electronics. Finally, the system incorporates a new control box to control the flow of fluid from the accumulator to the motor. This will be advantageous in the efficiency challenge, since the fluid can be released at finite increments.

4.2 Hydraulic System

4.2.1 Circuit Design
For the proposed hydraulic system, our team has identified four different fluid flow conditions necessary to achieve optimal performance of the bike through the variety of races in the competition. For deciding the components that we were going to use in our circuit, we used a similar method with Pugh matrices as above, including factors, weights, and an average of our individual scores to make our decisions. A sample of some of the calculations that were made to predict the performance of the bike using our proposed hydraulic system is shown in Appendix B.

1. **Direct Drive**
The first fluid flow condition is the normal cruising operation, where fluid is pressurized by the pump, that is driven by the rider pedaling. The pressurized fluid will then flow to the motor, which will turn to drive the back wheel. The normal cruising operation will be used most frequently during the competition.

2. **Charging Accumulator**
The accumulator charging mode will be used most when the rider input is not required to keep the bike in motion, such as traveling downhill. The rider input, instead of flowing to the motor, will be directed to the accumulator where the fluid is stored under pressure.

3. **Discharging Accumulator**
When this mode is activated, the pressurize fluid in the accumulator is directed to the motor to provide extra power and speed to the bike. The accumulator fluid can also be released during the normal cruising mode to assist the rider with uphill climbs, and provide an rpm boost to the motor for increased vehicle speed. This mode will also utilize the electrical components by controlling the release of the pressurized fluid in finite increments. This will benefit the bike during the efficiently challenge, because it will provide the most efficient use of the fluid to power the motor.

4. **Brake Energy Recovery**
In this mode, the motor mounted on the rear wheel will act as a pump to pressurize fluid and store the pressurized fluid in the accumulator. It would be activated when the rider slows down the bike to make a turn, and the rotation of the motor will pump fluid into the accumulator. This mode would also be used when the bike does not require the motor rotation to continue its motion. The rotational motion of the back wheel to turn the pump also provides resistance to the wheel, and functions as a brake system for the bike.

The hydraulic circuit shown below in Figure 4 includes all of the different desired flow conditions that we would like to obtain in our design.

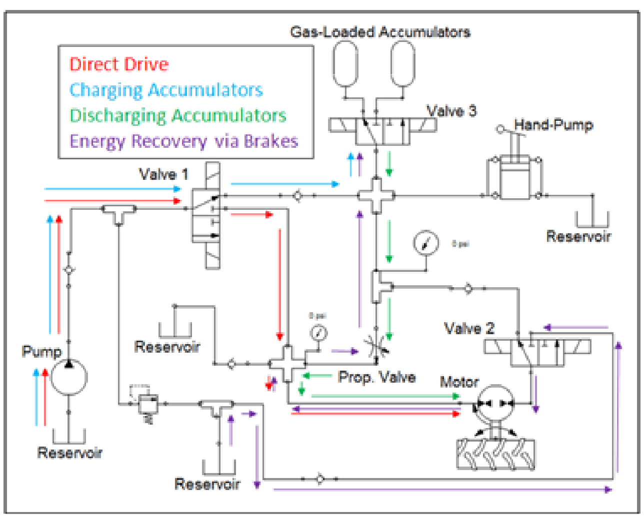


Figure 4: Hydraulic Circuit Schematic

4.2.2 Pumps/Motors

The Parker F11 series are bent axis, fixed displacement heavy-duty hydraulic motors/pumps. They can be used in a variety of applications in open and closed loop hydraulic circuits. The 40-degree angle between the shaft and cylinder barrel allows for a compact, lightweight motor and pump. The F11 series contain few moving parts, making them very reliable components. The F11 pumps and motors are available in frame sizes of 5, 6, 10, 12, 14, and 19 cc. As the frame size increases, the displacement also increases from 4.9 cm^3/rev (5 cc) to 19.0 cm^3/rev (19 cc). The weight also increases with the frame size, from 4.7 kg (5 cc) to 11 kg (19 cc) (Hydraulic Motor/Pump Series F11/F12, 2004). For this competition, our team was given performance information on the 5 and 10 cc pumps, so we continued our analysis of these components using those two frame sizes. The performance analysis and decision matrix for the 5 and 10 cc variants are found in Appendix A.

The Parker H3 series is a variable displacement, closed loop piston pump that was included in the analysis for the final design. The H3 is constructed from high strength aluminum, allowing the pump to be lightweight and corrosion resistant. An advantage of the H3 pump is the variable displacement, which can be varied while the pump is operating. The H3 displacement is 10.2 cc/rev, which is comparable to other F11 series 10 pumps. One of the biggest disadvantages of the H3 pump is the size, which would make it difficult for mounting purposes. The H3 weighs in at 3.6 kg, which is less than ether F11 series pumps. Also, the low speed (~500 rpm) efficiency of the H3 pump is approximately 20% lower than either the F11 5 or 10 series pump (Variable Volume Piston Pumps H3/H4/HP2 Series, n.d.).

The Parker PGP/PGM 500 series gear pumps/motors are advanced performance versions of the international bushing block style pumps. The PGP/PGM 500 pumps/motors offer superior performance, high efficiency, and low noise during operation at high pressures. The pumps/motors are produced in the PGP/PGM 505 and PGP/PGM 511 variants, which vary in frame size and displacement as well. The pumps are made from aluminum, and can be used in a variety of applications. Our team was given efficiency data on the 3cc, 6cc, and 10cc variants of the PGP505 pump. At an operating condition of 500 rpm, and 1000 psi, the 3cc, 6cc, and 10cc produce total efficiencies of 45%, 80%, and 88%, respectively. The 3cc variant weighs approximately 2.22 kg, while the 6 and 10cc variants weigh 2.38 and 2.58 kg (*PGP/PGM 500 Series, 2008)*.

The AP1C/AM1C aerospace series has a high overall efficiency of 92%. The AP1C/AM1C is an axial piston and fixed displacement configuration. The previous recumbent and upright design both use the aerospace series. One advantage of the aerospace pumps and motors over the F11 series is that they are much lighter. However, the aerospace series cost $10,000 per unit.

The various pumps/motors were simulated using the data that was provided from Parker. The analysis included a wide range of operating rpm that the pumps would be subject to during the various races. Using the change in rpm, the instantaneous horsepower, displacement, and flow rate were calculated. The overall efficiency for each pump was calculated, and this helped our team determine which pump to select for our design. Our team selected the AM1C-31 aerospace pump for this year's design. This pump offers a high efficiency of 84% at 600 rpm, displacement volume of 5.1 cm^3/revolution, and a flow rate of 2,558.9 cm^3/minute. This pump is also the lightest of the pumps at four pounds. Further pump/motor analysis can be found in Table 2 and Appendix A.

Table 2: Pump/Motor Analysis

Pumps	Flow Rate out	Hydraulic HP	Volume Occupied	Total Efficiency @ 500 RPM	Weight	Displacement volume	Cost
F 11-5 P@800	2206.9 CC/m	0.271	83.66 in^3	90.4%	11 lbs	4.9CC/rev	$600
F 11-10 P@400	4315.3 CC/m	0.265	118.13 in^3	88.4%	16.5 lbs	9.8CC/rev	$715
AM1C-31	2558.9 CC/m	0.252	38.25 in^3	84% @ 600 RPM	4 lbs	5.1 CC/rev	$800
PGP505 P@800	2270.58 CC/m	0.234	34 in^3	78%	5.26 lbs	6CC/rev	$250

4.2.3 Accumulators

The purpose of an accumulator in the hydraulic circuit is to store the energy produced by the rider. This is accomplished by pressurizing the fluid through the system and storing it at a high pressure so it can be released back into the system when the rider chooses, and this will provide additional energy to the motor for higher rpm. This higher rpm will be directed to the rear hub, which will deliver the rotational motion to propel the bike forward. During the efficiency race, teams will be allowed to charge the accumulators, and only the charged fluid in the accumulator can be used to propel the bike. The three types of accumulators that were considered for the system were: Bladder, Diaphragm, and Piston. Several accumulators provided by Parker were evaluated on the basis of: maximum working pressure, overall weight, dimensions, and volume of storage. The goal of this analysis was to identify the accumulator with a sufficient capacity, and minimal dimensions and weight.

Based on the data from Parker Hannifin that was provided to previous teams, accumulators of different types were ranked in terms of their performance. Accumulators for this hydraulic system were desired to have a high power to weight ratio, but the lower weight criterion was weighted the heaviest among all the other factors. Each accumulator was evaluated on factors of capacity (gal.), maximum pressure, weight, and the energy density. The energy density calculation was based on the potential energy, or work of the accumulator, over the weight of the accumulator when it is full of hydraulic fluid. The aerospace accumulator () achieved the highest figure in this category, and it also satisfies our capacity needs. The accumulator is one of the lightest accumulators available, and it was donated to our team, so the cost would not be a factor for this accumulator. The performance and decision matrices for the accumulators are found in Table 3 and Appendix A.

Table 3: Accumulator Analysis/Decision Matrix

Parker Accumulators	Gal	Weight (lb)	Weight (w/ oil)	PSI	Dimensions	Power vs. Weight
BA02B5T01A1	2.5	120	138.13	5000	22.5 x 9.6	1742
BA01B5T01A1	1	50	57.25	5000	17.25 x 7	1681
BA02B3T01A1	2.5	80	98.13	3000	21" x 9"	1471
BA01B3T01A1	1	34	41.25	3000	17"x6.75"	1400
AD280A25T1A1	0.74	20	25.37	3600	10" x 7"	2022
TOBUL 4.5AL-20	1.08	21.1	28.29	3000	49"x 4.6"	2205

4.2.4 Valves

Our team has a few options for the valves that will be needed to complete this system. We have also begun to look in the addition of electronic valves to the system. Most of the valves in the system will be implemented in a manifold, which will help keep the system centralized, and more compact. Solenoid valves would be used in the manifold to control the flow of hydraulic fluid from one path to the next. The hydraulic system will implement typical t-connectors between various hydraulic lines, flow control valves to direct the flow of fluid, and a variable control valve to manipulate the flow of pressurized fluid from the accumulator to the motor. The variable control valve and flow control valves will be electrically controlled, and they will be solenoid valves.

4.3 Bike Components/Analyses

4.3.1 Component Layout

Once the frame had been selected, the component placement and the mounts to the frame could be determined. After the components were selected, the size and weight information was known. The placement of each component was determined by the function, weight, size, rider position, and circuit location. The initial design is shown in Figure 5.

First, the pump needed to be located lower than the reservoir to increase the gravity feed for the flow input. It also needed to be located near the pedal crank for the energy input. The pump was mounted vertically underneath the rider using a right angle gear, which allows for clearance of the riders legs while obtaining energy from the pedal. The vertical orientation also allows for easier assembly/disassembly of the hydraulic lines.

Placement of the motor needed to be near the rear wheel to take the energy from the fluid flow and direct it to a set of gears to rotate the tire. A vertical orientation was also implemented to allow for the simplest circuit assembly. A right angle gear was also used to reduce the cross section of the bike, which increased the aerodynamic performance of the bike.

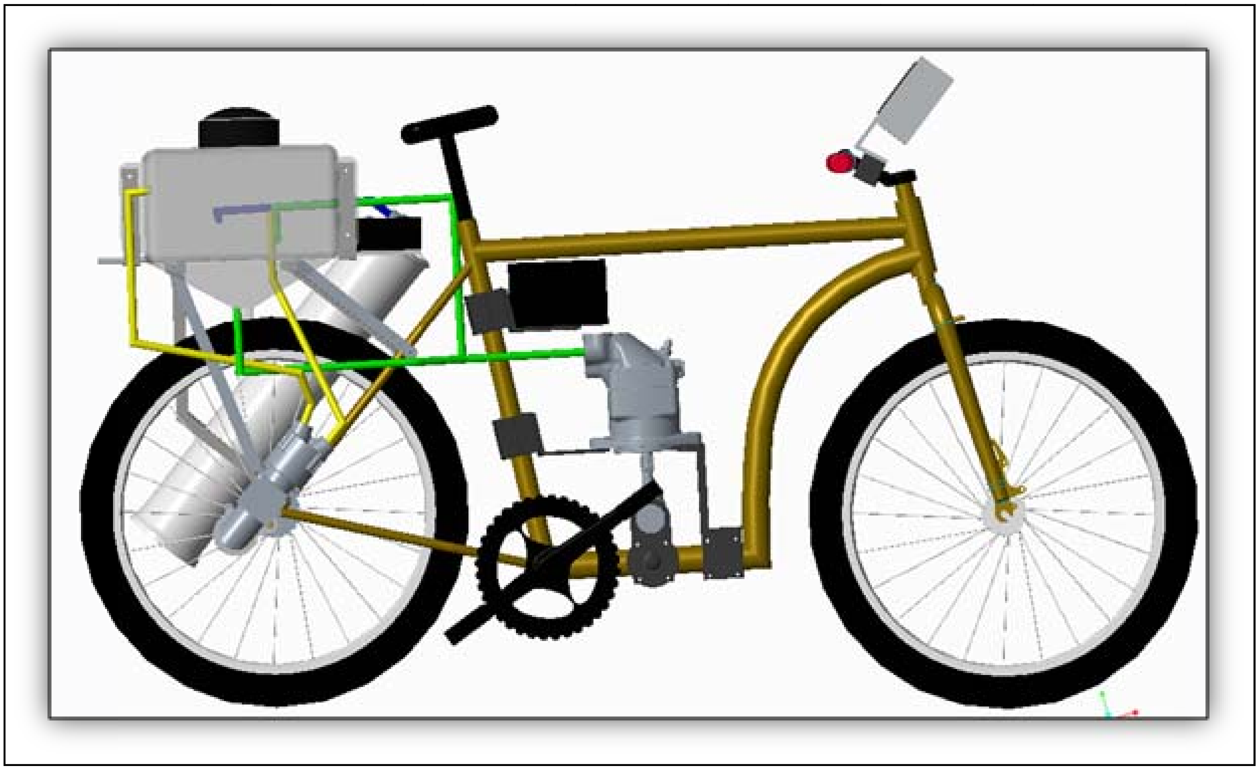


Figure 5: Original CAD Model

The location of the accumulators was chiefly based on the weight distribution of the bike. The accumulators represent a large portion of the weight, so the locations had to accommodate a large enough mount to securely place them. One accumulator was mounted in the center over the back tire, which would help maintain the balance during operation. The second accumulator was mounted on the side of the frame to offset the weight from the reservoir and the motor. The placement for the accumulators reduced the length of fluid line between them, and allowed for full rider movement.

Placement of the reservoir was based on the circuit that was developed and the other hydraulic component locations. The only restriction on the location of the reservoir was the elevation in reference to the pedal pump and the hand pump. Since the volume of the reservoir was quite large, it was decided to be mounted behind the rider and offset from the center to counter the weight from the accumulator.

The location for the directional control valves was decided to be placed behind the rider on a plate mount which would consolidate all the valves in one location. The valves were centered above the rear tire to maintain a minimal weight distribution, and the consolidation of the valves reduced the length of line that would be run between them.

4.3.2 Pump Mounting

The pedal pump mount was designed to secure the pump during operation, and restrict the movement while the gears are engaged. The mount was designed to clamp onto the frame to prevent linear motion. A second mount for the pump was included to attach from the frame to the 90 degree angle mount to reduce the motion caused by the gear rotation from the angle gear into the pump. Both brackets were manufactured from aluminum to provide adequate strength for the mounts, and to keep the overall weight as low as possible. The pump bracket is shown below in Figure 6.

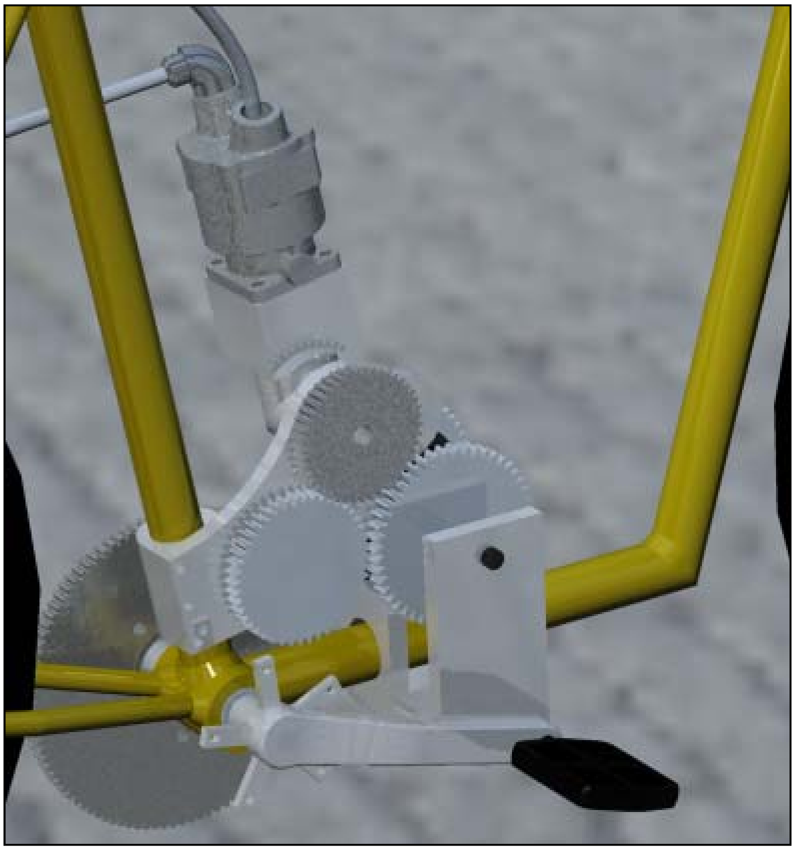


Figure 6: Pump Mounting Bracket

4.3.3 Motor Mounting

The motor bracket was attached to the frame from three different locations. It was manufactured from a block of aluminum, and the right angle gear system was tightened to it with set screws. Since the bracket could not be clamped to the frame, it was bolted on near the rear gear hub. The second mount for this bracket included another bracket that was mounted higher on the frame, and was attached with a turnbuckle. The turnbuckle allowed the tension to be adjusted, which gave the ability to adjust the gear alignment from the motor to the rear hub. The motor bracket was also supported by the steel tubing that ran from the motor output to the rear mounting plate. The addition of this tubing ensured that the motor would endure minimal motion from the movement of the bike. The motor mount bracket is shown in Figure 7.

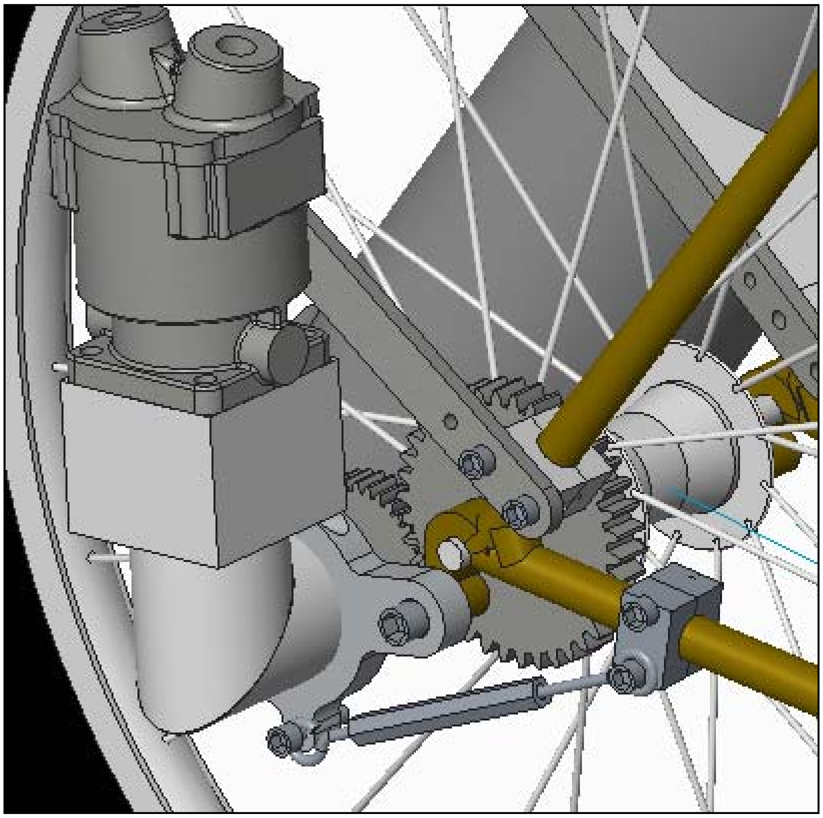


Figure 7: Rear Motor and Mounting Assembly

4.3.4 Accumulator Mounting

Since the accumulator is the heaviest single component, and is highly pressurized, it is imperative that it is securely mounted. The mounting brackets for each of the accumulators are of the same design, but are mounted to different parts of the bike. The first mount is located along the side of the frame, and is secured to the steel arms from the rear mounting bracket. The bracket incorporates a semi circle cut out for the accumulator to fit securely into. High strength metal ties are then wrapped around the other half of the accumulator and bolted into the bracket. The second accumulator is mounted above the rear tire and under the rear mounting plate. The same bracket design is incorporated for this location, and it is bolted to the plate above it. Metal ties again are used to fully secure the accumulator. The design of these mounting brackets also allows for easy access and maintenance to the accumulators. Figure 8 below shows the accumulator mounting bracket attached to the side of the frame.

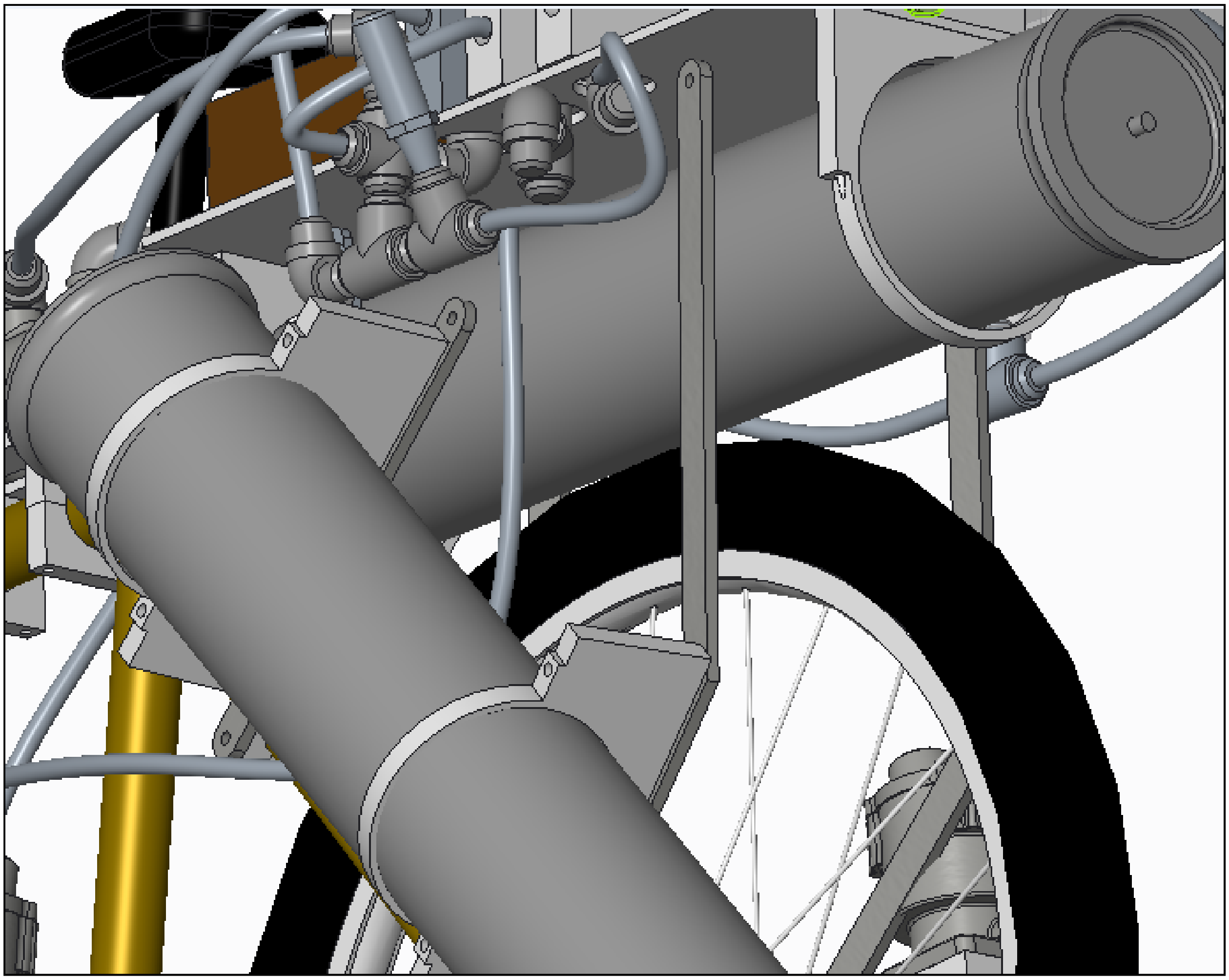


Figure 8: Accumulators and Mounting Brackets

4.3.5 Rear Mounting Plate

The rear mounting plate is vital to the placement of the valves and other various hydraulic and electrical components, so it must be properly mounted to ensure these components can function correctly. The body of the plate is made from aluminum, and is attached to the frame at four different locations. The bottom of the plate contains four brackets that are welded to it. Four steel beams are anchored to these brackets, and provide the needed support for the weight of the plate. Additional brackets were manufactured, and clamped to the frame to attach to the other end of the beams. The combination of the welded and clamped brackets provides a rigid structure to support the weight of the plate and the components that are mounted on it. An additional angle piece of aluminum was mounted from the middle of the frame to the rear of the beams to reduce the motion of the structure during operation. It is shown below in Figure 9.

Figure 9: Rear Mounting Plate

4.3.6 Hand Pump Mounting

The hand pump is one of the most important components of the hydraulic system. It is used to charge the accumulators to the correct pressure, and it can also be used to power the bike if the direct drive mode fails. Since the pump will be used extensively, the bracket must be able to withstand the constant force that it will be subjected to during the hand pump operation. The hand pump itself is mounted under the seat, so the bracket had to incorporate a small volume. Two angle pieces of aluminum are located on either side of the pump, and are bolted to two brackets that are clamped to the top tube. The analysis of this bracket is shown in Figure 10.

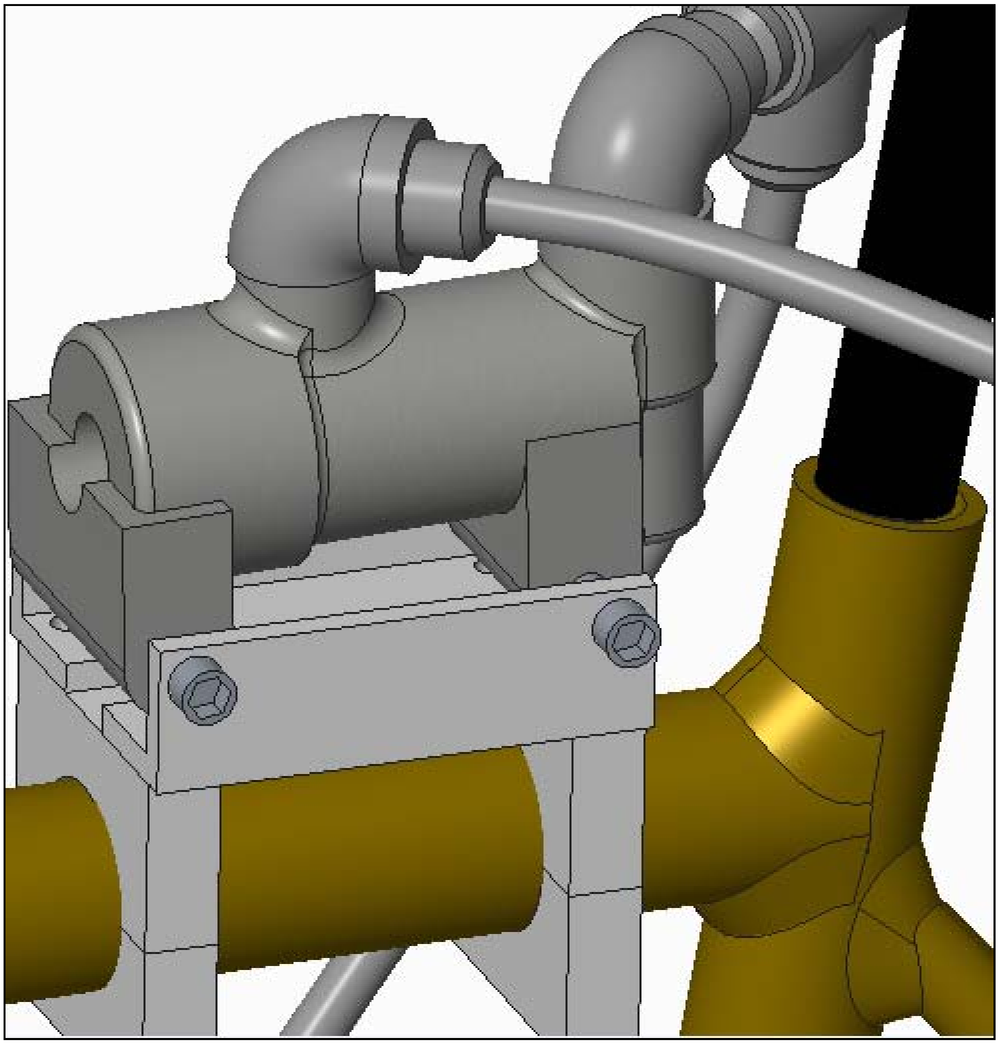


Figure 10: Hand Pump Mounting Bracket

4.3.7 Gear Train System

1. Pedal to Pump Gear Train

To achieve the desired pump rotational speed over 600 RPM, it's necessary to create a gear ratio of at least 1:10. With this gear ratio, the rider would have to maintain a pedal RPM of 60, which is very difficult in this application. A larger gear ratio was established to aid the system to achieve the highest pump RPM through various situations. The pedal to pump will have a ratio of 1:6, combined with a Milwaukee 90-degree bend having a ratio of 1:1.5, and a Shimano Alfine SG-S501 hub containing eight different gears spanning a gear ratio of 1:0.53 to 1:1.62. This means when in the highest gear we can achieve our target pump RPM of 600 with the rider pedaling at approximately 35 RPM. With this wide range of gears, it enables the rider to start the bike off with a very low ratio reducing the initial torque, while also giving the ability to increase the ratio during cruising to hit our target pump RPM where pump efficiency is highest. Our gear ratio range with this set-up will span from a ratio of 1:4.77 to a ratio of 1:14.58.

2. **Motor to Wheel Gear Train**

When looking into gear ratios from the motor to the wheel we were less concerned about initial torque because of the hub we had placed in the front of the drive train. The drive train in the rear is basic, a direct gear interaction between the motor to the back hub will drive the wheel. Knowing we did not need as many gears in the rear of the drive train we targeted a smaller hub. The hub that stood out was the Sram i-3. This hub has three gears with outputs of 73%, 100%, and 136% of the input. This creates the ability to increase the output of the motor without having a large hub. Also, we already have a wheel with this hub integrated into it so it reduces time we would have to fabricate/assemble a new wheel/hub assembly. So if the rider can maintain an RPM of 50 we can get a speed between 10 mph to 23 mph depending on the gear selection.

4.4 Electrical System Design

4.4.1 System Requirements

The aim of the electronic control system is to allow implementing all the required configurations of the hydraulic circuit with minimal intervention from the rider. Such a system must be able to set the appropriate discharge of the directional valves and provide the means to regulate the release of the pressurized oil in the accumulator. In addition, the system must be capable of producing measurements of speed and pressure, take input from the rider, give visual feedback about the status of the circuit, and enforce safety.

4.4.2 System Specifications

Based on the stated requirements the following specifications were identified:

1. The control system must accept commands from the rider.
   - A way must be provided to switch the system on and off
   - The system must allow the rider to set the five hydraulic operation modes
   - The system must give the rider the ability to control the flow through the proportional valve
2. The control system must be able to set the discharge position of each directional valve following a proper sequence.
   - The control system must manage the power supply to the solenoids on the directional valves.
3. The control system must regulate the liquid flow rate through of the proportional valve.
   - The system must have the ability to increase the flow rate
   - The system must have the ability to decrease the flow rate
   - The system must have the ability to shut off the proportional valve
4. The control system must measure the traveling speed and pressures from two different locations of the hydraulic circuit.
   - The system must incorporate a speed sensor.
   - The system must incorporate two pressure sensors.
5. The control system must give the rider real-time visual feedback on the traveling speed and status of the hydraulic circuit.

- Pressure readings from accumulators must be provided.
- The traveling speed must be indicated by the system.
- The system must show the selected mode of hydraulic circuit operation.

6. The control system must enforce basic safety requirements.

- The system must give warning when the speed limit is being approached (Parker imposes maximum speed limit of 45 MPH for all vehicles taking part in the Hydraulic Bicycle Challenge Competition [5]).

4.4.3 Design Parameters

The following parameters were adhered to:

- A microcontroller will process user input, generate signals to drive the solenoids, and collect sensor data.
- Graphical LCD display will provide the rider with all the feedback data simultaneously.
- User commands will be received by the microcontroller through push buttons.
- The control system will be powered from separate voltage sources:
    - Low current components (microcontroller and LCD display) will be powered from a 9 VDC battery.
    - High current components (solenoids) will be powered from a 12 VDC battery.
    - Non-galvanic interfaces will isolate the digital circuitry from the high current circuitry.
    - Linear isolator circuits will interface the microcontroller with the pressure sensors.

4.5 Safety

As with any engineering project, safety was considered among the most important factors in the design of the hydraulic circuit and the components involved. On each bracket and other mounting components finite element analysis (FEA) was performed for proper safety during operation. A pressure relief valve was implemented to ensure the pressure developed in the system never exceeds the safe working limits of the components. All valves as well as the accumulator are all rated for a minimum of 3000 PSI. Finally, mounting hardware and other additional equipment was designed manufactured with safety in mind, with no protruding edges or sharp corners.

4.6 Final Product

4.6.1 Final Product and Testing

Upon completion of final assembly, the bike was tested for performance and functionality in order to ensure optimal riding conditions for the competition. The overall weight of the final assembly was measured at about 155 pounds with oil included. Several tests runs were completed on campus to ensure the modes of operation were functioning correctly. The direct drive mode, as well as the charging and discharging of the accumulator were verified to operate the bike successfully. A picture of the final assembly is shown below in Figure 11.

Figure 11: Bike after Final Assembly

5.0 Design Analysis

5.1 CAD and Bracket Analysis

Upon creating the bracket system that is used to support our components including the accumulator, reservoir, manifold with solenoids, and an electrical control box, it was then necessary to analyze this system virtually under expected loading conditions. The simulation for the Finite Element Analysis (FEA) on our CAD model was done using CREO Simulate. This step is a crucial part in the fabrication of components to ensure that the system is safe. To the right in Figure 12 is a model of the final design component bracket that has been selected. Forces that are acting on this model include a reservoir weight of 20 pounds (including fluid), 17 pounds acting on each accumulator bracket, and an accumulated weight of 20 pounds acting as miscellaneous components secured on the top plate. These components consist of manifolds, solenoids, and an electrical control box to be used in the

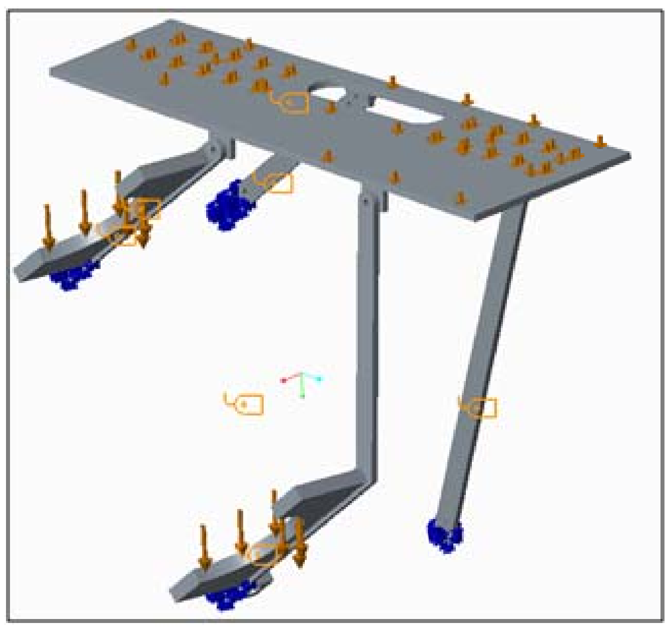


Figure 12: FEA on Rear Mounting Plate and Supporting Brackets

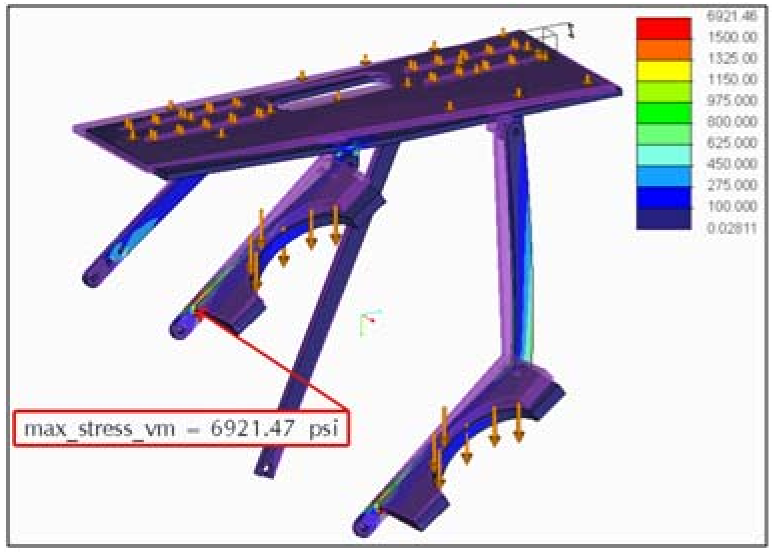


Figure 13: Von Mises Stress Distribution

design. The weights of these components were measured in lab, and then over exaggerated in our simulation to account for a worst case scenario.

There are two materials to be used in the fabrication of this bracket system. Steel bars are to be used for the supporting of the component plate where it would be expected to fail. The yield strength of steel is much higher than that of aluminum which is why this setup was selected. To reduce the weight of the system, 6061-T6 Aluminum was selected to be the material used for the accumulator brackets, and the component plate. This material is used in areas where the least amount of bending would take place hence the use of steel to hold up these other brackets. Above in Figure 13 is a simulation of the forces acting on the support system while the bike remains at an upright position. The maximum Von Mises stress magnitude is located on the system below which occurs in the steel material. With the yield strength of the steel material to be 42,000 psi, and a satisfactory safety factor of 5, this system has tested to withstand the stresses accumulated from the weight of the components.

Displacement for the simulation, as shown in Figure 14, was calculated to have a magnitude of only 0.00365 inches downwards, towards the front of the component plate. This amount is deemed satisfactory in a sense that it is not going to generate issues when mounting components or placing hydraulic lines in the system.

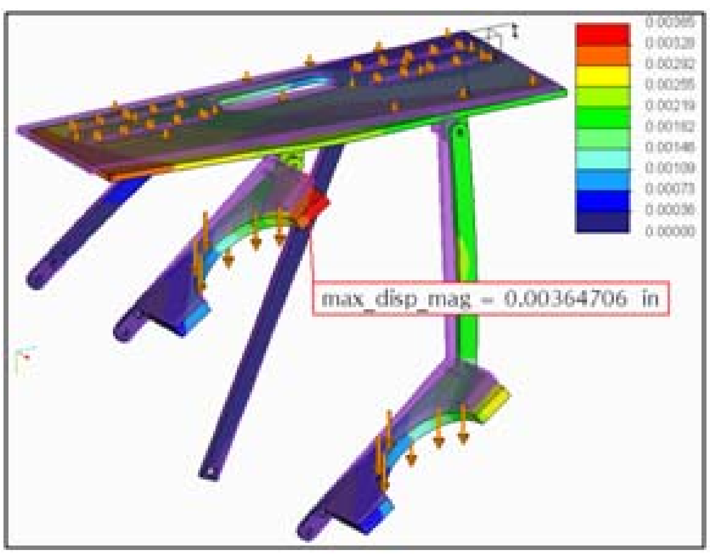


Figure 14: Deformation Distribution

After a frame was selected, and a basic hydraulic circuit was developed, the next step was to develop a CAD model of the system. The team used CREO Parametric 3.0 software to produce a visual representation of the bike and the hydraulic system. The goal of the CAD model was to verify the positioning of the components on the frame. The model could be used to determine if the location of the mounted components were feasible for the design. The CAD model of the design would also assist the team in the determination of modifications that were needed to accommodate the hydraulic components. The CAD model below showcases the current concept for the bicycle design.

5.2 Electrical Design Analysis

The electronic control system was implemented with several interconnected components. These components are:

- Control panel
- Push buttons
- Speed sensor
- Power control box
- Solenoids
- Pressure sensors

5.2.1 Control Panel

The control panel was developed in order to facilitate the interaction of the rider with the control system. This panel was composed of a rigid box containing an STM32F4 Discovery microcontroller board, a μLCD-43PT graphic LCD display, and a custom-made interface board with several ports for connecting other peripheral devices in the system. The panel was mounted at the center of the handlebar to give the rider direct view of the information displayed on the LCD screen.

The LCD display and the microcontroller were programmed to provide information on the speed of the vehicle, travelled miles, pressure in the accumulators and on the motor line, current configuration of the hydraulic circuit, and a line of text describing an existing alarm condition. Originally, a high speed alarm and a high pressure alarm were considered, but after some thought, the high pressure alarm was considered unnecessary due to the existence of a pressure release valve in the hydraulic circuit. Figure 15 provides an initial representation of the proposed control panel next to actual panel after final assembly.

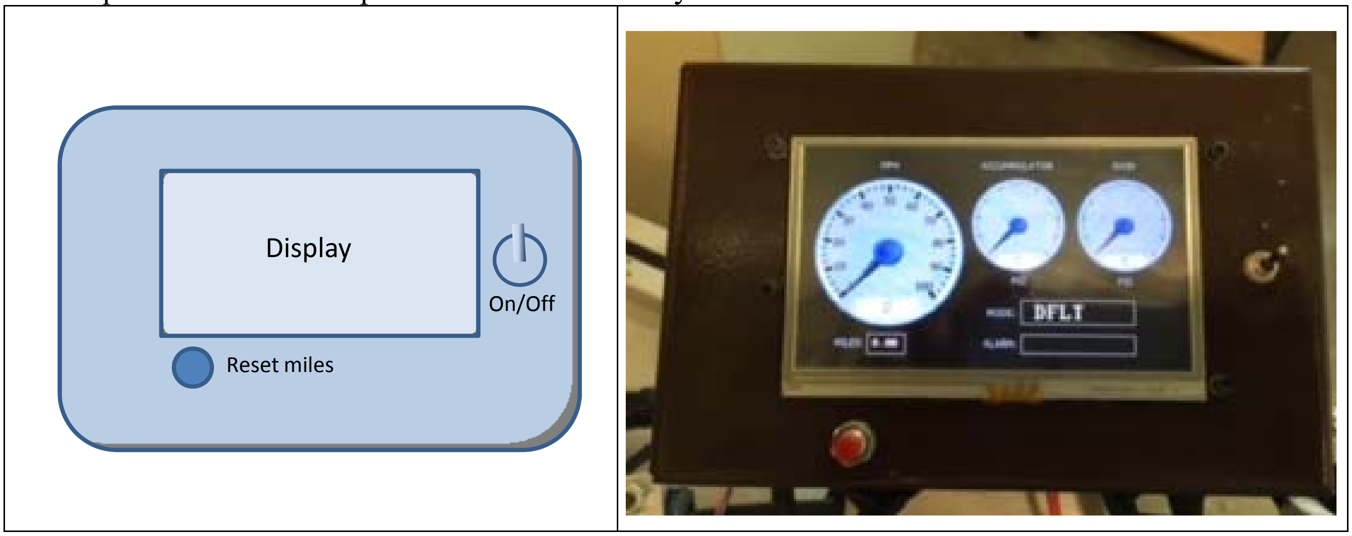


Figure 15: Planned layout of the control panel (left). Finished control panel showing the gauges that provide information on the display (right).

A circuit diagram showing how the components of the control panel were interfaced is shown in Figure 16.

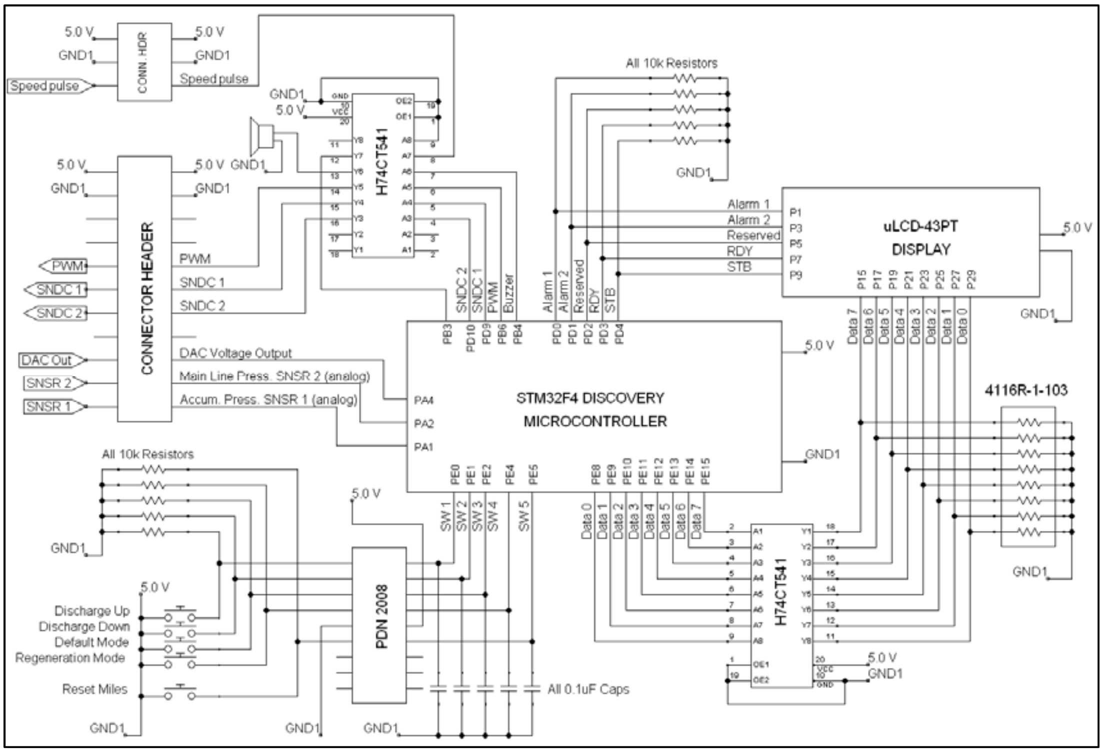


Figure 16: Control panel interfacing circuitry

5.2.2 Pushbuttons

User commands are issued to the microcontroller through pushbuttons. The available commands allow setting the hydraulic circuit in four basic modes of operation: Default Mode, Charging Mode, Discharge Mode, and Regeneration Mode. Another push button, mounted on the top face of the control panel, is used for resetting the mile counter after the bicycle has travelled some distance. The buttons that control the operation of the hydraulic circuit are mounted near the grips of the handlebar, so as to provide easy access to the rider. Three buttons have been placed on the right-hand side, and one button is located near the grip on the left-hand side. The buttons on the right-hand side have been programmed to allow the rider set a discharge rate of fluid from the accumulators, charge the accumulators via the pedal pump, and to quickly return the bicycle to idle state (Default Mode). The single button on the left-hand side of the handlebar is used to toggle the hydraulic circuit between the Default and Regeneration modes. Figure 17 shows the actual placement of the control buttons on the handlebar.

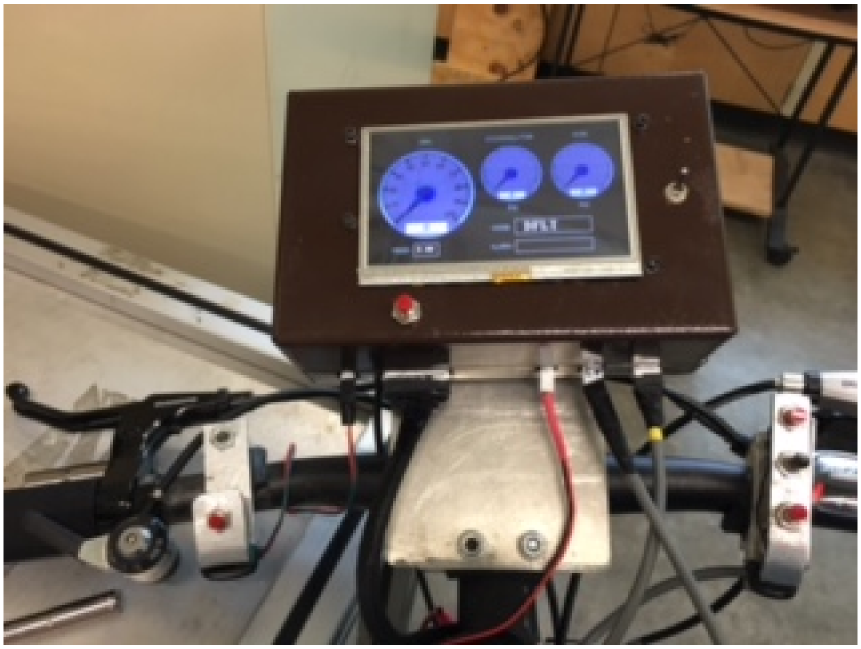


Figure 17: View of the handlebar with the control panel mounted and the pushbutton plates on either side.

5.2.3 Speed Sensor

The speed sensor for the control system is composed of an A1469 hall-effect sensor in the typical wiring configuration. This sensor is manufactured by Allegro Microsystems. It outputs a high state signal at the level of the supply voltage when no magnetic field is present. When a magnetic element comes in close proximity with the sensor, the output quickly toggles to a low state. The magnetic field in this case is provided by a magnet attached to the spokes on the bicycle's front wheel. The magnet passes near the sensor each time a revolution is completed. The output of the speed sensor is connected by cable to the interface board in the control panel. The board ties the sensor, through a non-inverting buffer, to a microcontroller pin configured for input capture functionality in combination with one of the microcontroller timers. To calculate the speed of motion of the bicycle, the microcontroller keeps track of the time elapsed between subsequent revolutions. The distance covered by one revolution divided by the time it took to complete the 360-degree turn is the speed of the bicycle. The value calculated this way is shown by a speed gauge on the LCD screen of the control panel. The speed sensor circuit is provided in Figure 18 as shown below.

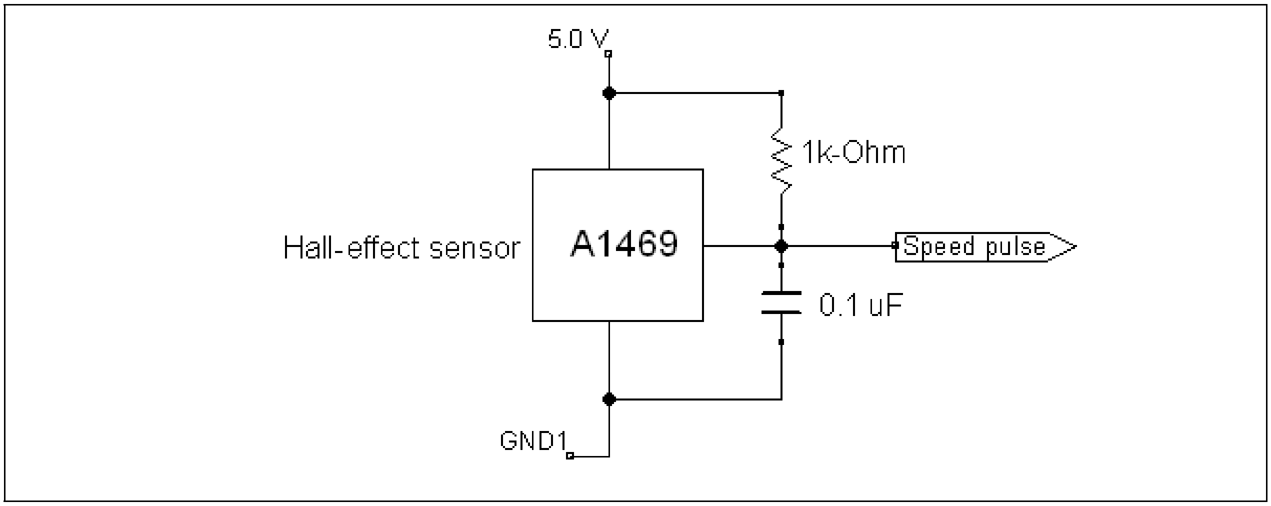


Figure 18: Speed sensor circuit based on an A1469 Hall-effect sensor.

5.2.4 Power Control Box

The actual operation of the hydraulic components occurs inside the power control box. The box is mounted in the rear of the bicycle, and serves as the interface between the control panel and the solenoid valves and the pressure sensors. The power control box is made of a rigid enclosure which houses a custom-made circuit board. The board contains four electronic circuits that are responsible for operating three solenoids and for conditioning the output signals from the two pressure sensors monitoring the hydraulic circuit. Commands to energize or de-energize the valve solenoids come from the control panel, through a cable link, once the user has issued a command by pushing one of the buttons on the handlebar. The cable link is also used to transfer the output of the pressure sensors to the control panel to be processed and displayed, after being converted to voltage signals in the power control box. The power control box operates with two voltage levels: 5 VDC and 12 VDC, which come from the two separate batteries that power the system. The interaction between the components on these two power sources is accomplished using optoisolators, which shield the digital components on the 5-volt power source from the noisy operation of the solenoids on the 12-volt circuit side. Two of the circuits built on the power control box board manage the power to the two on/off solenoids on the hydraulic system. These solenoids operate the valves that set the fluid discharge for the Charging and Regeneration modes. The third circuit is a voltage-controlled current source that is used to provide different current levels to the solenoid mounted on the proportional valve. This valve controls the discharge from the accumulators. The fourth circuit is composed of two linear isolators whose function is to transfer the sensor signals from the 12-volt supplied side to the 5-volt circuitry. A picture of the finished power control board is shown in Figure 19.

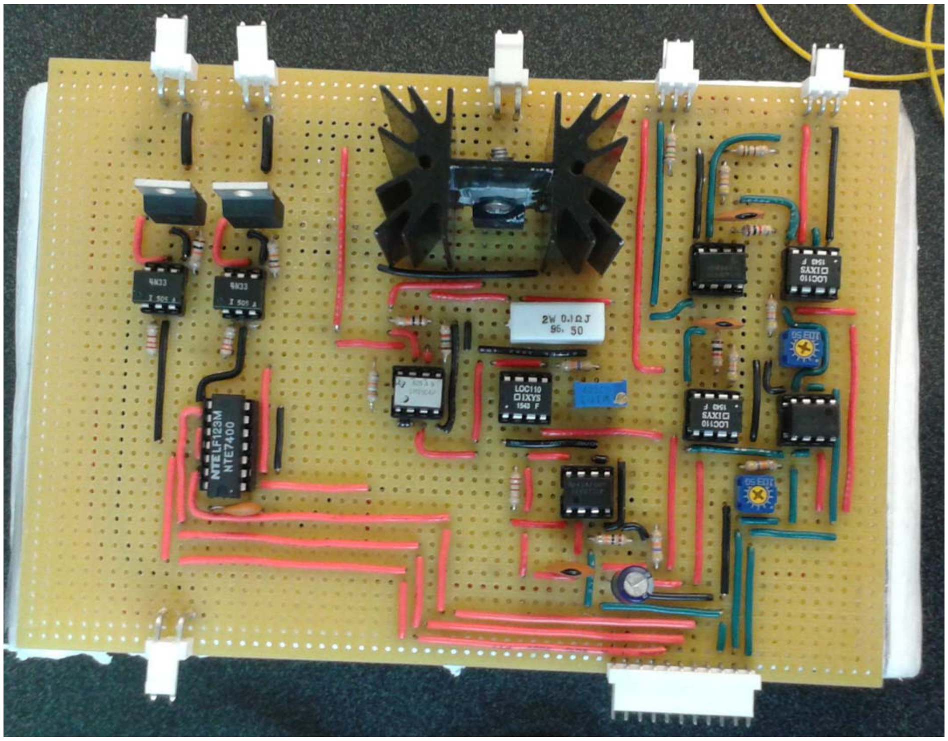


Figure 19: Finished power control box circuit board

5.2.5 Solenoids

The solenoids used in this application are standard 19-Watt Parker solenoids. Power to the two on/off solenoids was provided through the circuit shown in Figure 20.

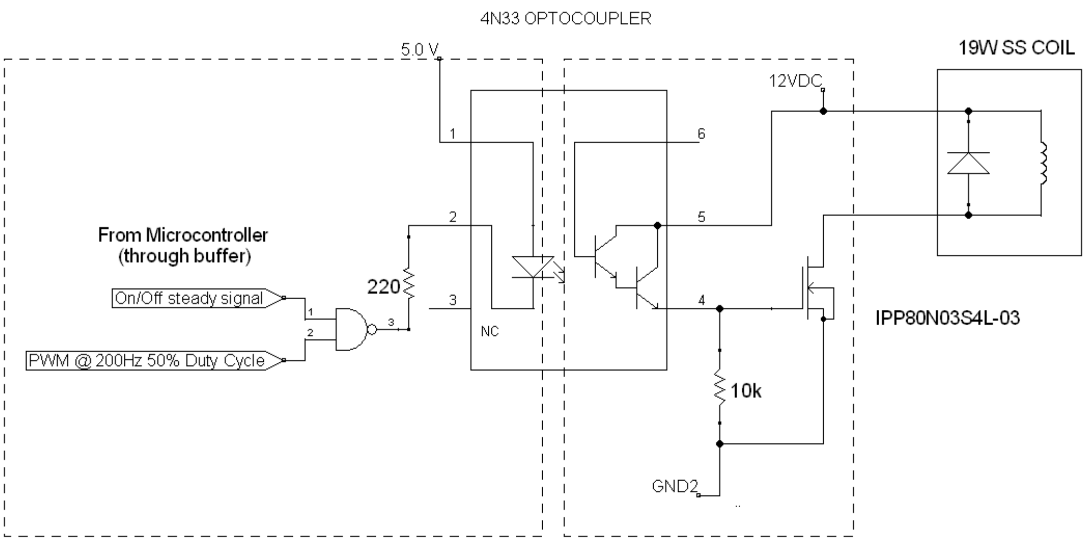


Figure 20: Microcontroller-solenoid interface inside the power control box

Two signals from the microcontroller were used to switch the solenoids on and off. One signal was just a steady low or high state, and the other signal was a square wave with a frequency of 200 Hertz and 50 percent duty cycle. The square wave signal was common to two of the solenoids in the system, so a total of three signals were used to control two solenoids. The solenoid on the proportional valve was controlled using a circuit as depicted on Figure 21. This circuit is a linear voltage-controlled current source capable of providing a current range between 0.003 and 1.09 Amps for the solenoid to operate.

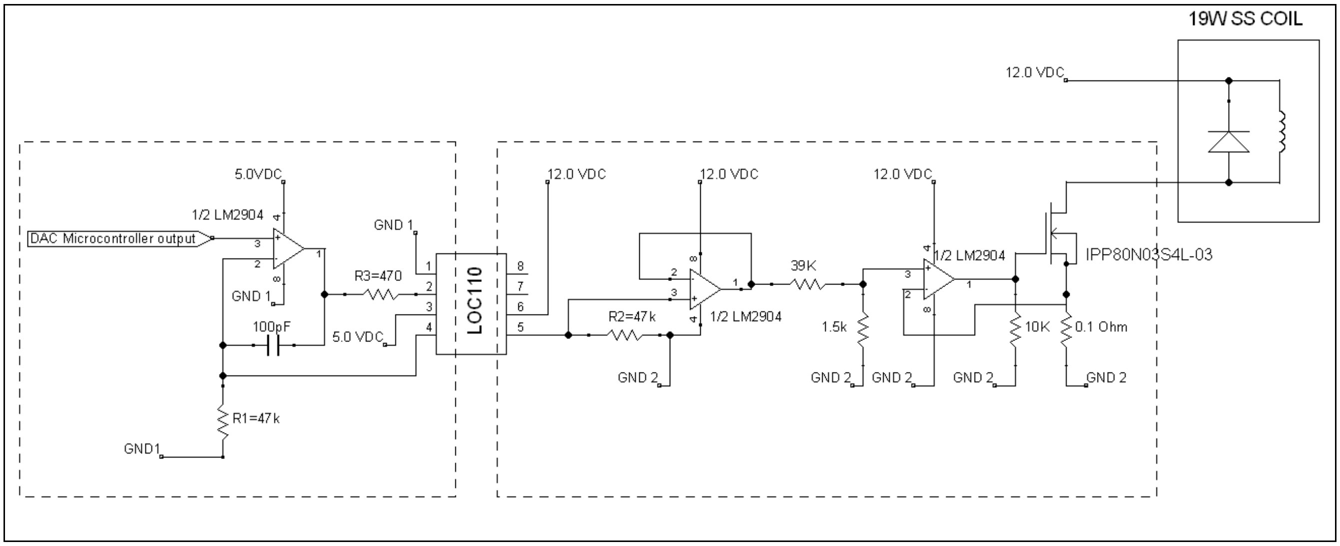


Figure 21: Interface circuit between the microcontroller and the solenoid on the proportional valve

5.2.6 Pressure Sensors

The pressure sensor selected for this application was Parker's electronic pressure sensor SCP01-3000P-25-07. This sensor is rated for 3000 PSI. It operates at voltages between 9 and 30 VDC and indicates pressure through an output current ranging between 4.0 and 20 mA. Two of these sensors are used in the system to monitor and display pressure at the accumulators and at the motor line on the hydraulic circuit. Because of their close proximity to the power control box, and to limit power consumption on the microcontroller battery, the sensors are powered from the 12-Volt battery through the power control box. The sensors' output signals are first converted to a voltage range between, 0.6 and 3.0 Volts through 150-Ohm resistors, and then isolated with a unity gain through linear opt coupler circuits as shown in Figure 22.

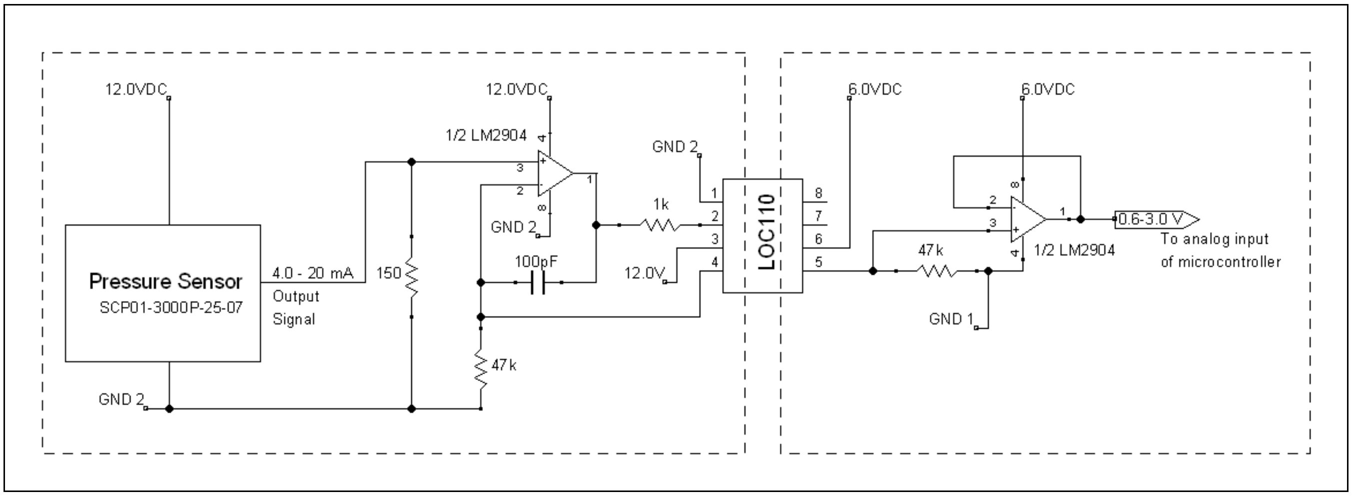


Figure 22: Circuit to isolate the output signal from Parker's SCP01-3000P-25-07 pressure sensor

5.2.7 System Operation

Upon powering the control system, the hydraulic circuit is configured in Default mode. In this mode, none of the solenoids is energized, and the bicycle remains idle. In the Default mode, the hand pump can be used to charge the accumulator without the need to operate any valve.
If the button for the Default mode is pressed and held with the bicycle already in Default mode, then the Charging mode is activated. In this mode, the accumulators can be charged using the pedal pump in addition to the hand pump.

The top button by the right-hand side grip is the discharge-up button. The function of this button is to provide a current to the proportional valve solenoid that can be increased in steps. Each time the button is pressed, after the first push, the current through the solenoid is increased by about 100 mA, which results in a larger amount of fluid going through the proportional valve. Also on the right-hand side, but at the bottom of the button plate, is the discharge-down button. This pushbutton has been programmed to decrease the flow through the proportional valve by reducing the current through the solenoid by about 100mA each the button is pressed. When the number of pushes on the discharge-down button equals the number of times the discharge-up button was pressed, the hydraulic circuit is returned to the Default mode. Ideally, on the first push on the discharge-up button, the microcontroller should be able to check the rate of speed at which the bicycle is going, as well as the pressure in the accumulators, in order to determine what should be the optimal opening for the proportional valve. Adding this kind of logic to the microcontroller program, however, requires testing for an amount of time that was not available during the design phase.

The Regeneration mode can be set current by depressing the single pushbutton on the left-hand side. The microcontroller has been programmed to check the accumulator pressure and the speed of the bicycle before the mode is set. The product of these two parameters must be below certain threshold for the mode to be allowed by the microcontroller. This check is intended to avoid bringing the bicycle to a sudden stop when travelling at a relatively high rate of speed. The appropriate threshold below which setting the Regeneration mode should be allowed has not been established with clarity for this system. At the moment the check-up has been implemented in the code with a threshold set at 6000. This threshold has been used to test that the system is capable of "making a decision" on whether or not the mode can be allowed, but is probably still too low to be of practical value. If the Regeneration mode cannot be set, or the button is released, the hydraulic circuit is configured in Default mode.

The system has been programmed to allow only one mode of operation to be current at a time. The function of the last button pressed overrides the previously existing circuit configuration and sets the one requested by the most recent user command.

5.3 CAD Models

Figure 23: CAD rendering of the handlebars, pushbuttons, and display screen

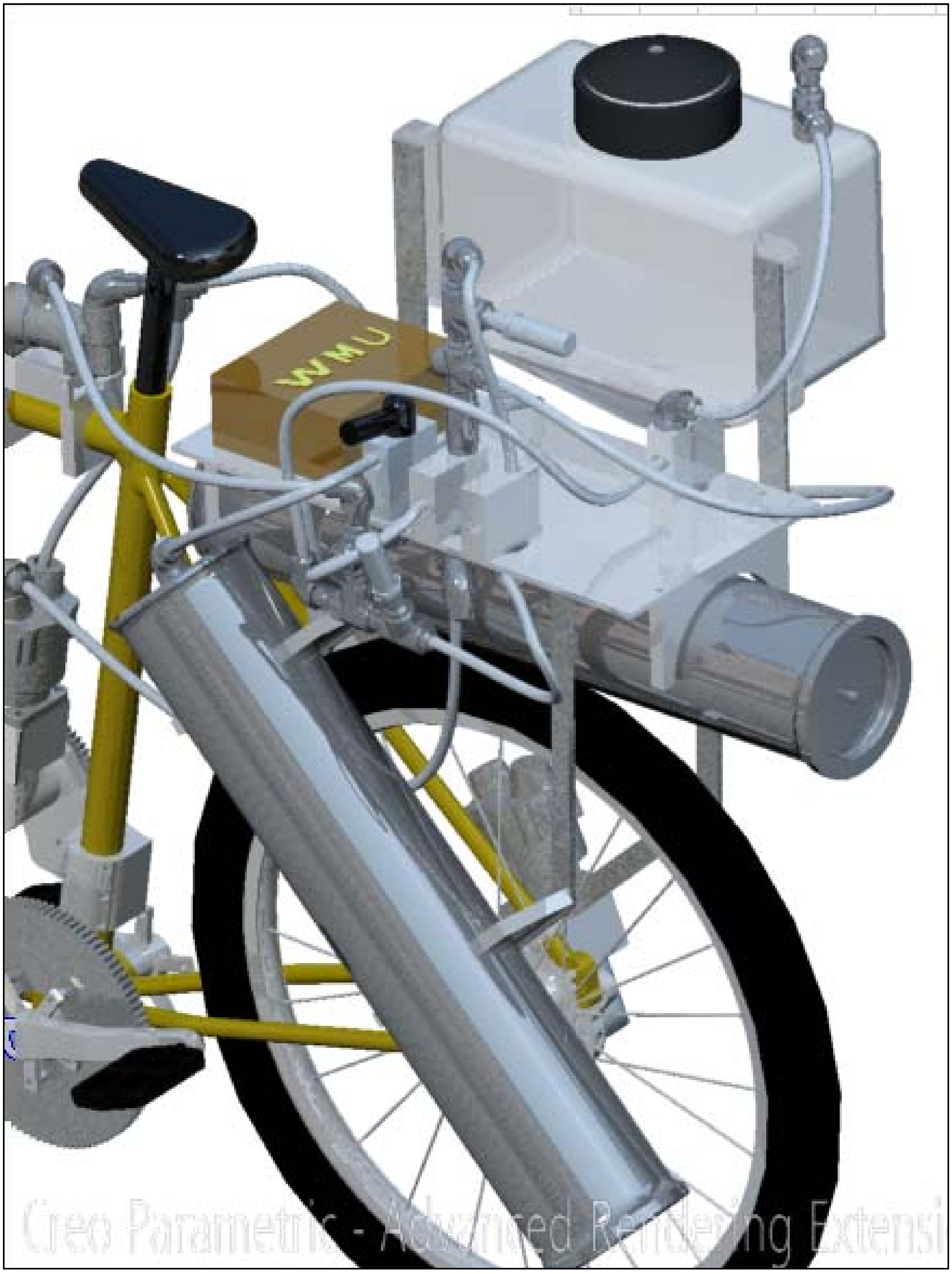


Figure 24: CAD rendering of the rear section of the bike

Figure 25: CAD rendering of the bike with a manikin riding

Figure 26: CAD rendering of the completed bike

Figure 27: CAD rendering of the front hub, pump, and gear train subassembly

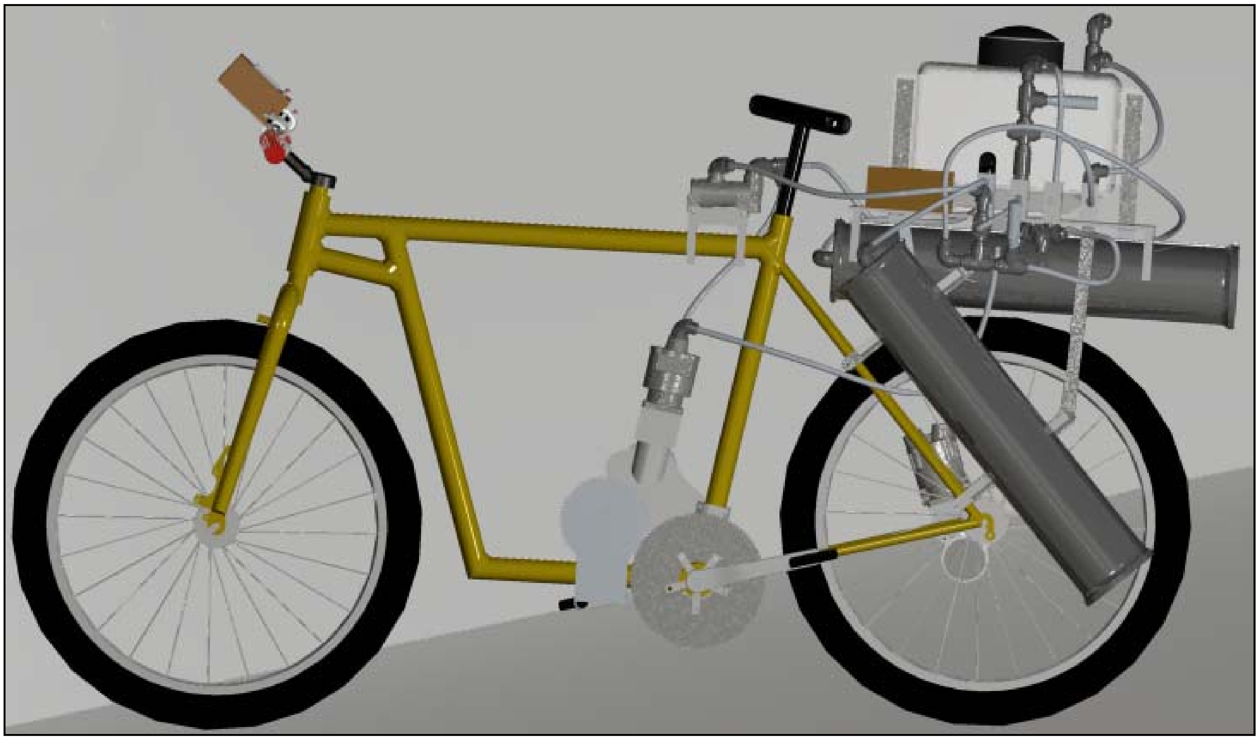


Figure 28: Left side view of the bike

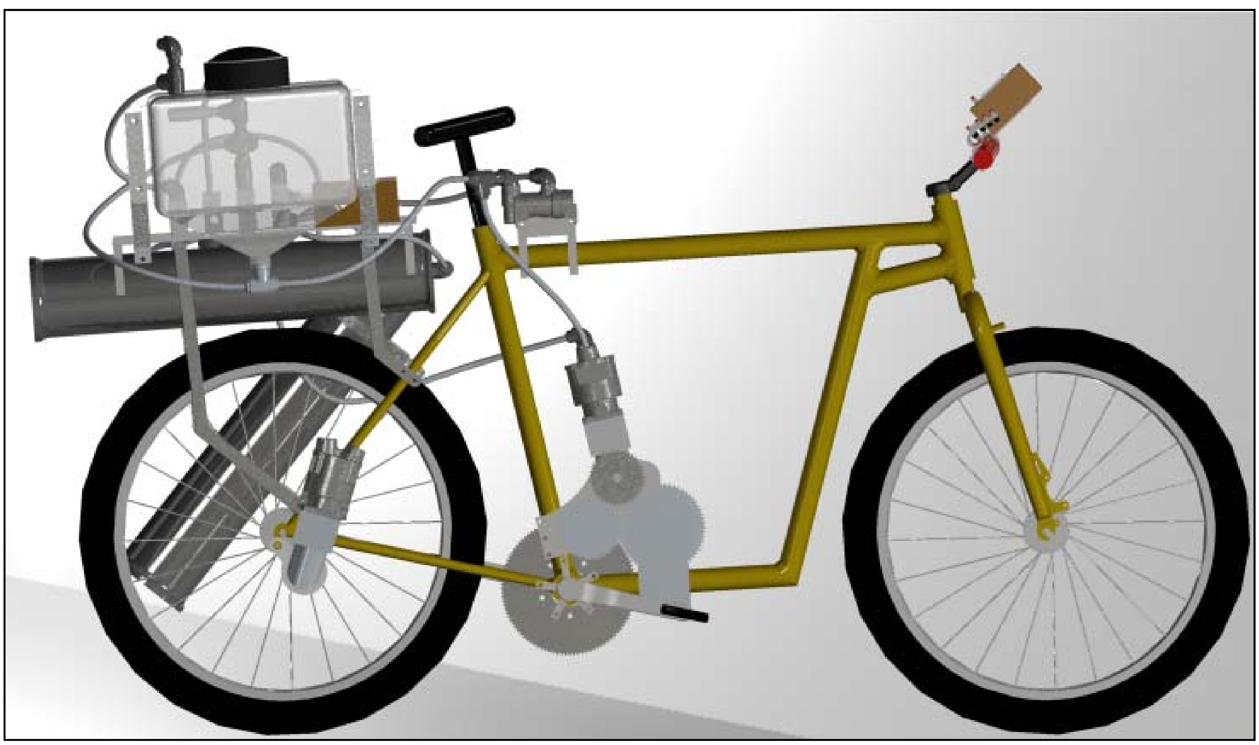


Figure 29: Right side view of the bike

6.0 Component List

Item#	Component	Description	Qty
Mechanical System			
1	Surly Traveler's Check Frame	Upright Bicycle Frame	1
2	Shimano Alfine SG-S501	Front Hub	1
3	Strumey Archer S3X	Rear Hub	1
4	B08-2-A6P	Pressure Relief Valve	1
5	J416A-6SS-5	Check Valve	4
6	JPO2C-20	Proportional Valve	1
7	B08-3-A6T	Directional Control Valve	2
8	915-8D27	Hand Pump	1
9	AM1C-31	Direct Drive Pump/Motor	2
10	TOBUL4.5AL-20	Aerospace Accumulator	2
11	2.5 Gallon Polypropylene Tank	Reservoir	1
12	Smooth Bore Stainless Steel Braided PTFE	⅜" and ½" Steel Hose	~12ft.
13	Tough Cover 451TC-6	Rubber Hose	~1ft.
14	C6X	37 Degree Swivel Elbow	12
15	S6X	37 Degree Swivel Branch T	4
16	KVU	Union Cross	2
17	TRTXN	2-Piece Nut & Insert	6
18	F870MX	37 Degree Flare Male Connector	12
19	C80MX	37 Degree Flare Male Elbow	2
20	HTX0	37 Degree Flare Union	3
21	Miscellaneous Nuts & Bolts	Fasteners	N/A
22	1/8" x 1' x 36" Aluminum Angle	Angle Stock	1
23	Shimano Rotor	Gear Union for Front Hub	1
24	Shimano Alfine Cassette Assembly	Shift Assembly	1
25	Enamel, Paint, and Clear Coating	Finishing	3
26	Turnbuckle	Front Hub Mounting	2
Control Panel			
1	Micro-LCD- 43 PT	LCD Display	1
2	STM32F4 Discovery Board	Microcontroller	1
3	H74CT541 IC	Octal, Non-inv Digital Buffer	2
4	Push Button	N.O. Momentary Switch	5
5	On/Off Switch	SPST Toggle Switch	1
6	Battery Holder	For 6 AA-size Batteries	2
7	2 Watt Heat Sink	TO 220 w. Pins, 1.5-in Tall	1
8	Capacitors	10 µF, 25V	7
9	10pF Capacitor	Ceramic Capacitor	20
10	10 k Ohm Resistor	¼ Watt, 10% tol. Carbon Film	3
11	Resistor Array	10K-Eigth Pins	1
12	Buzzer	3-16 Volt Ceramic Buzzer	1
13	Enclosure Boxes	Steel Boxes	2
14	LM7805 IC	5-Volt Voltage Regulator IC	1
15	A1469 IC	Hall-Effect Sensor 4SIP	1
16	Perforated Prototyping Board		1
Power Box			
17	4N33 IC	Optocoupler	3

18	LOC110 IC	Linear Optocoupler	3
19	IPP80N03S4L-03	N-Channel MOSFET	3
20	LM2904 IC	Single Polarity Dual Op-Amp	4
21	NTE7400	Quad NAND Gate TTL Comp	1
22	12-Volt Battery	N/A	1
23	10 k Ohm Resistor	¼ Watt, 10% Tol. Carbon Film	8
24	1.2 k Ohm Resistor	¼ Watt, 10% Tol. Carbon Film	4
25	150 Ohm Resistor	¼ Watt, 10% Tol. Carbon Film	2
26	47 k Ohm Resistor	¼ Watt, 10% Tol. Carbon Film	5
27	39 k Ohm Resistor	¼ Watt, 10% Tol. Carbon Film	1
28	100 Ohm Resistor	¼ Watt, 10% Tol. Carbon Film	4
29	10pF Capacitor	Ceramic Capacitor	20
30	Capacitors	220 µF, 25V	2
31	2 Watt Heat Sink	TO 220 w. Pins, 1.5-in Tall	1
32	Perforated Prototyping Board	N/A	1
33	Cable Connectors	Multiple Positions, .1mm Pitch	16
34	#22 Board to Board Cable	Fe. to Fem Crimped with Housings	6
35	#22 Cable	20 ft.	20

7.0 Actual Test Data and Analysis

7.1 Pump and Motor Testing

Pump and motor testing was done at Parker Aerospace of Kalamazoo, MI. Unfortunately, due to the nature of their business and products we were unable to collect or retain any hard data. However, we were able to collect valuable information on the function of the pump/motor. The pump and motor are designed to be a fixed directional but, for our application, pressures and flow rates 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.

7.2 Trial Runs and Accumulator Testing

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. Only one accumulator was used in the first three runs to reduce the number of variables that could affect our results. The accumulator in use was the horizontal one located above the rear tire for the first two runs and the third run used the other accumulator located on the angle. We ran these tests inside the building in the middle of the night due to the inclement weather we were experiencing at the time, thus limiting us to the length of the building at 400 meters.

We found after charging the accumulator to a pressure of 2600 psi, with a nitrogen pre-charge of 500 psi, it took approximately 1000 psi in the first 10 meters to get the bike up to a reasonable speed. A concern of ours was how the balance of the bike would be at a slow initial speed upon takeoff. We were pleased to discover this would be a non-issue, behaving very similarly to a regular bicycle despite the increase in weight. After traveling the first 10 meters, the amount of pressure dissipated to keep the bike moving decreased significantly, with approximately 900 psi on average being used to travel the next 390 meters. These results are all indicated in the Table 4 below. It should be noted that upon reaching the end of the building the bike was still traveling at 9 mph. Taking into account we would be moving still at 400 meters and we wouldn't have to waste 1000psi to get the bike started with the second accumulator, we estimate we could go over about 800-900 meters in ideal conditions. One mock run was made outdoors right before packing the bike up, but we have no recorded data from that run other than that the bike traveled a half a mile, or 804 meters, prior to stopping.

Table 4: Accumulator Trial Runs

Run #1		Run #2		Run #3	
Distance (m)	**PSI**	**Distance (m)**	**PSI**	**Distance (m)**	**PSI**
0	2600	0	2600	0	2600
10	1600	10	1650	10	1620
100	1330	100	1350	100	1340
150	1150	150	1170	150	1160
200	900	200	910	200	900
300	810	300	810	300	810
400	720	400	720	400	720

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.

One issue we experienced when testing was the periodic loss of pressure in the system during usage of only the direct drive mode. One hose would make a loud hissing sound while under pressure, so that was replaced. This did not solve the issue; instead we continued experiencing the problem. We proceeded to swap out all parts and components along the route of the direct drive system one at a time, testing to see if we had found the culprit. We were unsuccessful in determining what this loss of pressure is before the shipping date, but the bike is still operational and can successfully compete in the competition. Upon returning the bike to WMU we look forward to more extensive testing to determine the issue.

8.0 Cost Analysis

This section presents the cost analysis of launching a new bicycle in the market, the Silver Bullet, a human assisted vehicle powered with hydraulic fluid. This bike is capable of performing well in a variety of operating conditions such as endurance races, sprint races, efficiency challenges, and normal riding conditions as well.

The cost of producing a single bike is presented in the table below. It is based on the information presented in Section 6.0 Component List, where the cost of the competition bicycle is presented. There are several modifications that are made to the competition bicycle in order to reduce the overall cost and have a commercial bike, and those are noted in the table. Most of the modifications that are made to the competition bike focus on substituting the aerospace quality components for cost-efficient parts for everyday use.

8.1 New Product Proposal

For an annual production of 500 bicycles, the following considerations are included in the analysis:

- A modified pre-assembled bike will be used as the base for the hydraulic system. The frame is modified to accommodate the hydraulic components, and reduce assembly time
- Eliminate one accumulator on the bike to reduce the overall weight of the system, and reduce some costs.
- Replacement of pump and motor to commercial grade. This will reduce the efficiency of the hydraulic system, but will greatly reduce the price for the bike.
- The commercial product will be easier to use, utilize a smaller assembly time, and at a more affordable price level that the competition bike

8.2 Bill of Materials and Labor

The current bill of materials can be seen in Table 5 below. This table includes components from both the mechanical and electrical teams. Our team has utilized pumps and motors from past designs that are still operational and we were also donated an accumulator this year, so those components will not have to be ordered. The team also had to purchase valves, hosing, and various components (mechanical and electrical) to create the functional prototype for the Chainless Challenge. The list below includes all of the necessary components that are needed for the complete assembly of the proposed design. It is important to note that some components listed will not be ordered from Parker Hannifin. The table is color coordinated to show what components were donated to or reused by our team (orange) and what components were actually purchased with this year's funding (green). Totals are at the bottom of table in red.

Table 5: Bill of Materials

Item#	Component	Description	Qty	Unit $ P	Total $
Mechanical System					
1	Surly Traveler's Check Frame	Upright Bicycle Frame	1	$478.99	$478.99
2	Shimano Alfine SG-S501	Front Hub	1	$174.44	$174.44
3	Strumey Archer S3X	Rear Hub	1	$87.99	$87.99
4	B08-2-A6P	Pressure Relief Valve	1	$63.60	$63.60

5	J416A-6SS-5	Check Valve	4	$57.13	$228.52
6	JPO2C-20	Proportional Valve	1	$153.52	$153.52
7	B08-3-A6T	Directional Control Valve	2	$156.00	$312.00
8	915-8D27	Hand Pump	1	$250.00	$250.00
9	AM1C-31	Direct Drive Pump/Motor	2	~$800.00	~$1600.00
10	TOBUL4.5AL-20	Aerospace Accumulator	2	~$850.00	~$1700.00
11	2.5 Gallon Polypropylene Tank	Reservoir	1	$23.96	$23.96
12	Smooth Bore Stainless Steel Braided PTFE	⅜" and ½" Steel Hose	~12ft.	N/A	N/A
13	Tough Cover 451TC-6	Rubber Hose	~1ft.	N/A	N/A
14	C6X	37 Degree Swivel Elbow	12	N/A	N/A
15	S6X	37 Degree Swivel Branch T	4	N/A	N/A
16	KVU	Union Cross	2	N/A	N/A
17	TRTXN	2-Piece Nut & Insert	6	N/A	N/A
18	F870MX	37 Degree Flare Male Connector	12	N/A	N/A
19	C80MX	37 Degree Flare Male Elbow	2	N/A	N/A
20	HTX0	37 Degree Flare Union	3	N/A	N/A
21	Miscellaneous Nuts & Bolts	Fasteners	N/A	N/A	$67.70
22	1/8" x 1' x 36" Aluminum Angle	Angle Stock	1	$14.83	$14.83
23	Shimano Rotor	Gear Union for Front Hub	1	$19.07	$19.07
24	Shimano Alfine Cassette Assembly	Shift Assembly	1	$10.59	$10.59
25	Enamel, Paint, and Clear Coating	Finishing	3	$4.91	$14.73
26	Turnbuckle	Front Hub Mounting	2	$8.99	$17.98
Control Panel					
1	Micro-LCD- 43 PT	LCD Display	1	$145.00	$145.00
2	STM32F4 Discovery Board	Microcontroller	1	$15.83	$15.83
3	H74CT541 IC	Octal, Non-Inv Digital Buffer	2	$0.63	$1.26
4	Push Button	N.O. Momentary Switch	5	$1.21	$6.05
5	On/Off Switch	SPST Toggle Switch	1	$1.49	$1.49
6	Battery Holder	For 6 AA-Size Batteries	2	$1.39	$2.78
7	2 Watt Heat Sink	TO 220 w. Pins, 1.5-in Tall	1	$1.45	$1.45
8	Capacitors	10 µF, 25V	7	$0.15	$1.05
9	10pF Capacitor	Ceramic Capacitor	20	$0.03	$0.60
10	10 k Ohm Resistor	¼ Watt, 10% Tol. Carbon Film	3	$0.10	$0.30
11	Resistor Array	10K-Eigth Pins	1	$0.58	$0.58
12	Buzzer	3-16 Volt Ceramic Buzzer	1	$1.80	$1.80
13	Enclosure Boxes	Steel Boxes	2	$5.00	$10.00
14	LM7805 IC	5-Volt Voltage Regulator IC	1	$0.53	$0.53
15	A1469 IC	Hall-Effect Sensor 4SIP	1	$2.63	$2.63
16	Perforated Prototyping Board		1	$8.10	$8.10
Power Box					
17	4N33 IC	Optocoupler	3	$0.65	$1.95
18	LOC110 IC	Linear Optocoupler	3	$2.63	$7.89
19	IPP80N03S4L-03	N-Channel MOSFET	3	$1.45	$4.35
20	LM2904 IC	Single Polarity Dual Op-Amp	4	$0.86	$3.44
21	NTE7400	Quad NAND Gate TTL Comp	1	$7.50	$7.50
22	12-Volt Battery	N/A	1	$25.00	$25.00
23	10 k Ohm Resistor	¼ Watt, 10% Tol. Carbon Film	8	$0.10	$0.80
24	1.2 k Ohm Resistor	¼ Watt, 10% Tol. Carbon Film	4	$0.10	$0.40
25	150 Ohm Resistor	¼ Watt, 10% Tol. Carbon Film	2	$0.10	$0.20

26	47 k Ohm Resistor	¼ Watt, 10% Tol. Carbon Film	5	$0.10	$0.50
27	39 k Ohm Resistor	¼ Watt, 10% Tol. Carbon Film	1	$0.10	$0.10
28	100 Ohm Resistor	¼ Watt, 10% Tol. Carbon Film	4	$0.10	$0.40
29	10pF Capacitor	Ceramic Capacitor	20	$0.03	$0.60
30	Capacitors	220 µF, 25V	2	$0.20	$0.40
31	2 Watt Heat Sink	TO 220 w. Pins, 1.5-in Tall	1	$1.45	$1.45
32	Perforated Prototyping Board	N/A	1	$8.10	$8.10
33	Cable Connectors	Multiple Positions, .1mm Pitch	16	$0.35	$5.60
34	#22 Board to Board Table	Fem - Fem Crimped with Housings	6	$3.09	$18.54
35	#22 Cable	20 ft.	20	$2.00	$40.00
Total Material Worth of Entire Design					$5597.96
Expenses to Our Team in 2015-2016					$524.94

Below in Table 6 the estimated labor costs for the prototype/competition vehicle are shown. It was assumed that someone working on a specialized engineering task such as the one presenting in the Chainless Challenge would be paid a generous salary, hence the $60.00/hour wage shown in the table.

Table 6: Bill of Estimated Labor Costs for Prototype/Competition Vehicle

Item #	Production Process	Time to Complete the Given Task in Hours	Cost/Hr	Total Cost
1	Frame Modification	2.5	$60.00	$150.00
2	Gear Train Mount	4.0	$60.00	$240.00
3	Pump Mount	0.5	$60.00	$30.00
4	Rear Mounting Plate	5.0	$60.00	$300.00
5	Accumulator Brackets	0.5	$60.00	$30.00
6	Reservoir Mounts	2.0	$60.00	$120.00
7	Hand Pump Bracket	1.0	$60.00	$60.00
8	Battery Mount	0.5	$60.00	$30.00
9	Control Box Mount	0.5	$60.00	$30.00
10	Misc. Brackets	4.0	$60.00	$240.00
11	Fluid Line Manufacture	3.0	$60.00	$180.00
12	General Assembly	6.0	$60.00	$360.00
Total Estimated Labor Costs for Prototype/Competition Vehicle				$1,770.00
Combined Total of 2015-2016 Material Worth of Vehicle and Estimated Labor Costs				$7,367.96

The table shown below represents analysis of the cost for 500 production vehicles for commercial use. Cost reduction was attributed to bulk purchasing along with a reduction in labor costs through streamlining the fabrication and assembly processes with jigs and fixtures. Through these processes, we were able to achieve a 33.55% reduction in cost. Due to high cost of aerospace components, it would be appropriate to implement most cost efficient components in commercial production, so this was taken into account during our cost analysis.

Table 7: Commercial Cost Analysis for 500 Vehicles

Subsystem	Description	Part Cost	Labor Cost	Quantity Discount	New Part Cost	New Labor Cost
Hydraulic Components	Pumps/Motors, Accumulators, Hand pump, Reservoir	$3,573.96	$0.00	Bulk discount: 25%	$2,680.47	$0.00
Valves	Pressure relief valve, check vlave, proportional valve, directional control valve	$757.64	$0.00	Bulk discount: 25%	$568.23	$0.00
Bicycle Components	Bicycle frame	$478.99	$0.00	Bulk discount: 30%	$335.29	$0.00
Hydraulic Connections	Hose, fittings, adapters	$730.47	$0.00	Bulk discount: 30%	$511.33	$0.00
Gear Train	Front hub, rear hub, misc. gears	$665.22	$90.00	Bulk discount: 20%	$532.18	$0.00
Electronics	Control panel, power box, etc.	$250.98	$0.00	Bulk discount: 40%	$150.59	$0.00
Fabrication	misc. materials, aluminum and steel	$181.12	$1,770.00	Bulk discount: 35%	$117.73	$885.00
Misc. materials	bolts, nuts, screws	$88.43	$0.00	Bulk discount: 50%	$44.22	$0.00
Cost of Parts and Materials		$6,726.81			$4,940.03	
Cost of labor	Parts preparation		$1,860.00			$885.00
Cost of labor	Assembly		$360.00		Jig/fixture assembly and set up	$120.00
Total Cost			$8,946.81			$5,945.03
Percent Reduction						33.55%
Total Cost (500 units)						$2,972,514.50

9.0 Lessons Learned

Our team has learned a plethora of things from the Chainless Challenge project. Prior to beginning back in September, we had a limited knowledge on hydraulic systems, their components and how they worked together. Throughout the course of the project we've had to become familiar with all of the various components at our disposal. On the other side of the spectrum, important lessons we've learned include applying the Engineering Design Process in a real life situation, prioritizing, troubleshooting, networking, and working in a group.

We learned the value of using the standard design process framework to properly plan and implement the project to ensure all steps are followed. Prioritizing what needed to be worked on and when was an important milestone in our path to success. This became very apparent when completing necessary work to meet hard deadlines such as the midway review and presentation, vehicle verification video, and shipment of bike. Troubleshooting went hand-in-hand with prioritizing. As problems occurred, we needed to prioritize our work to troubleshoot critical issues. Using methods such as, fishbone charts and the process of elimination we had the ability to overcome problems and meet the deadlines. Networking may have been the most surprising lesson learned. The ability to network with the local bicycle shop and professors has given us specific knowledge into bicycles and hydraulic systems. Also, pump/motor testing capabilities at Parker HD aerospace have been a tremendous help to our project. Group work was the most important lesson learned. Having the ability to split up tasks to the members that were best suited for completing them, be that mechanical or electrical, helped streamline the process. Working together and allowing leadership within the group helped keep everyone on task, provided great group processing and accountability. All of these lessons have come together to create a premiere real world educational experience using the Engineering Design Process and working together as a group.

10.0 Conclusions

This project can be considered a successful one. Before the bike was transported to the competition, all the modes of operation were tested and determined to function correctly to operate the bike. Since this project was conducted as a senior engineering project, it was carried out through every process of the engineering design process. Looking at the objectives specified for this project, we can determine if they were all satisfied by this project.

Objective 1 - To design, fabricate and test a unique fluid power system that is human assisted and perform well in the three different races. This objective has been accomplished; our team created a model of the prototype, machined/fabricated all the necessary components and modifications, and finally tested the bike to ensure it functioned correctly. The endurance race was tested through the direct drive operation, the efficiency race was tested through the charge/discharge of the accumulators, and the sprint race tested both circuits at the same time.

Objective 2 - Minimize the cost of the competition vehicle. For the competition, our team was provided 2000 dollars to use for various components to order. For this project, the costly components (such as the pump/motor, and accumulators) were reused from previous years, so the overall cost of the bike was considerably lower. Because there was efficient use of the money, the funds provided were sufficient, and the team did not have to request additional funds from the college for the completion of the project. This was a good situation because it allowed the team to request funds to complement the travel allocation provided.

Objective 3 - Maintain the vehicle weight under 210 pounds. In order to compete in the Chainless Challenge, the vehicle had to weigh less than 210 pounds. Most of the material for the bike was made from aluminum, so that significantly reduced the overall weight. With the complete bike assembled, it weighed just less than 155 pounds, so this objective was accomplished.

Objective 4 - Implement electrical control of hydraulic circuit. The electrical team on this project designed and built a functional electrical system which consisted of a microcontroller, battery, pressure sensors, and a display screen. The integration of the electronics into the mechanical system was accomplished with few issues. The system was tested with the hydraulic system, fully implemented, and it successfully operated the valves and displayed accurate pressure readings throughout the hydraulic circuit.

After this project was completed, we can compare the actual performance of the team to the objectives mentioned above. A functioning hydraulic system was created, the component order from Parker Hannifin was kept under the allocated funds, the vehicle weighs less than the allowed limit, and a customized electronic control system was implemented. This project has completed all objectives that were outlined by the team.

10.1 Recommendations for Improvement

Since this vehicle was completed as a senior engineering design project, it is evident that several improvements could be made to this design. The project presented many challenges throughout both the design and fabrication processes. Listed below are the improvements that could be made in the future that the team identified for this project.

First, the hydraulic system components were not designed for this specific application. The pressure and RPM of the motor and the pump were rated for much higher values than were experienced in this system. An ideal scenario would allow a pump and motor to be designed and manufactured to be more efficient at the low RPM and pressures that were used when the bike was operated. Due to time constraints, standard pumps and motors were selected over custom components. The aerospace quality pump and motor functioned correctly for this application, but the efficiency of the system could have been improved with custom components.

The initial stability of the bike was an issue when the team began testing for the competition. Since the bike uses a two wheeled design, the stability of the bike under very low speed conditions was not the most desirable. In order to solve this issue, a few options would be available. The first would be the easiest, and it would involve implementing industrial grade training wheels on either side of the rear tire. This would allow the bike to stand upright without any balancing. Another option could involve relocating the second accumulator above the rear one to move the center of gravity closer to the middle of the bike.

The overall hydraulic system configuration was cumbersome for the platform that it was mounted on. Although the valves were centrally located on the rear mounting plate, there was an excessive amount of fluid lines that were ran between them. To solve this issue, a manifold can be implemented to consolidate the valves in the system. The manifold would also significantly reduce the amount of fluid lines in the system, thus making it more efficient for the competition.

One of the biggest improvements that could have been made to this system was the determination of max efficiency. Due to time constraints for this project, our team did not complete all of the testing that we would have liked to fully optimize our system. Further testing improvements that could be made include: determining optimal nitrogen pressure in the accumulator, simulating the entire gear train system for actual RPM readings, and implementing hydraulic simulation software further for more accurate fluid flow through the circuit. Further testing of the system could yield more efficient results for every mode of operation of the bike. There are several improvements that could be made to this system to make it fully optimized for this application. With the available resources on hand, the team designed and built a functioning fluid power vehicle that can compete in the three different races. The use of a hydraulic system that is human assisted, and incorporates different modes of operation with electrical controls can serve as a model for possible alternative transportation.

Also, it is recommended that next year's team start with the bike from this year's team. Starting from scratch adds a lot of pressure to the team to get an entire bike designed, built, and running prior to competition. This almost always leads to a time crunch at the end, like this year, and starting with this year's design would help to prevent that. This design is a great basis for a winning bike for next year, and with some refinement and simplification to the design, along with more testing time in the spring, next year's team should have an excellent opportunity at victory. Any of the team members from this team would be more than happy to come back to WMU and at least explain to next year's team the circuit and what has taken place with this design up to now.

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13.0 Appendix A: Design Components

Table 8: Pump/motor selection decision matrix

Factors	Weight Factor		F11-5	F11-10	AM1C-31	PGP505
Efficency	14		9.00	7.50	6.00	4.00
Occupied Space	12		4.00	2.25	8.25	9.00
Weight	8		4.50	2.50	9.00	7.75
Disp. Volume	6		3.00	9.00	5.25	7.00
Flow Rate	4		3.50	9.00	5.75	4.75
Cost	2		5.25	3.75	1.75	8.75
		Total:	1010	998	1252	1218

Table 9: Accumulator selection decision matrix

Factors	Weight Factor		BA005B3T01A1	AD280B25T9A1	BA01B3T01A1	T0BUL4.5AL-20
Energy Density	16		5.50	7.25	3.50	9.00
Dimensions	14		6.75	3.50	3.25	5.25
Weight	12		8.50	7.25	4.50	6.50
Capacity	10		3.00	4.50	6.50	9.00
Max. Pressure	8		5.75	8.25	5.75	5.75
Cost	4		3.00	4.75	6.50	2.75
		Total:	1490.00	1528.00	1170.00	1770.00

14.0 Appendix B: Calculations

Table 10: Fluid displacement input for pump/motor

	Fluid Displacement	
Motor	cm^3/r	in^3
Motor 1	4.9	0.2989

Table 11: Human power input and calculated efficiencies of system

Power				
HP	Pump Efficiency	Motor Efficiency	System Efficiency	Hydraulic HP
0.3	0.91945	0.91945	0.845388303	0.253616491

Table 12: Information on the tire size

Tire Information		
Diameter	26	inches
Circumference	81.681	inches

Table 13: Rear hub gear ratios

Gear Ratio (Motor to Tire)	
SRAM i-Motion 3	
Gear 1	**0.72**
Gear 2	**1**
Gear 3	**1.36**

Table 14: Pump calculations based on gear ratios and rider rpm

Pump 1								
RPM	Pump RPM	Torque (Pump Input) (lb-in)	Efficiency	Hydraulic HP	Flow Rate In (gpm)	Pressure In (psi)	Flow Rate Out (gpm)	Pressure Out (psi)
51	306	61.765	0.87644	0.26293	0.3959	1298.876	0.34702	1138.39052
52	312	60.577	0.87711	0.26313	0.4037	1273.897	0.35410	1117.34646
53	318	59.434	0.87775	0.26332	0.4115	1249.862	0.36117	1097.06426
54	324	58.333	0.87836	0.26351	0.4192	1226.716	0.36824	1077.50338
55	330	57.273	0.87896	0.26369	0.4270	1204.412	0.37531	1058.62613
56	336	56.250	0.87953	0.26386	0.4348	1182.905	0.38239	1040.39738
57	342	55.263	0.88008	0.26402	0.4425	1162.152	0.38946	1022.78434
58	348	54.310	0.88061	0.26418	0.4503	1142.115	0.39653	1005.75643
59	354	53.390	0.89910	0.26973	0.4581	1122.757	0.41184	1009.47307
60	360	52.500	0.89944	0.26983	0.4658	1104.044	0.41898	993.02201
61	366	51.639	0.89977	0.26993	0.4736	1085.945	0.42611	977.09765
62	372	50.806	0.90008	0.27002	0.4813	1068.430	0.43325	961.67514
63	378	50.000	0.90039	0.27012	0.4891	1051.471	0.44039	946.73117
64	384	49.219	0.90068	0.27020	0.4969	1035.042	0.44752	932.24383
65	390	48.462	0.90097	0.27029	0.5046	1019.118	0.45466	918.19255
66	396	47.727	0.90124	0.27037	0.5124	1003.677	0.46180	904.55796
67	402	47.015	0.90151	0.27045	0.5202	988.697	0.46893	891.32181
68	408	46.324	0.90177	0.27053	0.5279	974.157	0.47607	878.46692
69	414	45.652	0.90202	0.27061	0.5357	960.039	0.48321	865.97708
70	420	45.000	0.90227	0.27068	0.5435	946.324	0.49034	853.83696
71	426	44.366	0.90250	0.27075	0.5512	932.995	0.49748	842.03211
72	432	43.750	0.90273	0.27082	0.5590	920.037	0.50461	830.54884
73	438	43.151	0.90296	0.27089	0.5667	907.434	0.51175	819.37420
74	444	42.568	0.90317	0.27095	0.5745	895.171	0.51888	808.49592
75	450	42.000	0.90339	0.27102	0.5823	883.236	0.52602	797.90240
76	456	41.447	0.91156	0.27347	0.5900	871.614	0.53785	794.52473
77	462	40.909	0.91170	0.27351	0.5978	860.294	0.54501	784.32912
78	468	40.385	0.91184	0.27355	0.6056	849.265	0.55218	774.39164
79	474	39.873	0.91197	0.27359	0.6133	838.515	0.55934	764.70262
80	480	39.375	0.91210	0.27363	0.6211	828.033	0.56650	755.25287
81	486	38.889	0.91223	0.27367	0.6289	817.811	0.57366	746.03363
82	492	38.415	0.91236	0.27371	0.6366	807.837	0.58082	737.03658
83	498	37.952	0.91248	0.27374	0.6444	798.104	0.58799	728.25379
84	504	37.500	0.91260	0.27378	0.6521	788.603	0.59515	719.67771
85	510	37.059	0.91271	0.27381	0.6599	779.326	0.60231	711.30111
86	516	36.628	0.91283	0.27385	0.6677	770.264	0.60947	703.11714
87	522	36.207	0.91294	0.27388	0.6754	761.410	0.61663	695.11922
88	528	35.795	0.91304	0.27391	0.6832	752.758	0.62379	687.30108
89	534	35.393	0.91315	0.27394	0.6910	744.300	0.63095	679.65674
90	540	35.000	0.91325	0.27398	0.6987	736.030	0.63811	672.18047
91	546	34.615	0.91335	0.27401	0.7065	727.941	0.64527	664.86678
92	552	34.239	0.91639	0.27492	0.7143	720.029	0.65454	659.82741
93	558	33.871	0.91645	0.27494	0.7220	712.287	0.66170	652.77857
94	564	33.511	0.91652	0.27496	0.7298	704.709	0.66886	645.87866
95	570	33.158	0.91658	0.27497	0.7375	697.291	0.67602	639.12301
96	576	32.813	0.91664	0.27499	0.7453	690.028	0.68318	632.50716
97	582	32.474	0.91670	0.27501	0.7531	682.914	0.69034	626.02680
98	588	32.143	0.91676	0.27503	0.7608	675.946	0.69750	619.67782
99	594	31.818	0.91681	0.27504	0.7686	669.118	0.70466	613.45626
100	600	31.500	0.91687	0.27506	0.7764	662.427	0.71182	607.35833

Table 15: Motor calculations based on pump calculations

Motor 1				
Flow Rate In (gpm)	**Pressure In (psi)**	**Motor RPM**	**Efficiency**	**Torque (lb-in)**
0.2776	910.712	171.64	0.86307	46.721
0.2833	893.877	175.14	0.86375	45.893
0.2889	877.651	178.64	0.86440	45.094
0.2946	862.003	182.14	0.86503	44.322
0.3003	846.901	185.64	0.86564	43.576
0.3059	832.318	189.13	0.86622	42.855
0.3116	818.227	192.63	0.86679	42.157
0.3172	804.605	196.13	0.86733	41.481
0.3295	807.578	203.70	0.86721	41.629
0.3352	794.418	207.23	0.86774	40.975
0.3409	781.678	210.76	0.86825	40.342
0.3466	769.340	214.29	0.86875	39.728
0.3523	757.385	217.82	0.86923	39.132
0.3580	745.795	221.35	0.86969	38.554
0.3637	734.554	224.88	0.87015	37.993
0.3694	723.646	228.41	0.87058	37.447
0.3751	713.057	231.94	0.87101	36.917
0.3809	702.774	235.47	0.87142	36.402
0.3866	692.782	239.00	0.87182	35.901
0.3923	683.070	242.53	0.87221	35.414
0.3980	673.626	246.06	0.87259	34.939
0.4037	664.439	249.59	0.89312	35.273
0.4094	655.499	253.12	0.89335	34.808
0.4151	646.797	256.65	0.89358	34.354
0.4208	638.322	260.18	0.89379	33.913
0.4303	635.620	266.03	0.89386	33.772
0.4360	627.463	269.57	0.89408	33.346
0.4417	619.513	273.11	0.89428	32.931
0.4475	611.762	276.66	0.89448	32.526
0.4532	604.202	280.20	0.89468	32.131
0.4589	596.827	283.74	0.89487	31.746
0.4647	589.629	287.28	0.89505	31.370
0.4704	582.603	290.83	0.89523	31.002
0.4761	575.742	294.37	0.89541	30.643
0.4818	569.041	297.91	0.89558	30.292
0.4876	562.494	301.45	0.89575	29.949
0.4933	556.095	304.99	0.89592	29.614
0.4990	549.841	308.54	0.89608	29.286
0.5048	543.725	312.08	0.89623	28.966
0.5105	537.744	315.62	0.89639	28.652
0.5162	531.893	319.16	0.89654	28.345
0.5236	527.862	323.74	0.89664	28.133
0.5294	522.223	327.28	0.89679	27.837
0.5351	516.703	330.83	0.89693	27.547
0.5408	511.298	334.37	0.89707	27.264
0.5465	506.006	337.91	0.89720	26.985
0.5523	500.821	341.45	0.89734	26.713
0.5580	495.742	344.99	0.89747	26.446
0.5637	490.765	348.54	0.89760	26.184
0.5695	485.887	352.08	0.91026	26.290

Table 16: Speed calculations of bike based on pump and motor calculations at various rider rpm's

Speed (MPH)		
Gear 1	Gear 2	Gear 3
9.5591	13.2765	18.0561
9.75393	13.5471	18.4241
9.94876	13.8177	18.7921
10.1436	14.0883	19.1601
10.3384	14.3589	19.5281
10.5332	14.6295	19.8961
10.728	14.9	20.264
10.9228	15.1706	20.632
11.3445	15.7562	21.4284
11.5411	16.0293	21.7998
11.7377	16.3024	22.1712
11.9343	16.5754	22.5426
12.1309	16.8485	22.9139
12.3275	17.1215	23.2853
12.5241	17.3945	23.6566
12.7207	17.6676	24.0279
12.9172	17.9406	24.3992
13.1138	18.2136	24.7705
13.3104	18.4866	25.1418
13.5069	18.7596	25.5131
13.7035	19.0326	25.8843
13.9	19.3056	26.2556
14.0966	19.5786	26.6268
14.2931	19.8515	26.9981
14.4896	20.1245	27.3693
14.8156	20.5772	27.9851
15.0129	20.8513	28.3577
15.2102	21.1253	28.7304
15.4075	21.3993	29.103
15.6048	21.6733	29.4757
15.8021	21.9473	29.8483
15.9993	22.2213	30.221
16.1966	22.4953	30.5936
16.3939	22.7693	30.9662
16.5912	23.0433	31.3388
16.7884	23.3172	31.7115
16.9857	23.5912	32.0841
17.1829	23.8652	32.4567
17.3802	24.1392	32.8293
17.5775	24.4131	33.2019
17.7747	24.6871	33.5745
18.0298	25.0414	34.0563
18.2271	25.3154	34.4289
18.4243	25.5894	34.8015
18.6216	25.8633	35.1741
18.8189	26.1373	35.5467
19.0161	26.4113	35.9193
19.2134	26.6852	36.2919
19.4106	26.9592	36.6645
19.6079	27.2331	37.0371

Table 17: Reverse calculations to find necessary rider rpm's based on flow rate and pressure in the pump

Pump								
Efficiency	Pressure Out	Flow Rate OUT (gpm)	Pressure In	Flow Rate IN (gpm)	Hydraulic HP	Torque IN	Pump RPM	Biker RPM
0.0208	2706.499	0.00007	129949.502	0.00335	0.006	7309.558	2.586	0.431
0.0332	2154.109	0.00022	64974.751	0.00669	0.010	3654.779	5.171	0.862
0.0455	1969.979	0.00046	43316.501	0.01004	0.014	2436.519	7.757	1.293
0.0578	1877.914	0.00077	32487.375	0.01338	0.017	1827.389	10.343	1.724
0.0701	1822.675	0.00117	25989.900	0.01673	0.021	1461.912	12.928	2.155
0.0825	1785.849	0.00166	21658.250	0.02007	0.025	1218.260	15.514	2.586
0.0948	1759.544	0.00222	18564.215	0.02342	0.028	1044.223	18.100	3.017
0.1071	1739.816	0.00287	16243.688	0.02677	0.032	913.695	20.685	3.448
0.1194	1724.472	0.00360	14438.834	0.03011	0.036	812.173	23.271	3.878
0.1318	1712.197	0.00441	12994.950	0.03346	0.040	730.956	25.857	4.309
0.1441	1702.153	0.00530	11813.591	0.03680	0.043	664.505	28.442	4.740
0.1564	1693.784	0.00628	10829.125	0.04015	0.047	609.130	31.028	5.171
0.1687	1686.702	0.00734	9996.116	0.04349	0.051	562.274	33.614	5.602
0.1811	1680.631	0.00848	9282.107	0.04684	0.054	522.111	36.199	6.033
0.1934	1675.371	0.00971	8663.300	0.05019	0.058	487.304	38.785	6.464
0.2057	1670.767	0.01101	8121.844	0.05353	0.062	456.847	41.370	6.895
0.2180	1666.706	0.01240	7644.088	0.05688	0.065	429.974	43.956	7.326
0.2304	1663.095	0.01387	7219.417	0.06022	0.069	406.087	46.542	7.757
0.2537	1735.027	0.01613	6839.447	0.06357	0.076	384.714	49.127	8.188
0.2749	1786.042	0.01839	6497.475	0.06691	0.082	365.478	51.713	8.619
0.2943	1821.068	0.02068	6188.072	0.07026	0.088	348.074	54.299	9.050
0.3121	1843.748	0.02298	5906.796	0.07360	0.094	332.253	56.884	9.481
0.3286	1856.817	0.02529	5649.978	0.07695	0.099	317.807	59.470	9.912
0.3440	1862.359	0.02762	5414.563	0.08030	0.103	304.565	62.056	10.343
0.3582	1861.980	0.02996	5197.980	0.08364	0.107	292.382	64.641	10.774
0.3715	1856.929	0.03232	4998.058	0.08699	0.111	281.137	67.227	11.205
0.3840	1848.190	0.03469	4812.945	0.09033	0.115	270.724	69.813	11.635
0.3957	1836.541	0.03707	4641.054	0.09368	0.119	261.056	72.398	12.066
0.4067	1822.602	0.03946	4481.017	0.09702	0.122	252.054	74.984	12.497
0.5892	2552.114	0.05914	4331.650	0.10037	0.177	243.652	77.570	12.928
0.5968	2501.932	0.06190	4191.919	0.10372	0.179	235.792	80.155	13.359
0.6041	2453.192	0.06468	4060.922	0.10706	0.181	228.424	82.741	13.790
0.6110	2405.894	0.06746	3937.864	0.11041	0.183	221.502	85.327	14.221
0.6175	2360.026	0.07024	3822.044	0.11375	0.185	214.987	87.912	14.652
0.6237	2315.567	0.07303	3712.843	0.11710	0.187	208.845	90.498	15.083
0.6295	2272.486	0.07583	3609.708	0.12044	0.189	203.043	93.084	15.514
0.6352	2230.749	0.07863	3512.149	0.12379	0.191	197.556	95.669	15.945
0.6405	2190.316	0.08143	3419.724	0.12714	0.192	192.357	98.255	16.376
0.6456	2151.148	0.08424	3332.039	0.13048	0.194	187.425	100.841	16.807
0.6505	2113.202	0.08705	3248.738	0.13383	0.195	182.739	103.426	17.238
0.6551	2076.437	0.08987	3169.500	0.13717	0.197	178.282	106.012	17.669
0.6596	2040.809	0.09269	3094.036	0.14052	0.198	174.037	108.598	18.100
0.6639	2006.278	0.09551	3022.081	0.14386	0.199	169.990	111.183	18.531
0.6680	1972.801	0.09833	2953.398	0.14721	0.200	166.126	113.769	18.961
0.6719	1940.339	0.10116	2887.767	0.15056	0.202	162.435	116.355	19.392
0.6757	1908.854	0.10399	2824.989	0.15390	0.203	158.903	118.940	19.823
0.6793	1878.306	0.10682	2764.883	0.15725	0.204	155.523	121.526	20.254
0.6828	1848.661	0.10966	2707.281	0.16059	0.205	152.282	124.111	20.685
0.6862	1819.882	0.11250	2652.031	0.16394	0.206	149.175	126.697	21.116
0.6895	1791.937	0.11534	2598.990	0.16728	0.207	146.191	129.283	21.547
0.6926	1764.793	0.11818	2548.029	0.17063	0.208	143.325	131.868	21.978
0.6956	1738.418	0.12102	2499.029	0.17398	0.209	140.568	134.454	22.409
0.6986	1712.784	0.12387	2451.877	0.17732	0.210	137.916	137.040	22.840
0.7014	1687.862	0.12672	2406.472	0.18067	0.210	135.362	139.625	23.271
0.7041	1663.624	0.12957	2362.718	0.18401	0.211	132.901	142.211	23.702
0.7068	1640.045	0.13242	2320.527	0.18736	0.212	130.528	144.797	24.133
0.7093	1617.100	0.13527	2279.816	0.19070	0.213	128.238	147.382	24.564
0.7118	1594.764	0.13812	2240.509	0.19405	0.214	126.027	149.968	24.995
0.8110	1786.358	0.16010	2202.534	0.19740	0.243	123.891	152.554	25.426
0.8125	1758.795	0.16311	2165.825	0.20074	0.244	121.826	155.139	25.857
0.8140	1733.999	0.16612	2130.320	0.20409	0.244	119.829	157.725	26.287
0.8153	1708.937	0.16913	2095.960	0.20743	0.245	117.896	160.311	26.718
0.8167	1684.580	0.17214	2062.691	0.21078	0.245	116.025	162.896	27.149
0.8180	1660.899	0.17515	2030.461	0.21412	0.245	114.212	165.482	27.580
0.8193	1637.866	0.17816	1999.223	0.21747	0.246	112.455	168.068	28.011
0.8205	1615.456	0.18117	1968.932	0.22081	0.246	110.751	170.653	28.442
0.8217	1593.643	0.18418	1939.545	0.22416	0.246	109.098	173.239	28.873
0.8228	1572.406	0.18719	1911.022	0.22751	0.247	107.493	175.825	29.304
0.8239	1551.721	0.19020	1883.326	0.23085	0.247	105.936	178.410	29.735
0.8250	1531.567	0.19322	1856.421	0.23420	0.248	104.422	180.996	30.166
0.8261	1511.925	0.19623	1830.275	0.23754	0.248	102.952	183.582	30.597
0.8271	1492.776	0.19924	1804.854	0.24089	0.248	101.522	186.167	31.028
0.8281	1474.101	0.20225	1780.130	0.24423	0.248	100.131	188.753	31.459
0.8291	1455.883	0.20526	1756.074	0.24758	0.249	98.778	191.339	31.890
0.8300	1438.107	0.20827	1732.660	0.25093	0.249	97.461	193.924	32.321
0.8309	1420.755	0.21128	1709.862	0.25427	0.249	96.178	196.510	32.752
0.8318	1403.814	0.21429	1687.656	0.25762	0.250	94.929	199.095	33.183
0.8327	1387.269	0.21730	1666.019	0.26096	0.250	93.712	201.681	33.614
0.8335	1371.106	0.22031	1644.930	0.26431	0.250	92.526	204.267	34.044
0.8344	1355.313	0.22332	1624.369	0.26765	0.250	91.369	206.852	34.475
0.8352	1339.877	0.22633	1604.315	0.27100	0.251	90.241	209.438	34.906
0.8360	1324.786	0.22934	1584.750	0.27435	0.251	89.141	212.024	35.337
0.8367	1310.028	0.23235	1565.657	0.27769	0.251	88.067	214.609	35.768
0.8375	1295.594	0.23536	1547.018	0.28104	0.251	87.019	217.195	36.199
0.8382	1281.472	0.23837	1528.818	0.28438	0.251	85.995	219.781	36.630
0.8389	1267.653	0.24138	1511.041	0.28773	0.252	84.995	222.366	37.061
0.8396	1254.127	0.24439	1493.672	0.29107	0.252	84.018	224.952	37.492
0.8403	1240.885	0.24740	1476.699	0.29442	0.252	83.063	227.538	37.923
0.8410	1227.918	0.25041	1460.107	0.29777	0.252	82.130	230.123	38.354
0.8416	1215.217	0.25342	1443.883	0.30111	0.252	81.217	232.709	38.785
0.8423	1202.775	0.25644	1428.017	0.30446	0.253	80.325	235.295	39.216
0.8429	1190.584	0.25945	1412.495	0.30780	0.253	79.452	237.880	39.647
0.8435	1178.637	0.26246	1397.306	0.31115	0.253	78.597	240.466	40.078
0.8441	1166.925	0.26547	1382.442	0.31449	0.253	77.761	243.052	40.509
0.8447	1155.443	0.26848	1367.889	0.31784	0.253	76.943	245.637	40.940
0.8453	1144.183	0.27149	1353.641	0.32119	0.254	76.141	248.223	41.370
0.8754	1172.699	0.28408	1339.686	0.32453	0.263	75.356	250.809	41.801
0.8757	1161.216	0.28713	1326.015	0.32788	0.263	74.587	253.394	42.232
0.8761	1149.956	0.29018	1312.621	0.33122	0.263	73.834	255.980	42.663
0.8764	1138.912	0.29322	1299.495	0.33457	0.263	73.096	258.566	43.094

Table 18: Reynolds number calculations

Calculating Reynolds Number for 3/8" and 1/2" Hose							
	Area (in)	Area (ft)	Diameter (ft)	Flow Rate Appendix B from Table 13			
1/2" Hose	0.196349541	0.00136354	0.041666667		GPM	ft^3/s	
3/8" Hose	0.110446617	0.00076699	0.03125	Lowest Gear	0.5975	0.001331	
				Highest Gear	1.8262	0.004069	
Specific Gravity of Oil		Density of Water (lb/ft^3)					
s.g.	0.921	62.4					
Density of Oil		Kinematic Viscosity (ft^2/s)		Value Taken from Mobile.com			
ρ	57.4704	0.0003959					
Velocity of Fluid for High and Low Gear for Each Tube Size							
		Velocity (ft/s)					
1/2" Hose	High Gear	2.9840					
	Low Gear	0.9763					
3/8" Hose	High Gear	5.3049					
	Low Gear	1.7357					
Reynolds Number							
1/2" Hose	High Gear	314.0517	Laminar Flow				
	Low Gear	102.7521	Laminar Flow				
3/8" Hose	High Gear	418.7356	Laminar Flow				
	Low Gear	137.0028	Laminar Flow				