Cleveland State University
NFPA Fluid Power Vehicle Challenge
Project Report

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Cleveland State University
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RESTRICTED INFORMATION

Any reference required by Cleveland State University

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1.0 ABSTRACT

The 2016 -2017 Cleveland State University Fluid Power Vehicle Challenge team was made up of four undergraduate mechanical engineering seniors. Those students created a hydraulic design that was simple, efficient, and low cost that was used on a two-wheeled bicycle. Based on the new rule that allowed the hydraulic circuit to be modified for each race, the CSU team also designed the circuit so that it may be altered without losing any fluid from the circuit.

2.0 PROBLEM STATEMENT

The Fluid Power Vehicle Challenge (FPVC), also known as the Chainless Challenge, is a design challenge present by the National Fluid Power Association (NFPA). This challenge has students design a vehicle that does not use a chain or belt, but rather hydraulics or pneumatics. This challenge also provided students with experience in real world engineering applications under strict timelines of designing, simulation, ordering, building, testing, and demonstrating their designs. As well as to stimulate innovative thinking for designing and testing potential new technologies or concepts integrated into a vehicle platform. Once students finish the optimization of hydraulic or pneumatic vehicles, they will compete with other university teams with the possibility of winning awards. This competition will take place in late April of 2017, at Danfoss in Ames, IA.

3.0 PROJECT PLAN /OBJECTIVES

With multiple given restraints and a good base example, the students of this team were able to come up with multiple ideas. While there were multiple good ideas, with the time restraint and funding limitations the design chosen was found to be the simplest, most efficient, and lowest in cost. This design took into consideration last year’s bike, where multiple parts were reused, such as: the accumulators, the motor/pump, and the reservoir. This year’s team also took into account failures seen previously, such as: the overall weight, the slipping of the gear train, and improvements needed for the friction wheel. This bicycle design consists of a standard light weight bike frame, a motor and pump, flexible hosing, a reservoir, two accumulators, three friction wheels, multiple gears to create a gear train, and multiple other minor components.

3.1 OBJECTIVES AND DESIGN SPECIFICATIONS

The objectives and design specifications were given at the start of the competition by the NFPA for students involved in this challenge to abide by. Those objectives and requirements were as following:

- Stimulate education in practical hydraulics, pneumatics, and sustainable energy devices for motion control.
- Provide students with experience in real world engineering under a strict timeline of designing, simulating, ordering, building, testing, and demonstrating their designs.
- Stimulate innovative thinking for designing and testing potential new technologies or concepts integrated into a vehicle platform.
- Provide an industry recruitment opportunity for high potential engineering seniors by engaging directly with practitioners in the field.
- The vehicle must be human powered with an assist of hydraulics, pneumatics, or electronics.
- Maximum weight of 210 pounds without rider, if the vehicle is being shipped. If the vehicle is being transported by students, the weight is unlimited.
- No requirement on number of wheels
- Must use environmentally-friendly fluid

3.2 TIMELINE

The students of the Chainless Challenge understood that there was a strict schedule throughout the project, it was best found to form a timeline to follow over the last year. With this timeline, goals were set per Fall 2016 and Spring 2017 semesters with the end goal being the competition in late April.

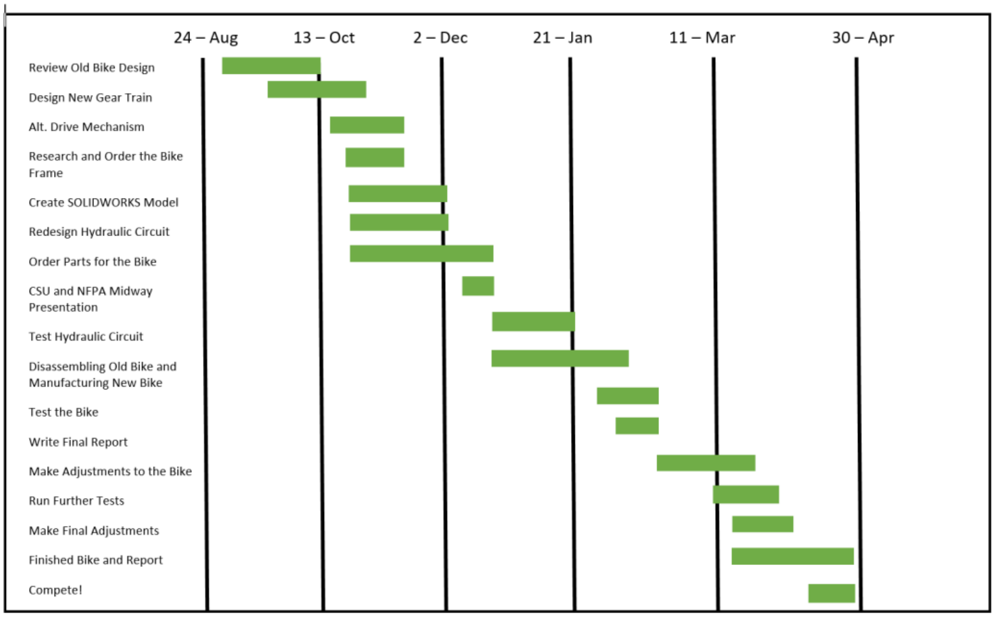


Figure One: Timeline for the Fall and Spring Semesters

3.3 RESEARCH

Cleveland State University has competed multiple times throughout the years in the Chainless Challenge. In the College of Engineering it is a widely known senior capstone project for students in both the Mechanical Engineering and Mechanical Technology departments. Due to this, multiple projects from the last few years are available to students to analyze and understand the strengths and weaknesses of each project and evaluate what can be done to improve. Since the 2015 - 2016 design performed the best out of the past year's challenges, the students choose to concentrate on improving that design.

3.3.1 CSU PREVIOUS DESIGNS

The 2015 – 2016 Cleveland State Universities Chainless Challenge bike initiated the process of powering the bicycle by pedaling. A gear train was used to increase the RPM to the pump. The hydraulic pump transferred the power to the motor that turned the friction wheel. The friction wheel applied force to the rear tire which turned the tire and acted as a gear reducer in the back, which provided the necessary torque to move the bicycle. The system also used accumulators to help give the rider extra assistance and allowed for regenerative braking.

3.3.2 RESEARCH SYNOPSIS

The approach to designing a vehicle to compete in the competition event was to consider past years' vehicles and understand what did and did not work for the events. From this research, a two-wheeled bike was chosen, as is tended to be lighter leading to better efficiency. Vehicles with more than two wheels lead to lower scoring final competition results. From there a closer examination of last year's competing bike was performed to determine its strengths and weaknesses. From this examination, the greatest design flaws were determined to be the gears slipping upon the competition event and the friction wheel not performing up to expectations. While other strong suits were the hydraulic circuit and the frame choice. The newly designed vehicle goals were to improve upon both the strengths and weaknesses.

4.0 DESIGN

The team designed a two-wheeled vehicle that aligned with the objectives and design specifications given by the NFPA, as well as improved the design of the 2015 – 2016 Chainless Challenge bike. The final design chosen was based off its simplicity, efficiency, cost, and availability of materials.

4.1 INITIAL DESIGN CONCEPT

During the 2016 Fall Semester, the initial design was produced for the bicycle. The design included:

- The Jamis Coda 2017 bike frame; due to it being light weight, having a easily weldable material, and its low cost influenced its purchase.
- The creation of a 25.5:1 gear train, consisting of six steel gears. For this gear train one would be used for the pedal crankshaft, one for the hydraulic pump, and four intermediate gears.
- From the 2015 – 2016 Chainless Challenge Bicycle: Two accumulators, a motor, a pump, and reservior. As well as the plan to improve upon the friction wheel idea that was first introduced on this bicycle.

- To improve upon the previously used hydraulic circuit, in which the team studied the application of a directional control valve configuration to introduce to the circuit.

4.2 FINAL DESIGN

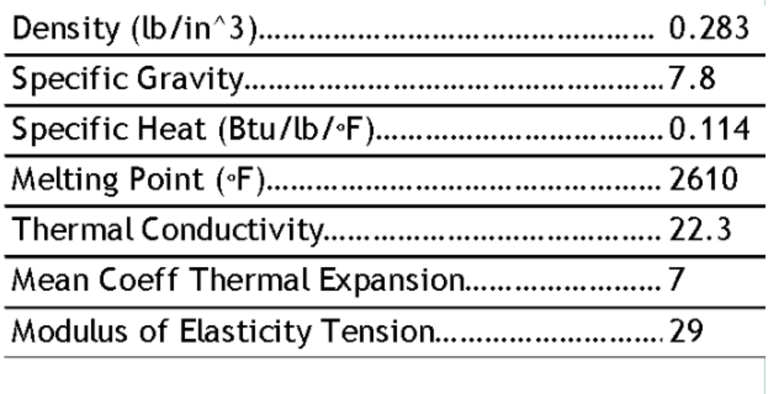
The final design of the bike followed in suit to the initial concept, with further research being conducted, and an in-depth review of the mechanics of the previous year's bike. From there the team formed a plan to create the gear train, hydraulic circuit, and found more ways to mount the other parts to the bicycle. This final design started with the rider initiating the process by applying power to the pedal, which then was applied to the gear train to increase RPM to the hydraulic pump. The pump then transferred the power onto the motor, which was connected to the friction wheel. This friction wheel applied the power onto the rear tire, applying a force to turn the tire. The friction wheel is also known as a gear reducer on the back tire, this gear reducer created enough torque that applied to move the bicycle forward and allowed for regenerative breaking. The final components necessary to build this design are as following: the bicycle frame, motor, pump, two accumulators, friction wheel, hydraulic circuit, reservoir, gear train assembly, and various mounting components. The components chosen for the creation of the final design were those that were cost efficient and readily available. Most components were donated or reused from last year's bike, while the remaining were purchased through the given budget.

Figure Two: Finalized Bike

4.2.1 BICYCLE

The bike frame chosen to be the skeleton of the design is the 2017 Jamis Bike Coda Series (See Figure Three). The frame material, overall weight, and cost were the three significant deciding factors. The material of the bike frame is 4130 Steel. This material provides an exceptional combination of high-temperature mechanical properties, corrosion resistance, and forgeability characteristics (See Figure Four). Developed for use in the 1400°-1700°F (760°-927°C) temperature range, the alloy has excellent structural stability and unusually good fabricability (See Figure Five). The mechanical properties of 4130 Steel are ideal for the application of mounting and welding different components onto the bike frame. The nominal weight of the bike is 30.25 pounds. After removing unnecessary components such as the derailleurs, shift levers, chain, cassette, and crankset the presumed weight of the bike will be around 25 pounds. An initial frame weighing 25 pounds is an improvement of about 20 pounds from last year's bike frame. With an MSRP of $369, the Coda is quite practical compared to other bikes in its class.

Figure Three: Stripped Bicycle Frame



Density (lb/in^3)	0.283
Specific Gravity	7.8
Specific Heat (Btu/lb/◦F)	0.114
Melting Point (◦F)	2610
Thermal Conductivity	22.3
Mean Coeff Thermal Expansion	7
Modulus of Elasticity Tension	29

Figure Four: 4130 Steel Physical Constants

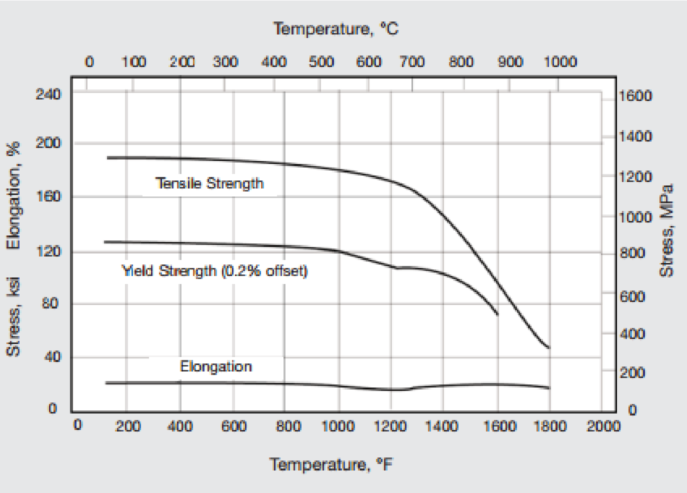


Figure Five: 4130 Steel Physical Properties

4.2.2 MOTOR AND PUMP

The motor and pump chosen for this design were reused from last year's bike. The motor and pump are both Parker F-11-05 Motor-Pumps (See Figure Six). The pump will be attached at the end of the gear train that will have a speed increase of 25.5:1. The high efficiency operation for the F-11-05 is ideal for the low RPM input to a high torque/ high RPM output (See Figure Seven).

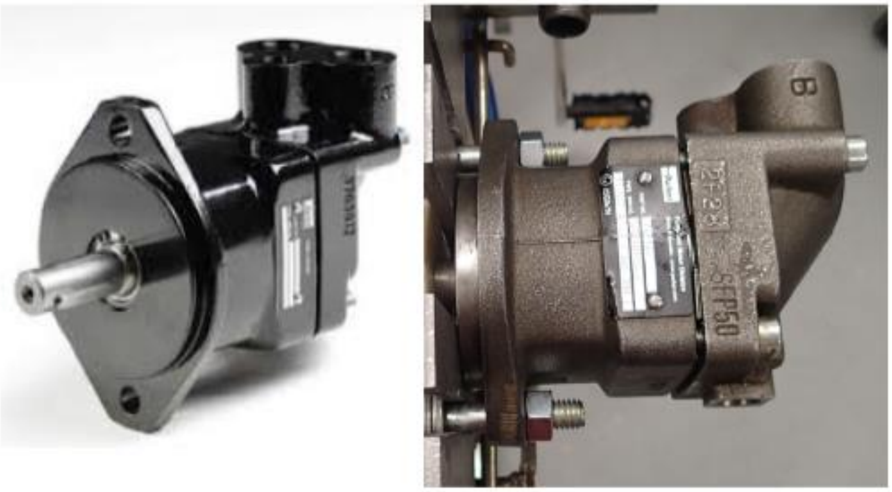


Figure Six: Parker F-11-05 Motor-Pump

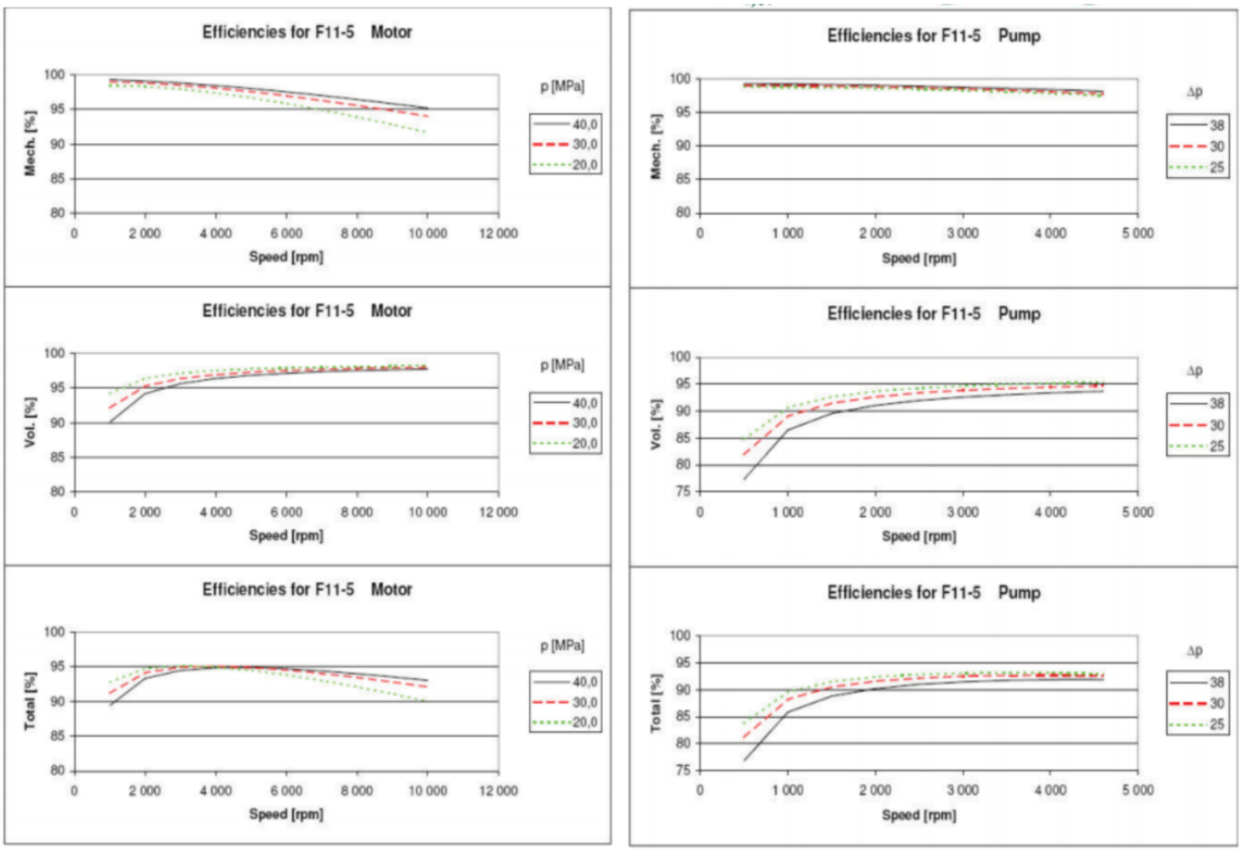


Figure Seven: Efficiencies of a F-11-05 Motor and Pump

4.2.3 ACCUMULATOR

The accumulators chosen for this design were a reused item from last year's bike. They are two Parker 3000 PSI Piston Accumulators (See Figure Eight). The main reason to reuse these accumulators was due to the weight of only 10 pounds each (See Figure Nine). While a main concern was to always keep weight low, the 20 pounds total was a small comparison to other options seen as single accumulator weight averaged around 25 pounds. Another consideration was the ability to be able to position these piston accumulators any direction. Due to this positioning option, the weight was able to be distributed evenly by attaching a accumulator on each side of the upper bicycle frame.

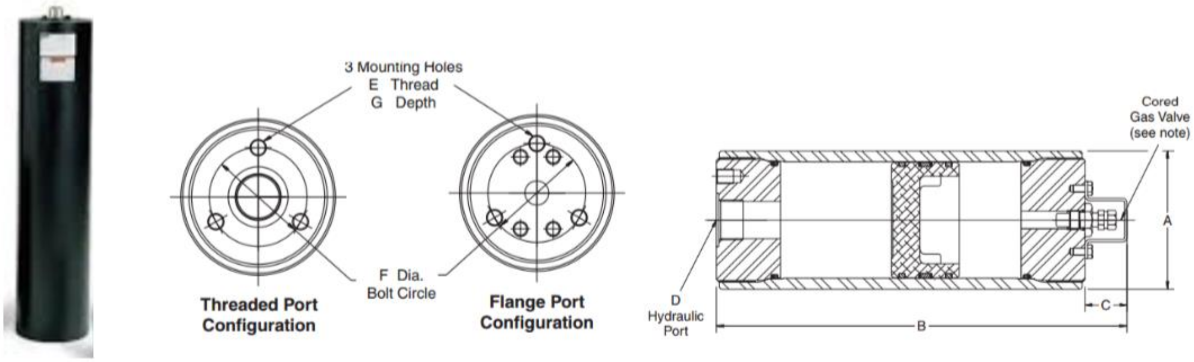


Figure Eight: Parker 3000 PSI Piston Accumulator

Specifications	Dimensions
Weight (lb)	10
Length (in)	24
Diameter (in)	2.38
Volume (in^3)	58
Pre - Charging Pressure (PSI)	400
Max Operating Pressure (PSI)	3000

Figure Nine: Specifications per Accumulator

4.2.4 FRICTION WHEEL

An idea introduced for last year’s bike was the use of a rubber friction wheel to implement power from the motor to the back wheel (See Figure Ten). The friction wheel for the design this year will be based of the ideal 2.7:1 gear ratio of a bicycle. By applying this ratio, the friction wheel would have been between 3 to 10 inches in diameter. After testing the team decided that the ideal size of the friction wheel was 4 inches in diameter. A variety of friction wheels were purchased due to their value of friction coefficient. This was based off testing that an increase in friction value would have better constancies with wheel contact and avoid slipping as the pressure builds up in the accumulators.

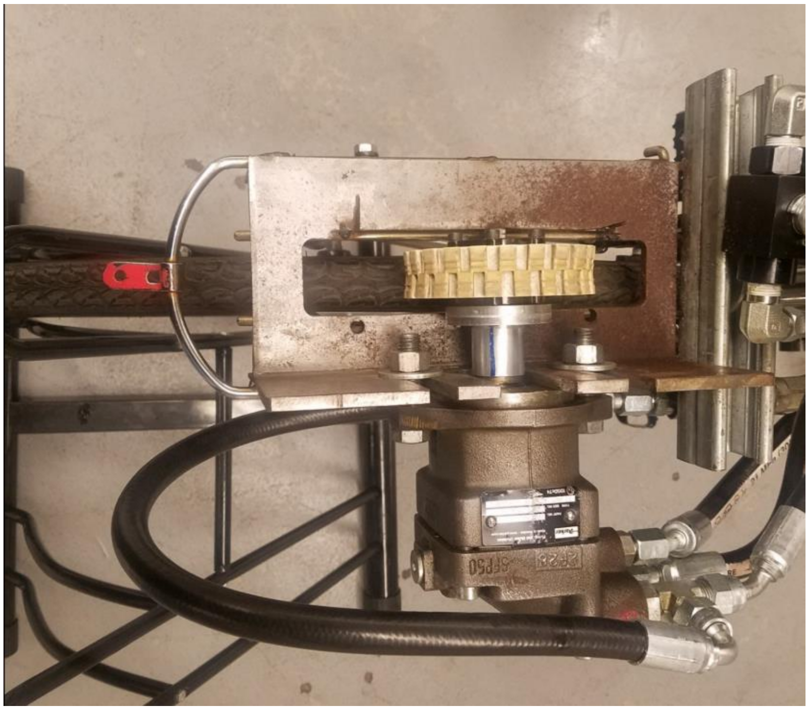
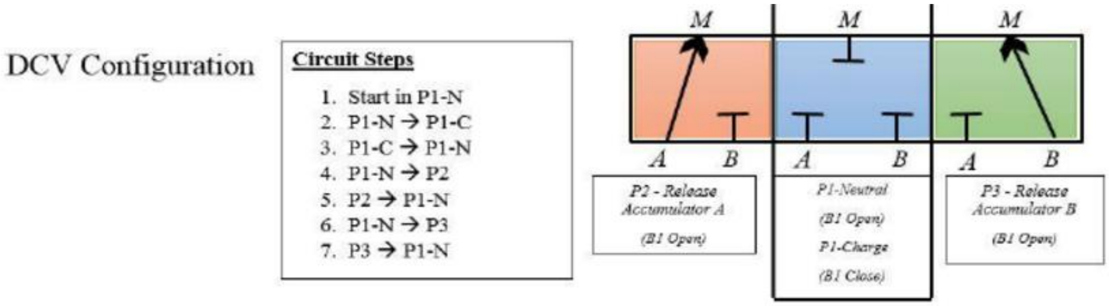


Figure Ten: Friction Wheel Fitted on the Back Tire of the Bicycle

4.2.5 HYDRAULIC CIRCUIT

The basic form shows all the components of the hydraulic circuit and how they are connected. The hydraulic circuit consist of a pump and motor, a reservoir, 4 check valves, 1 ball valve a directional control valve and two accumulators (See Figure 11). The five figures shown are the hydraulic circuit in each stage: basic form, neutral, charging, assist from accumulator A and assist from accumulator B and A simultaneously. The driving circuit represents the circuit powered by human work alone. The charging circuit is for when accumulator’s A and B are being charged, this occurs when ball valve 1 is closed and the directional control valve is in position 2, the center closed position. The two-assist circuit is for when the accumulators are released to give an extra boost to the rider. This can happen one of two ways; by moving the directional control valve to position 1, accumulator A is released providing a boost or when the DCV is moved to position 3, accumulator B and A is released simultaneously. In each figure the highlighted lines represents how fluid will flow through the system at each stage.



DCV Configuration

Circuit Steps

1. Start in P1-N
2. P1-N → P1-C
3. P1-C → P1-N
4. P1-N → P2
5. P2 → P1-N
6. P1-N → P3
7. P3 → P1-N

Figure 11: Directional Control Valve Configuration

Figure 12: Directional Control Valve Placement

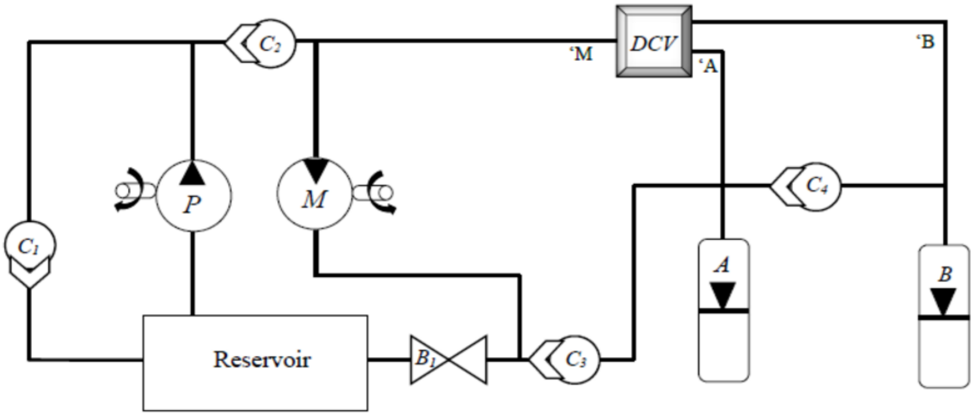


Figure 13: Hydraulic Circuit

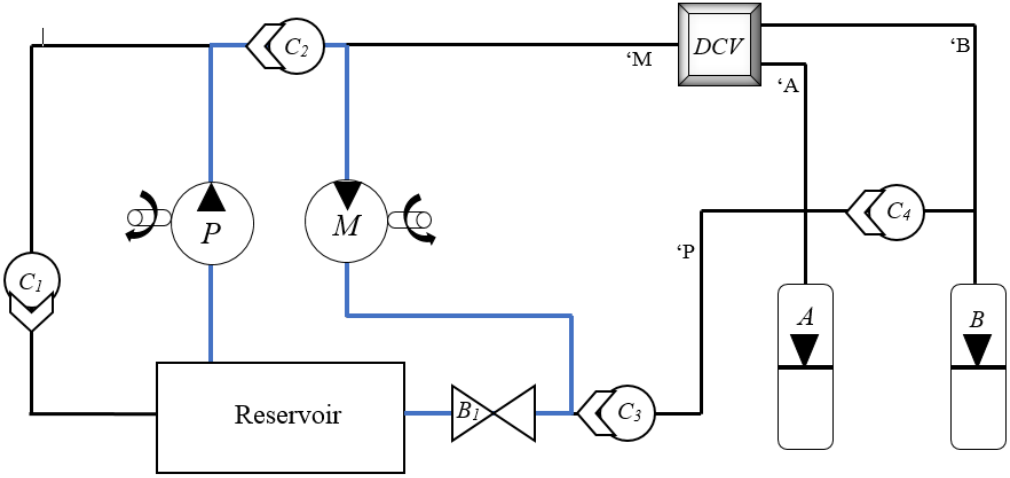


Figure 14: Hydraulic Circuit Driving

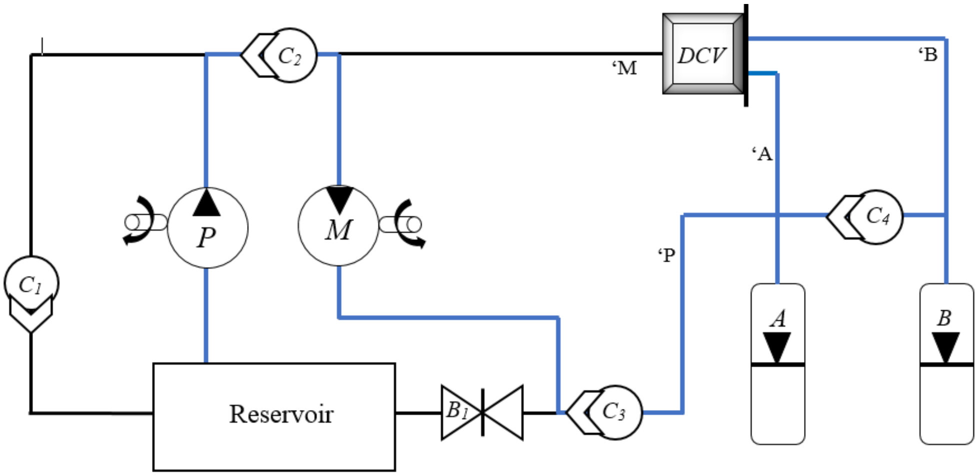


Figure 15: Hydraulic Circuit Charging

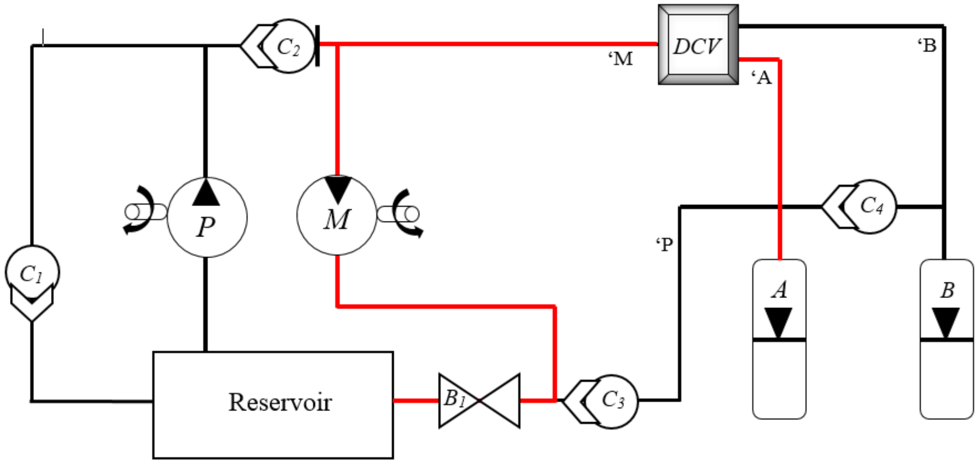


Figure 16: Hydraulic Circuit Assist from Accumulator A

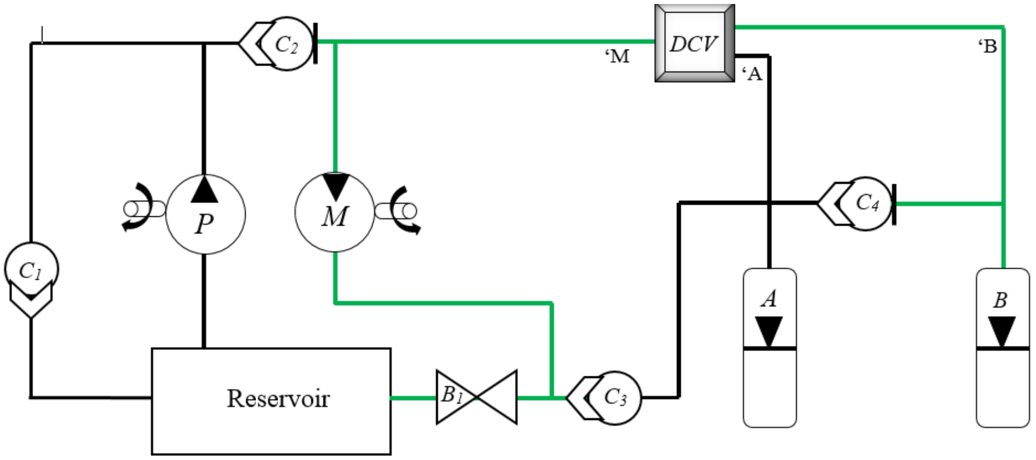


Figure 17: Hydraulic Circuit Assist from Accumulator B and A Simultaneously

4.2.6 HYDRAULIC HOSE

The hydraulic circuit used on this bicycle used flexible hosing (See Figure 18). By using flexible hosing, it allowed for easier installation since the hosing did not have to be bent into a designated shape for the circuit. This hosing also allowed for the adaptability for each change made in the design of the bike as the team continued to make it more compact, where if the hosing had been bent it would have had to be remade each time changes were made. The specific hosing on this bicycle was 3/8 inches in diameter, which was desired to allow free flow. This was important to keep the pressure in the circuit down and minimize pressure drops. The hoses for this bike were donated and fitted by Parker Hannifin in Wickliffe, OH.

Figure 18: Flexible Hydraulic Hose Installed on Bicycle

4.2.7 CHECK VALVES AND BALL VALVES

The hydraulic circuit that was implemented has four check valves and one ball valve. Check valves were used to stop the fluid from flowing in the wrong direction. This team used Parker MFMF-5 CV-370 check valves which were 3/8 inches in diameter. The check valves used in this circuit (See Figure 19). Ball valve allowed different parts of the circuit to be engaged and disengaged by turning the handle (See Figure 20). All of these parts were donated by Parker Hannifin.

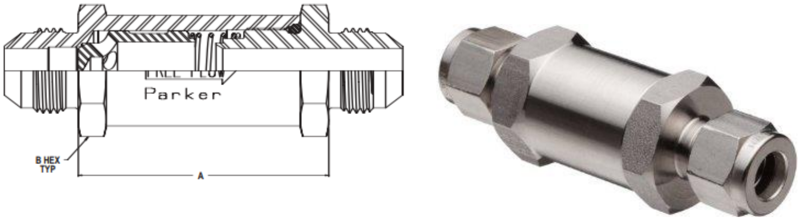


Figure 19: Parker MFMF-5 CV-370 Check Valve

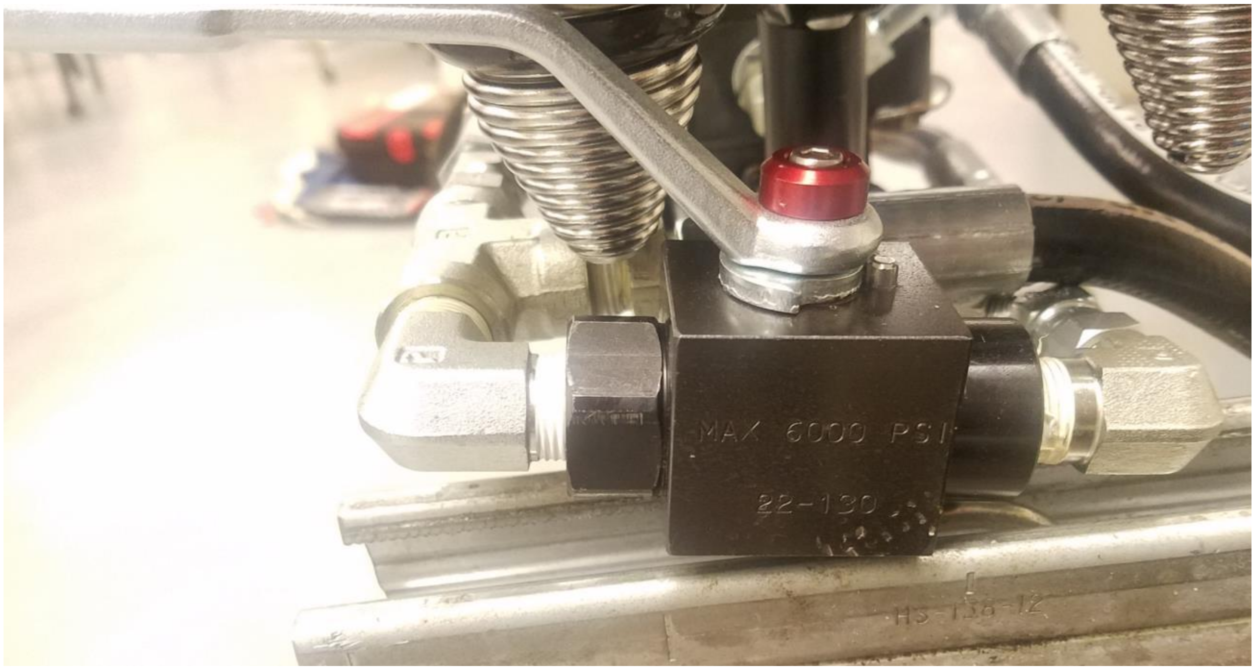


Figure 20: Ball Valve Mounted in Hydraulic Circuit

4.2.8 RESERVIOR AND FLUID

For the hydraulic circuit and ease of application, an external reservoir was the best fit. This reservoir was reused from this past year’s bike. The volume of this reservoir was 2.5 liters, but the full volume should not be required for this circuit. The volume that is required for this circuit was based off the accumulators, the amount of fluid needed for the hosing, and lastly the motor/pump. From these calculations, the accumulators would need 1.90 liters, the hosing required 0.15 liters, and the motor and pump would need .10 liters, this would lead to a total of 2.15 liters of fluid required for this circuit. The reservoir was placed on top of the bike frame at an angle to allow for an easy fill location and angled to have a gravity assist (See Figure 21).

Figure 21: Reservoir Fitted on the Bicycle

4.2.9 GEAR TRAIN

The prior year bike design heavily influenced the decision to use a gear train versus a gear hub. The gear train from last year looked good on paper, but had some issues that were crucial to the bikes performance during the Final Competition. Unravelling the issues from last year provided a great starting point for understanding the fundamentals of gears and their various applications. The new gear train design consists of six steel spur gears and two steel bevel gears, the following gears were used: one for the pedal crankshaft, five intermediate gears, one bevel intermediate gear, and one bevel gear to the hydraulic pump. The six spur gears had a pitch of 16, a pressure angle of 14.5 degrees, and a face width of 0.5 inch. While the two bevel gears had a pitch of 10, a pressure angle of 20 degrees, and face width of .44 inches. All eight gears had a key bore and set screw as well. The seven gears had an identical key width and depth of 0.125 inch and 0.063 inch respectively, this is with the exception that the eighth gear for the pedal had been machined to size. The pitch diameter of the six spur gears, in inches, are: 3.75 (x3), 1.5, 1.375, and 1. These six spur gears provided three vital ratios for a revolution per minute (RPM) ‘step up’. The product of these ratios returns the totaled a RPM increase ratio. The two bevel gears did not affect the RPM increase ratio due to the 1:1 speed ratio. The RPM increase ratio of our selected gears was 25.5:1. That meant that for every one full revolution of the pedal crankshaft gear, the pump gear was revolved 25.5 times. A step up (speed increase) ratio of 25.5:1 was a significant improvement from last year’s bike of 15:1.

Figure 22: Mounted Gear Train

5.0 DESIGN DRAWINGS

All modeling for the final design of bicycle were drawn on SolidWorks, a 3D modeling program. These models were used to assist with the positioning of the accumulators and the gear train with relation to bicycle frame.

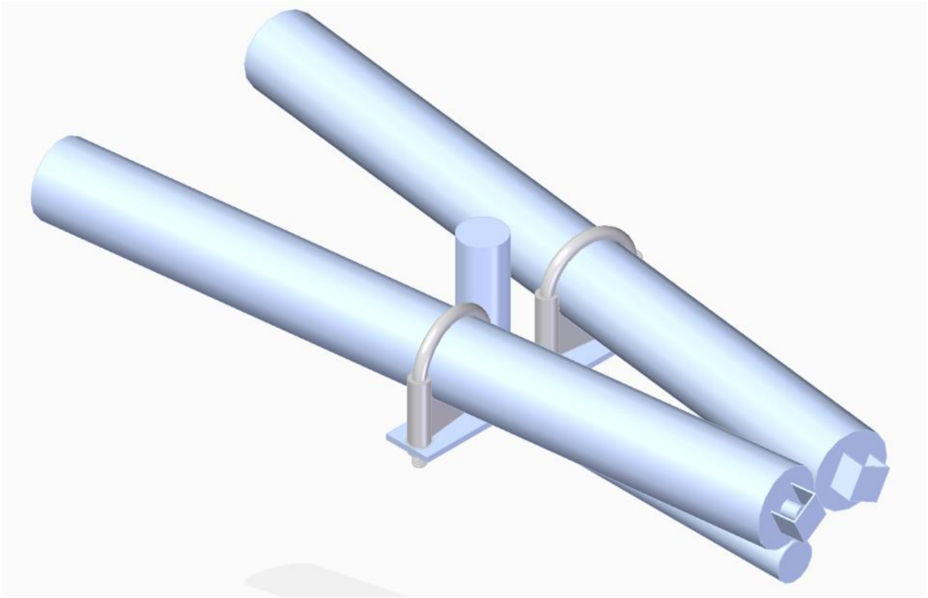


Figure 23: Accumulators and Mountings in SolidWorks

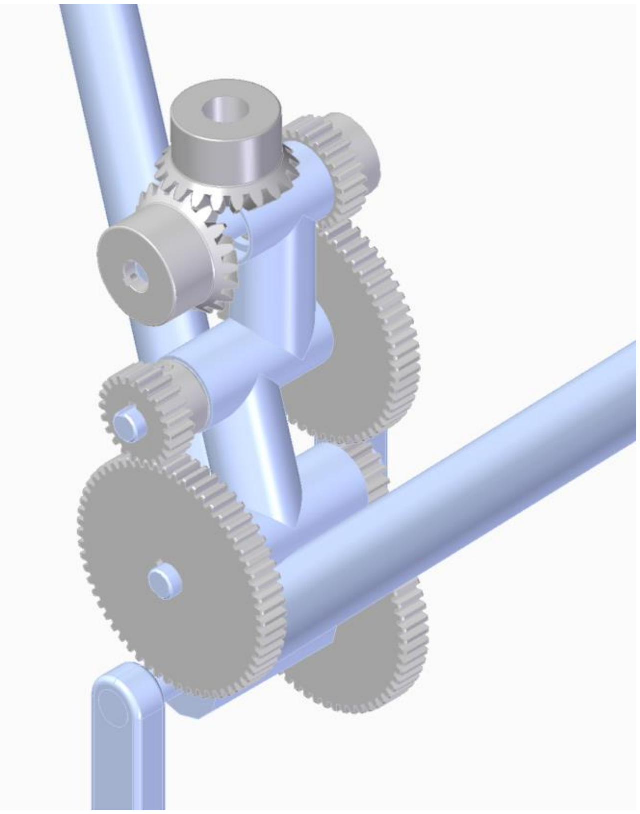
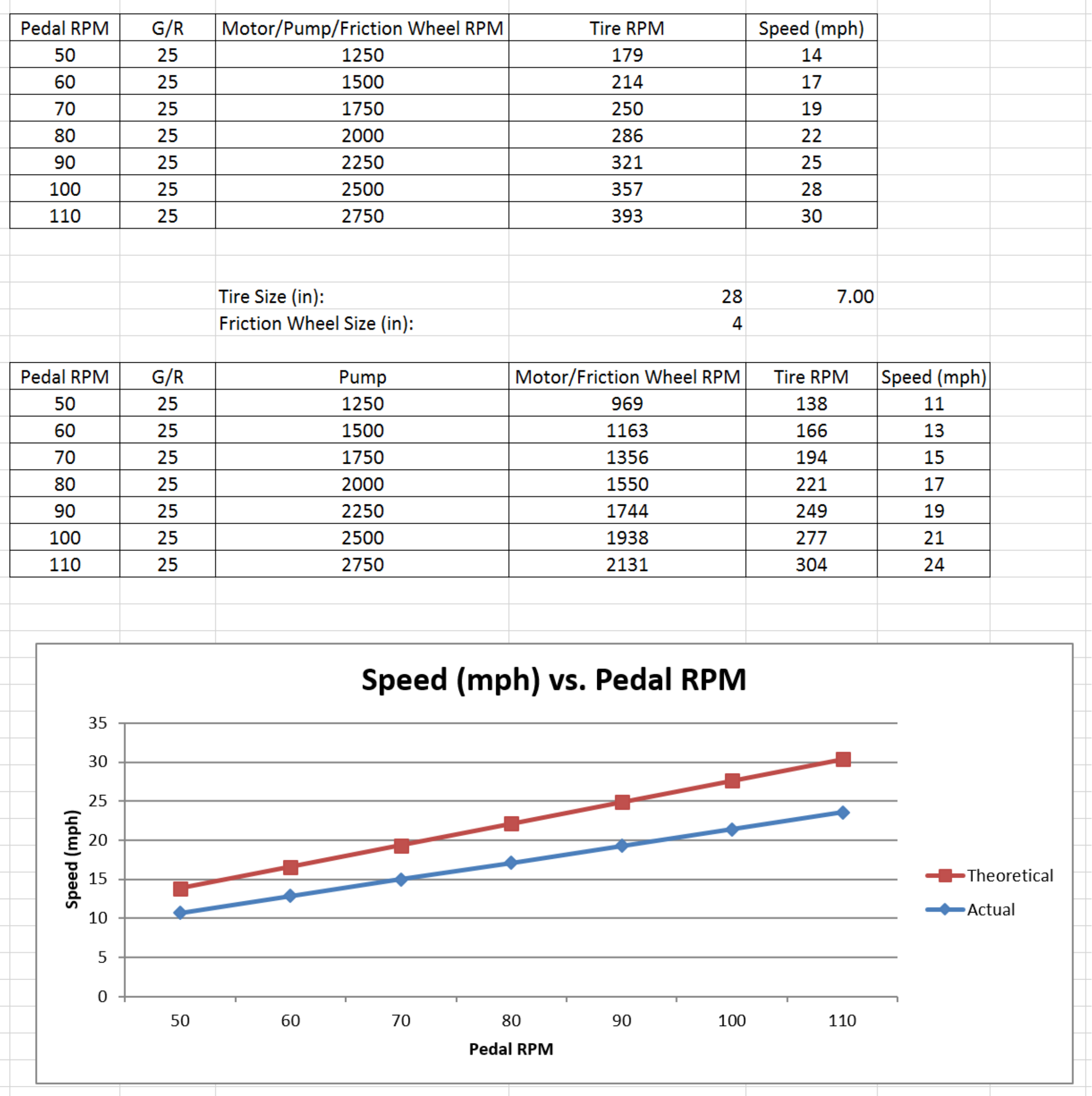


Figure 24: SolidWorks Gear Train

6.0 ACTUAL TEST DATA COMPARED TO ANALYSIS

Rider's Weight (lbs)	Length of Pedal Arm (in)	Max Torque	Shaft Diameter (in)	Shear Stress (ksi)	Factor of Safety
140	6	840	1	8.6	2.43
145	6	870	1	8.9	2.35
150	6	900	1	9.2	2.27
155	6	930	1	9.5	2.19
160	6	960	1	9.8	2.13
165	6	990	1	10.1	2.06

Figure 25: Rider’s Weight Compared to the Factor of Safety



Pedal RPM	G/R	Motor/Pump/Friction Wheel RPM	Tire RPM	Speed (mph)
50	25	1250	179	14
60	25	1500	214	17
70	25	1750	250	19
80	25	2000	286	22
90	25	2250	321	25
100	25	2500	357	28
110	25	2750	393	30

Tire Size (in): 28 7.00

Friction Wheel Size (in): 4

Pedal RPM	G/R	Pump	Motor/Friction Wheel RPM	Tire RPM	Speed (mph)
50	25	1250	969	138	11
60	25	1500	1163	166	13
70	25	1750	1356	194	15
80	25	2000	1550	221	17
90	25	2250	1744	249	19
100	25	2500	1938	277	21
110	25	2750	2131	304	24

Figure 26: Theoretical RPM vs. Actual RPM

7.0 COMPONENT LIST AND COST ANALYSIS

Part	Number of Parts	Price per Part	Total Price of Part	Purchased this Year
Allen Key Set	1	$10.77	$10.77	Yes
Caliper Tool	1	$25.89	$25.89	Yes
Gear 60T/22T	1	$153.94	$153.94	Yes
Gear 60T/Ball Bearing	4	$34.66	$138.64	Yes
Gear 24T/Key Stock	1	$36.06	$36.06	Yes
Gear 60T/16T/Keyed Shaft	1	$163.59	$163.59	Yes
Jamis Coda 19" Bike	1	$409.32	$409.32	Yes
Crank Puller/Left Crankarm	1	$37.80	$37.80	Yes
BB Tool	1	$19.44	$19.44	Yes
Metal Cranks	2	$8.59	$17.18	Yes
4130 Sheet Metal	1	$53.38	$53.38	Yes
Miter Gears/Gear 24T/Ball Bearings	2	$95.66	$191.31	Yes
4" Friction Wheel	3	$9.66	$28.98	Yes
Screw Shackle/U-Bolts(2x)	2	$14.11	$28.23	Yes
Shaft Collar/DCV Mounts	1	$61.21	$61.21	Yes
Reservoir Mounts	1	$9.25	$9.25	Yes
Bike Seat/Tire Air Pump	1	$86.40	$86.40	Yes
U-Haul Parker Trip	3	$55.73	$167.19	Yes
SAE Wrench Set (10piece)	1	$32.37	$32.37	Yes
Bolt Kit	1	$150.00	$150.00	Donated
Directional ControlValve	1	$750.00	$750.00	Donated
Subplate	1	$300.00	$300.00	Donated
F11-05 Motor/Pump	2	$396.34	$792.68	Last Year
58 Cubic Inch 3000 PSI Piston Accumulator	2	$120.00	$240.00	Last Year
2.5 Liter Reservior	1	$27.09	$27.09	Last Year
Steel Plate	1	$50.00	$50.00	Last Year
18" Strut Channel	1	$20.00	$20.00	Last Year
Nuts and Bolts	N/A	$10.00	$10.00	Last Year
Check Valve	4	$50.00	$200.00	Donated
3/8" Hose and Fittings	N/A	$359.64	$359.64	Donated
Pressure Gage	1	$50.00	$50.00	Donated
1/2" Ball Valves	1	$77.08	$77.08	Donated
		Complete Total:	$4,697.44	
		Purchase Total:	$1,670.95	

Figure 27: Component and Cost

8.0 LESSONS LEARNED

The four mechanical engineering seniors went into this challenge with little to no knowledge of fluid power and the understanding that this allowed for the opportunity to expand that knowledge greatly. This challenge allowed an opportunity to design a bicycle to utilize a hydraulic circuit for turning human power into enough power to propel a bike with ease. While all four students had to overcome multiple challenges by having different strong suits and weaknesses, this challenge brought together students to understand new concepts.

9.0 CONCLUSIONS

The students of the Cleveland State University team for the Fluid Power Vehicle Challenge successfully built a bike that met the initial design objectives stated at the beginning of the of challenge. With analysis of the 2015-2016 CSU Chainless Challenge bicycle, the team could form ideas on how to integrate old parts as well as improve upon known problems seen in this design. While keeping these problems in mind, the team was able to create an initial design that also aligned with requirements set by the NFPA for the Fluid Power Vehicle Challenge. After various factors were considered, such as ways to overcome the lack of belts or chains, the final design of the bicycle was come to. This final design was chosen because it is the simplest, lowest cost, and most efficient design to overcome the three proposed races. Once the design was confirmed, parts were purchased and recycled from last year’s bike based off ease of availability and overall weight. After all parts were collected the build and machining process began, followed by initial testing. Thereafter adjustments were made to continue to optimization and to improve the performance of the bicycle for the upcoming challenge. The final bicycle design was considered successful based off a confirmation video sent to the NFPA and will be further be tested in the challenges at the end of April of 2017.

10.0 ACKNOWLEDGEMENTS

The CSU Chainless Challenge team would like to thank everyone who has helped our team over the last year with the design for our bicycle. Some specific people who we would like to address that contributed to our team are as following; Scott Metzler from the Parker Store in Wickliffe who donated his time and parts for the hydraulic circuit, David Epperly from Cleveland State University for machining and welding components for this finished bicycle, Dr. Rashidi and Dr. Kovach for guiding our team over the last year, Eaton for the donation of parts, and Alyssa Burger of the NFPA who organized and made arrangements for the Fluid Power Vehicle Challenge.

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