University of Cincinnati
NFPA Fluid Power Vehicle Challenge
Project Report

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University of Cincinnati
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TABLE OF CONTENTS

1.0 ABSTRACT

The goal of this challenge is to design a fluid powered vehicle driven by a single human, unassisted by any outside power sources. The vehicle must be able to compete in three separate challenges and comply with all safety requirements, as called out by the NFPA. The design is also required to consider factors related to mass production and consumer needs. This report will cover the design, component selection, and cost analysis of the University of Cincinnati's 2017 fluid powered vehicle.

2.0 PROBLEM STATEMENT

Design, build, and test a human powered vehicle utilizing hydraulics as a means of power transmission. The vehicle will compete in three events:

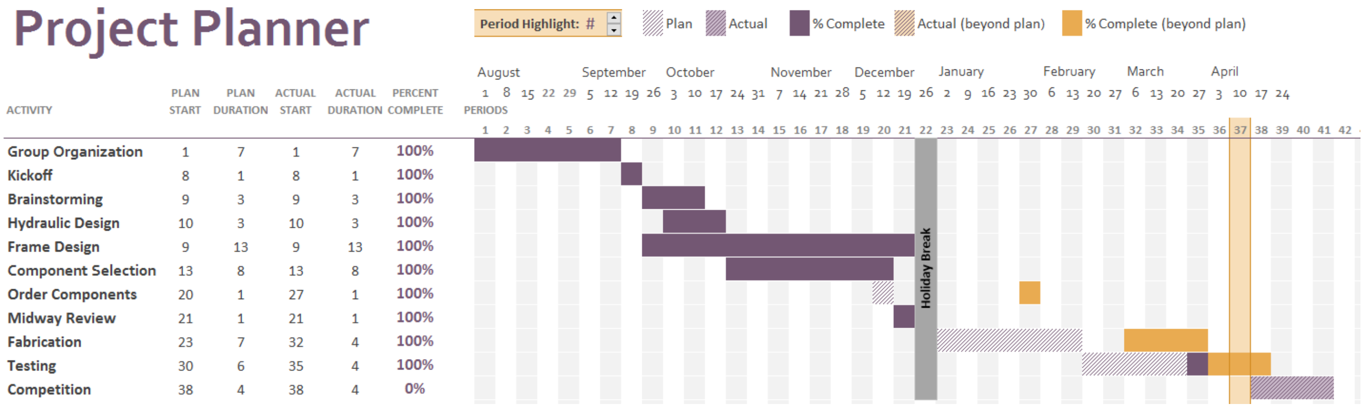
1. Sprint Race
    a. This event will demonstrate the ability of the vehicle to move a distance where the weight of the vehicle is proportional to the human propulsion
2. Durability Race
    a. This event will demonstrate the reliability, safety, replicability, and durability of the fluid power system design and assembly
3. Efficiency Challenge
    a. This event will demonstrate the ability of the vehicle to effectively store and most efficiently use the smallest amount of stored energy to propel the unassisted vehicle the greatest distance proportional to the vehicle's weight

The following design restrictions must be observed:

- Must weigh less than 210 pounds
- Must accommodate a single rider who can enter and operate the vehicle unassisted
- Comply with all appropriate safety codes
- Vehicle cannot leak any hydraulic fluid
- Vehicle must have multiple, fully active, independent brakes
- Guards must be used to protect the rider from unsafe moving components
- No chains or belts can be utilized in the design

3.0 PROJECT PLAN

The project timeline is shown in Figure 1. At the beginning of the project, the team worked on overall organization of the team: logistics, team roles, and research was conducted during this stage. After kickoff, the team began reviewing the scope of the challenge and started brainstorming design concepts that would lead to a successful design. After a couple week of refinement, the hydraulic circuit and frame were ready to move on to the design phase. The design phase was expected to take a significant amount of time to ensure quality and safety in regards to each portion of the competition. Upon completion of the design phase, the design was reviewed by industry professionals at the midway review. The advisors recommended to make some minor modifications to the hydraulic circuit. Upon completing the changes from the review the parts were ordered and the team took a recess for the holiday break. Upon the return from the holiday break the team was notified the hydraulic components selected for the challenge were not available. New hydraulic components were implemented in the design after reevaluating their compatibility for the application. This caused the hydraulic components to come in two months later than what was initially anticipated. With the expedited timeline, the team rallied to manufacture, assemble, and test the bike in the weeks leading into the competition.



Project Planner

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Group Organization	1	7	1	7	100%
Kickoff	8	1	8	1	100%
Brainstorming	9	3	9	3	100%
Hydraulic Design	10	3	10	3	100%
Frame Design	9	13	9	13	100%
Component Selection	13	8	13	8	100%
Order Components	20	1	27	1	100%
Midway Review	21	1	21	1	100%
Fabrication	23	7	32	4	100%
Testing	30	6	35	4	100%
Competition	38	4	38	4	0%

Figure 1: Project Timeline

3.1 OBJECTIVES

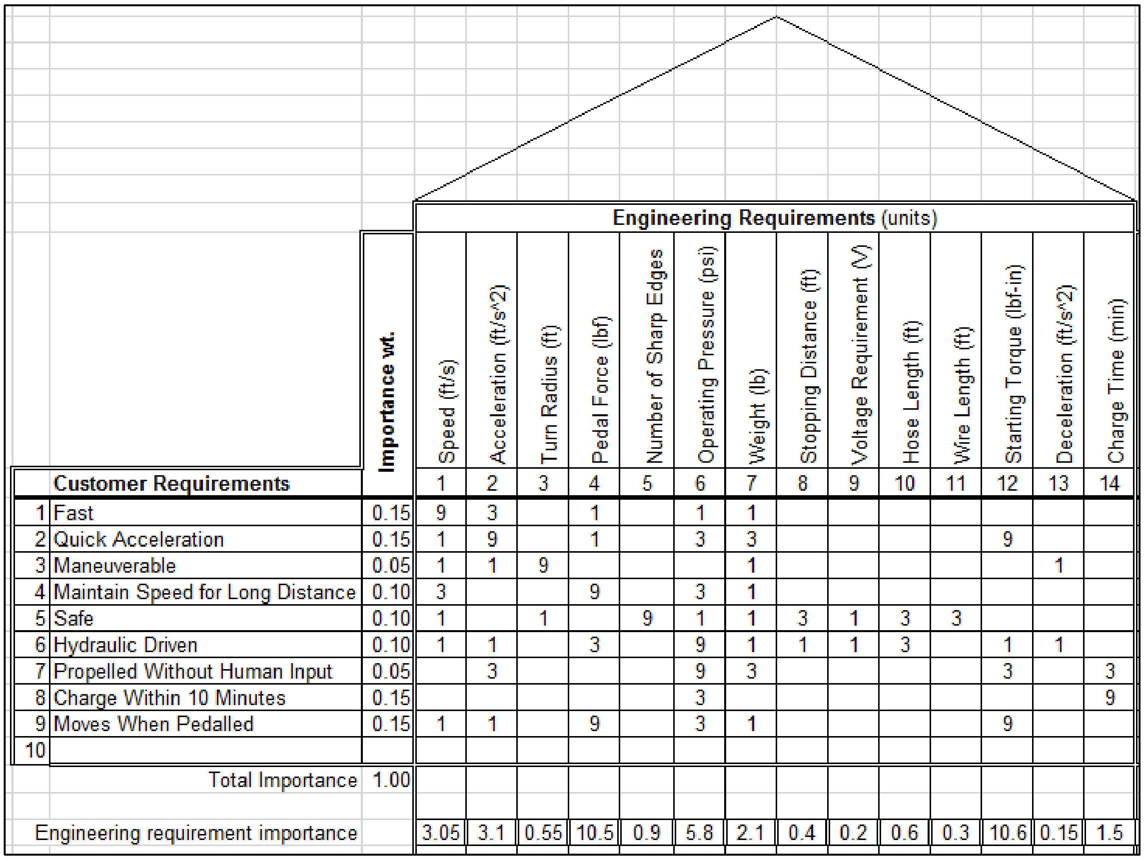
Simplicity has been the foremost tenant of the team’s design philosophy, and crucial for weight reduction. Minimizing the number of components and simplifying the hydraulic circuit assist in staying under the weight limit, as well as making troubleshooting easier in creating a 100% reliable vehicle. The overall goal of the vehicle design to is mass produce the hydraulic powered bicycle, which drives a practical design. A simple circuit would ensure low costs, assembly times, and possibility of factory defects. With this in mind, the additional efficiency gained by the regenerative braking system on the previous bike was far outweighed by the added complexity, weight, and need for electrical components. The battery used was heavy and unnecessarily oversized for the application. This year’s design would seek to eliminate all electrical components if possible, or provide the bare minimum voltage necessary to actuate valves or other components. In summary the objectives for this year’s challenge included:

1. Design a bike to be powered by fluid
2. Reduce the overall weight relative to the 2016 prototype
3. Eliminate all electronic components
4. Shorten hose lengths as much as possible
5. Change the input gear ratio leading into the pump
6. Use a two-wheeled bicycle frame

4.0 DESIGN

4.1 House of Quality

The first step in the design process was to create a house of quality, as seen in Figure 2, to identify areas of focus for the bike design. After safety, reliability and ease of use were the primary goals for the project. Using weighted values, it was determined that starting torque, pedal force, and operating pressure were the key factors involved in achieving a smooth riding experience.



			Engineering Requirements (units)													
		Importance wt.	Speed (ft/s)	Acceleration (ft/s^2)	Turn Radius (ft)	Pedal Force (lbf)	Number of Sharp Edges	Operating Pressure (psi)	Weight (lb)	Stopping Distance (ft)	Voltage Requirement (V)	Hose Length (ft)	Wire Length (ft)	Starting Torque (lbf-in)	Deceleration (ft/s^2)	Charge Time (min)
	Customer Requirements		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Fast	0.15	9	3		1		1	1							
2	Quick Acceleration	0.15	1	9		1		3	3					9		
3	Maneuverable	0.05	1	1	9				1						1	
4	Maintain Speed for Long Distance	0.10	3			9		3	1							
5	Safe	0.10	1		1		9	1	1	3	1	3	3			
6	Hydraulic Driven	0.10	1	1		3		9	1	1	1	3		1	1	
7	Propelled Without Human Input	0.05		3				9	3					3		3
8	Charge Within 10 Minutes	0.15						3								9
9	Moves When Pedalled	0.15	1	1		9		3	1					9		
10																
	Total Importance	1.00														
	Engineering requirement importance		3.05	3.1	0.55	10.5	0.9	5.8	2.1	0.4	0.2	0.6	0.3	10.6	0.15	1.5

Figure 2: House of Quality

4.2 Hydraulic Circuit Design

Figure 3: 2016 UC Vehicle

Upon completing the house of quality and clearly identifying the project objective, further research was conducted to learn more about hydraulic component applications. Research included a closer review of other school’s designs and exploring hydraulic schematics for similar applications in available textbook and digital formats. From the research it was concluded that the number of valves in the circuit could be reduced for this application. The 2016 prototype used one proportional valve, three check valves, and four solenoids. The proportional valve was used to vary the flow and pressure of the system depending on the challenge. The ability to vary the pressure and flow wasn’t necessary for this application, as the pump and motor would operate sufficiently under constant conditions. The four solenoid valves were used to propel the bike forward after building up pressure in the accumulator as well as to implement a regenerative braking system. The use of an electrical system didn’t provide much benefit with the regulations restricting the use of an electrical power source driving the pump. The bike would still be able to build up pressure in the accumulator by using a ball valve. The ball valve would be used to close the access to the motor portion of the circuit as the accumulator would charge. The regenerative braking system only seemed to be beneficial if the system was going to be slowing down frequently. There was only one of the three challenges that would warrant the use of braking, while the other two are more focused on speed and distance. It was then determined that the regenerative braking system was an unnecessarily complex for the challenge. The elimination of the regenerative braking system also reduced the number of check valves required for the circuit from three to one. The single check valve would be used to protect the pump from being exposed to back pressure from the system. The opposite was also a safety factor that needed to be considered. In the event that the system built up too much pressure it needed to have a means to depressurize without harm to the user.

The location of the pressure relief valve was initially thought to be placed behind the accumulator and before the ball valve. After reviewing the proposed circuit at the midway review with industry professionals, it was advised to move the pressure relief valve in front of the pump, before the check valve. This was a logical change for the design because had the pressure relief valve been implemented in the initial placement it might have limited the accumulator performance and the accumulator may still have encountered high pressures, which would have been a safety concern. The new location of the pressure relief valve ensured the system could not exceed the preset pressure.

In summary, the valves to be used for this year's prototype includes one pressure relief valve, one ball valve, and one check valve. The system is thus designed to operate with 38% of the number of valves from the previous year. Reducing the number of valves provides additional benefits besides functionality. It also would result in a decrease in the number of fittings and hoses required to build the prototype thus lowering the weight and cost of the project. The reduction of valves would also simplify the troubleshooting process. This would make the prototype more reasonable for mass production.

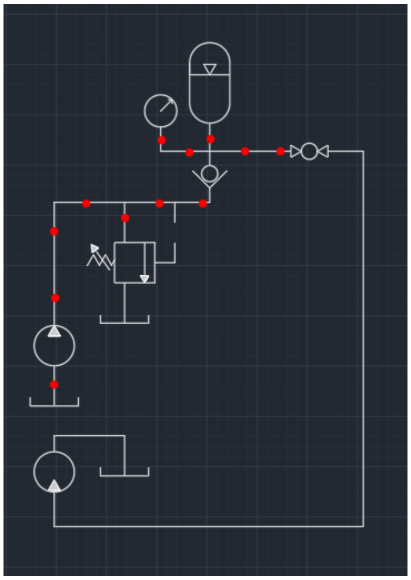


Figure 4: Hydraulic Schematic Charging Phase

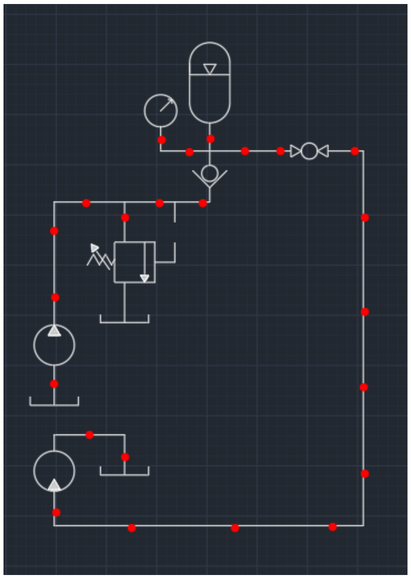


Figure 5: Hydraulic Schematic Discharging Phase

Schematics of the hydraulic circuit can be seen in Figure 4 and Figure 5. Figure 4 shows system during the charging phase: during this phase the ball valve is closed, closing off access to the motor portion of the circuit. By restricting flow to the motor portion of the circuit, the accumulator is able to build up pressure as a result of the rider turning the pedals, which are geared to a 3:1 ratio. As the rider rotates the pedals the pressure is built up from the pump. The pump pulls non pressurized hydraulic fluid from the reservoir. The pressurized fluid passes the pressure relief valve that is preset to approximately 2000 PSI. This means that if the pressure ever goes beyond 2000 PSI the pressure relief valve's pilot will reroute the pressurized fluid to the non-pressurized reservoir. While the fluid is below the pilot pressure of the pressure relief valve the fluid moves through the check valve. The check valve prevents fluid from returning from the portion of the circuit that it came from. The fluid continues to a 4-way junction including the accumulator, pressure gauge, and ball valve that is closed preventing the fluid from traveling any further in the circuit. The fluid is pumped into the 1.0-liter piston accumulator that is precharged with

Nitrogen pressurized to approximately 750-1500 PSI. The range of pressures is a due to the various challenges. At lower pressures the rider is able to charge the accumulator easier, but the distance the rider will travel due to this boost is lower than its higher pressure counterpart and vice versa.

Figure 5 illustrates the system during the discharge phase of operation. To initialize this phase of the circuit the rider simply rotates the handle of the ball valve 90 degrees opening up access to the motor portion of the circuit. The motor will first experience the release of pressure from any built up pressure from the accumulator. Upon the depletion of the pressure from the accumulator the rider may also provide input to continue to propel the bike forward.

4.3 Hydraulic and Mechanical Component Selection

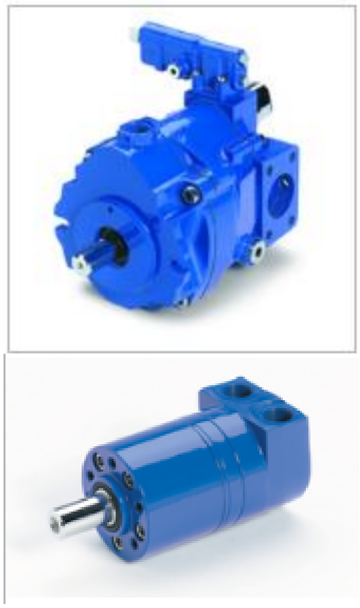
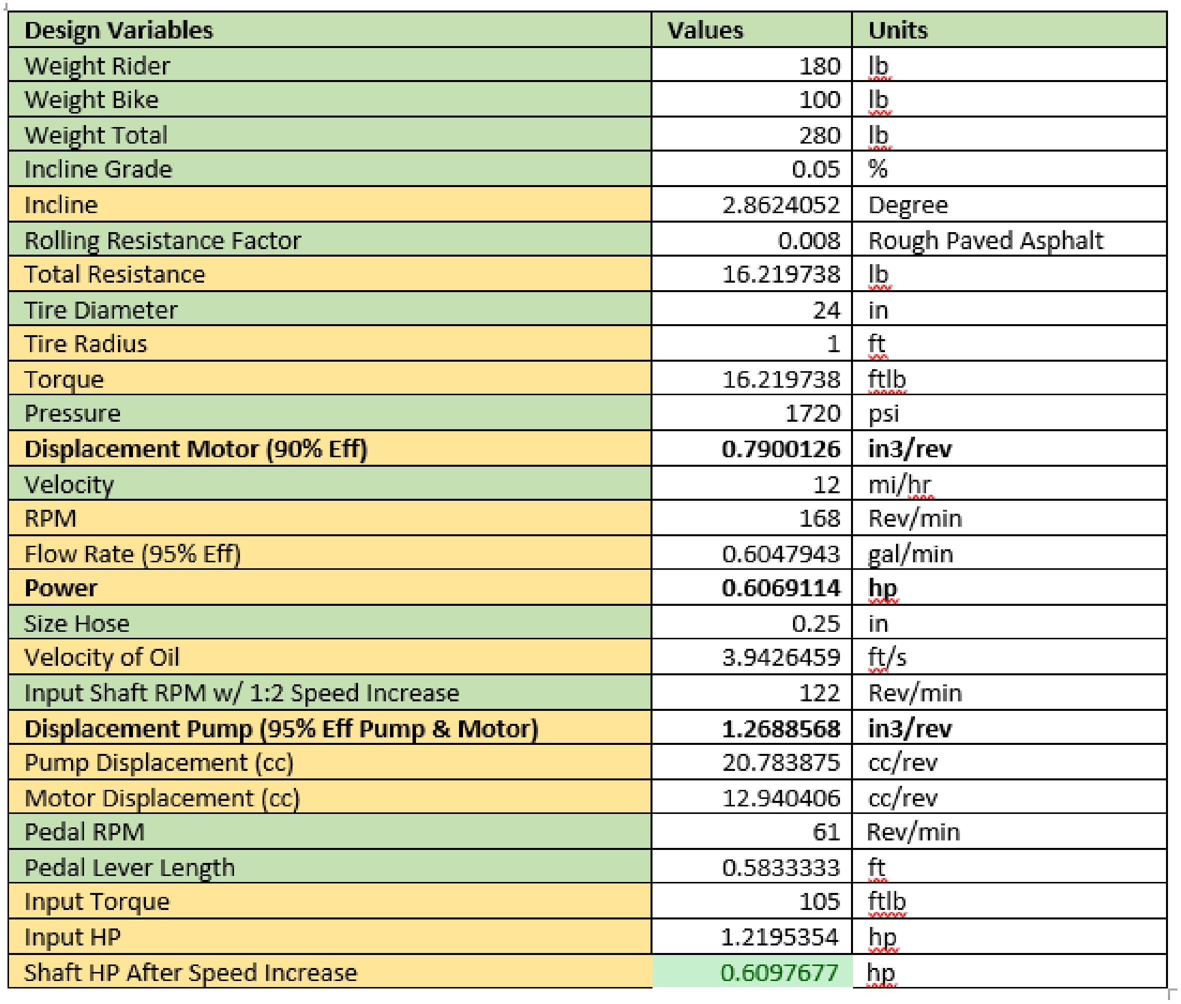


Figure 6: Piston Pump and Geroler Motor

Initial design concepts focused on use of a gear pump and motor. Specifically incorporating Eaton Series 26 gear pumps and motors, which had a minimum continuous flow rating of 750 RPM. The minimum continuous flow rating was the primary concern for using gear based components, as 750 RPM is impossible to achieve at a 1:1 input ratio. Assuming a human input of roughly 75 RPM with the resistance of the system, this concept incorporated a gear train that would offer a 1:10 speed increase to achieve a continuous flow to the pump and eliminate risk of cavitation in the pump. This idea was dropped due to the horsepower loss the gear train incurred, as pedaling the unpressurized system with only 10% power transmission would have been nearly impossible, not to mention the large expanse of exposed gearing posed a safety risk and was highly likely to encroach on the leg space needed by the rider.

The minimum continuous flow RPM became a big concern based on feedback from technical mentors. In light of the failure of the gear system to adequately mitigate the problem, a different pump model was pursued as an alternative solution. Piston pumps offer higher efficiency at lower RPMs, so an Eaton Vickers PVM variable displacement piston motor was selected, as it was rated for high efficiency at fluctuating RPMs between 0 and 500. Since the system is to be human powered, this was deemed ideal, as consistent RPMs are much harder to achieve when human power is used in the absence of an engine or motor. Additionally, a piston pump mitigates the suction issues that come with the use of a gear pump. This allows for far more flexibility in the design and placement of the reservoir. Similarly, a geroler motor appeared to offer the benefits needed for this system, as it's designed to be used in low RPM, high torque applications. The Eaton Char-Lynn model is rated at a maximum safe operating pressure of 2400 PSI, making it the lowest rated component for pressure in the system, and therefore, the component by which the operating pressure of the system is based upon.

Using Excel, all design variables and relevant calculations were placed into a spreadsheet, so that values could be easily manipulated and optimal conditions for various displacements could be determined. The incline grade and rolling resistance factors were intentionally overestimated to prepare for a worst case scenario, as discussed in the Project Plan section of this report. The maximum allowable weight of the bike and the heaviest rider's weight were used in determining the rolling resistance (See Table 1).



Design Variables	Values	Units
Weight Rider	180	lb
Weight Bike	100	lb
Weight Total	280	lb
Incline Grade	0.05	%
Incline	2.8624052	Degree
Rolling Resistance Factor	0.008	Rough Paved Asphalt
Total Resistance	16.219738	lb
Tire Diameter	24	in
Tire Radius	1	ft
Torque	16.219738	ftlb
Pressure	1720	psi
Displacement Motor (90% Eff)	**0.7900126**	**in3/rev**
Velocity	12	mi/hr
RPM	168	Rev/min
Flow Rate (95% Eff)	0.6047943	gal/min
Power	**0.6069114**	**hp**
Size Hose	0.25	in
Velocity of Oil	3.9426459	ft/s
Input Shaft RPM w/ 1:2 Speed Increase	122	Rev/min
Displacement Pump (95% Eff Pump & Motor)	**1.2688568**	**in3/rev**
Pump Displacement (cc)	20.783875	cc/rev
Motor Displacement (cc)	12.940406	cc/rev
Pedal RPM	61	Rev/min
Pedal Lever Length	0.5833333	ft
Input Torque	105	ftlb
Input HP	1.2195354	hp
Shaft HP After Speed Increase	0.6097677	hp

Table 1: Design Variables

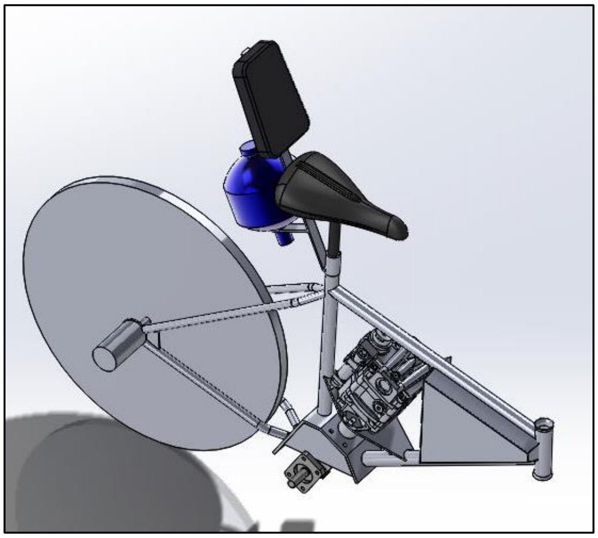
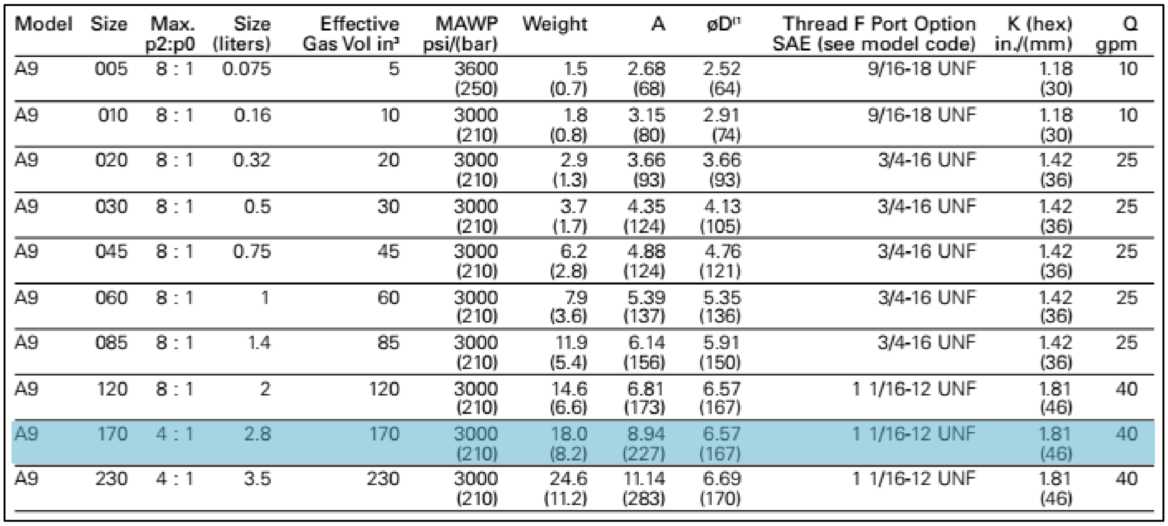


Figure 7: Piston/Geroler Design Concept Model

For the piston/geroler design, a 21.1 cc Vickers Variable Displacement Open Circuit Piston Pump was selected and paired with a 12.9 cc Char-Lynn J2 series Geroler Motor. The key design idea behind the displacements selected was to offer a mechanical advantage utilizing ratios to offer higher torque output from the motor with slower input required by the rider, similar to how a normal bicycle would offer mechanical advantage through a gear ratio. Since a hydraulic system is likely to offer high resistance to pedaling once it reaches higher pressures, the ratio would allow the rider to put slower, higher force strokes into the system. The relatively large pump and motor sizes also make the system effective at lower pressures. This design would overcome starting torque values at 1720 PSI. The main advantage of a lower pressure system would be evident in the efficiency challenge, as the accumulator is more effective the higher its charged pressure is above the operating pressure of the circuit. Knowing the maximum pressure, the circuit can handle is 2400, this allows for a possible pre-charge of 680 PSI above minimum operating pressure.

A diaphragm accumulator offered the best weight/volume ratio by a significant margin. General advantages of diaphragm style accumulators include low weight, compact design, and good response characteristics. Diaphragm accumulators are meant to be used in small flow volume applications, so it synergizes well with the use of the geroler motor. The best weight to volume ratio offered in the Eaton diaphragm accumulators is found in the 2.8-liter model, at 6.4 pounds per liter. Because the ratio is a critical component to the judging of the efficiency competition, it is the primary criterion for accumulator selection. Bladder accumulators offered a much more limited selection in smaller sizes, and practically sized options (namely 1-gallon) had a ratio of 8.1 pounds per liter.



Model	Size	Max. p2:p0	Size (liters)	Effective Gas Vol in³	MAWP psi/(bar)	Weight	A	øD$^{(1)}$	Thread F Port Option SAE (see model code)	K (hex) in./(mm)	Q gpm
A9	005	8 : 1	0.075	5	3600 (250)	1.5 (0.7)	2.68 (68)	2.52 (64)	9/16-18 UNF	1.18 (30)	10
A9	010	8 : 1	0.16	10	3000 (210)	1.8 (0.8)	3.15 (80)	2.91 (74)	9/16-18 UNF	1.18 (30)	10
A9	020	8 : 1	0.32	20	3000 (210)	2.9 (1.3)	3.66 (93)	3.66 (93)	3/4-16 UNF	1.42 (36)	25
A9	030	8 : 1	0.5	30	3000 (210)	3.7 (1.7)	4.35 (124)	4.13 (105)	3/4-16 UNF	1.42 (36)	25
A9	045	8 : 1	0.75	45	3000 (210)	6.2 (2.8)	4.88 (124)	4.76 (121)	3/4-16 UNF	1.42 (36)	25
A9	060	8 : 1	1	60	3000 (210)	7.9 (3.6)	5.39 (137)	5.35 (136)	3/4-16 UNF	1.42 (36)	25
A9	085	8 : 1	1.4	85	3000 (210)	11.9 (5.4)	6.14 (156)	5.91 (150)	3/4-16 UNF	1.42 (36)	25
A9	120	8 : 1	2	120	3000 (210)	14.6 (6.6)	6.81 (173)	6.57 (167)	1 1/16-12 UNF	1.81 (46)	40
A9	170	4 : 1	2.8	170	3000 (210)	18.0 (8.2)	8.94 (227)	6.57 (167)	1 1/16-12 UNF	1.81 (46)	40
A9	230	4 : 1	3.5	230	3000 (210)	24.6 (11.2)	11.14 (283)	6.69 (170)	1 1/16-12 UNF	1.81 (46)	40

Figure 8: Eaton Diaphragm Accumulator Specification Table

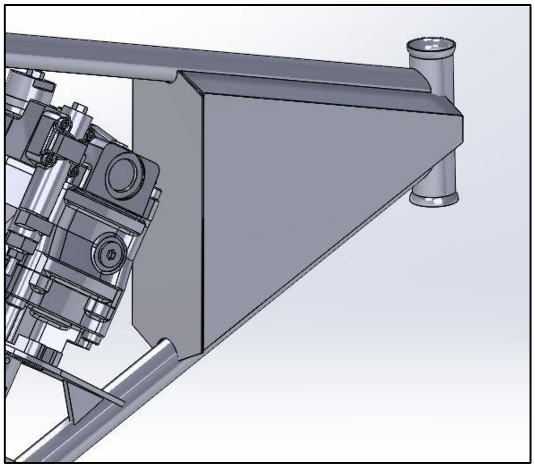


Figure 9: Frame-Fitting Reservoir Design

Piston accumulators were the least favorable choice, as they are not recommended for shock applications, and perform best at high flow rates. Piston accumulators at the sizes desired offered ratios around 15 pounds per liter, as such pistons were to be avoided.

The primary problem to overcome in the design, with regards to the accumulator, was positioning. The 2.8-liter accumulator posed two challenges in this respect: first was the size of the accumulator dictating the size of the reservoir. If the accumulator is 2.8 liters, then the reservoir must be equal to that as well as the volume of the rest of the circuit, which was deemed to be a total of 3.27 liters. The center cavity of the frame is a prime location for housing components, but with a large pump and more than 3-liter reservoir, very little room was left in that space. The space would be maximized by designing a reservoir to fit into the angle between the frame pieces.

The panels for the reservoir were to be plasma cut, welded to the frame, the interior would be cleaned out of debris with an acid wash, and finally internally coated with a resin to prepare it to receive and hold hydraulic fluid. This left the accumulator, which would be mounted via a bracket behind the seat of the bike (see Figure 7), keeping weight centralized to the mid-plane, and would serve to keep the reservoir out of the way of the rider’s legs as the bike was pedaled. In addition, a cushioned seat back would be added to the bracket installation to prevent the rider from sliding too far back and coming into contact with the hydraulic fittings behind them.

With all the hydraulic components considered, there came the issue of power transmission from the human input to the pump itself. The size of the pump demanded a central position to keep the bike balanced, so its shaft was located perpendicular to the pedals. In order to transfer the direction of the rotation 90 degrees, a cross-axis bevel gear box taken from the previous year's design would be used. The gearbox, a 1:2 ratio, was a good middle ground between this design and the initial speed increase design. The doubled input RPM allowed for the selection of the 21.1 cc pump. Despite the torque loss caused by the speed increase, the necessary power to drive the pump was 0.609 HP which is less than the halved expected output of the rider (See Table 1).

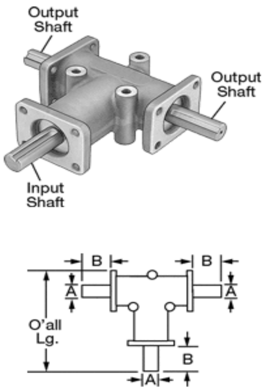


Figure 10: Cross Axis Gearbox

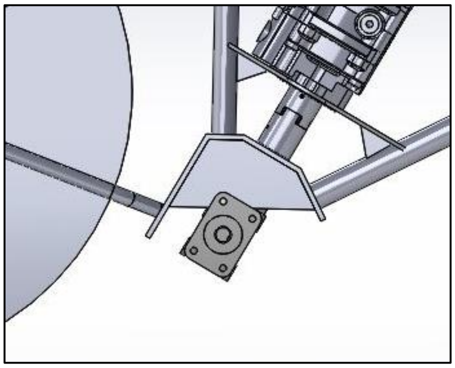


Figure 11: Gearbox Housing

The gearbox would be mounted in a steel housing, which would become a structural member of the frame, replacing the original cylindrical ball bearing housing situated at the base. The steel housing would serve the purpose of securing the gearbox in place, and maintaining the alignment of the output shaft to be coupled with the pump shaft. The rear plate would have a hole pattern matching that of the mounting holes on the gearbox, and it would be secured with the use of bolts and spacers.

This design was the culmination of the first semester of work, in Fall of 2016, and subsequently presented at the midway design review. All components were ordered in December, however in January logistical issues presented themselves via the supplier, and lead times pushed the delivery dates for the desired pump, motor, and accumulator past the date of the competition. With this development, a redesign was made necessary which would utilize the gear pumps on hand for immediate distribution at Eaton.

The first step in the redesign was to go back to the design variables table and retool it to match the feasible bounds of what can be accomplished with the pumps and motors that were being offered at this point.

Design Variables	Values	Units
Weight Rider	180	lb
Weight Bike	100	lb
Weight Total	280	lb
Incline Grade	0.05	%
Incline	2.862405	Degree
Rolling Resistance Factor	0.008	Rough Paved Asphalt
Total Resistance	16.21974	lb
Tire Diameter	24	in
Tire Radius	1	ft
Torque	16.21974	ftlb
Pressure	2200	psi
Displacement Motor (90% Eff)	**0.617646**	**in^3/rev**
Velocity	12.5	mi/hr
RPM	175	Rev/min
Flow Rate (95% Eff)	0.492541	gal/min
Power	**0.632199**	**hp**
Size Hose	0.25	in
Velocity of Oil	3.210867	ft/s
Pedal RPM	250	Rev/min
Displacement Pump (95% Eff Pump & Motor)	**0.504274**	**in^3/rev**
Pump Displacement (cc)	8.260016	cc/rev
Motor Displacement (cc)	10.11704	cc/rev

Table 2: Final Design Variables

After retooling the design parameters, the Eaton Series 26 8.2 cc gear pump was selected, paired with a Series 26 10.2 cc motor. The much smaller pump displacement necessitated a higher ratio speed increase to be feasible, so the gear ratio went from 1:2 to 1:3. A 1:3 speed increase was a compromise between power loss due to gears, and faster RPM to compensate for the efficiency loss of a gear pump. One hurdle on the way to achieving this new

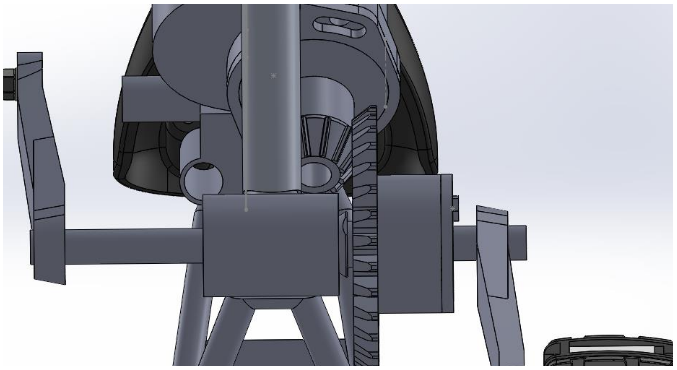


Figure 12: Bevel Gears and Original Bearing Housing

ratio was a lack of availability of cross axis gear boxes offering a 1:3 speed increase. In order to achieve the desired ratio, a 3:1 pinion and bevel gear were purchased, which served the purpose of changing the rotational direction as well as increasing the RPM. The steel pinion was keyed and press-fit to the input shaft of the pump to eliminate the need for a coupling since space was at a premium. There needed to be room left between the pump and the reservoir to accommodate fittings and hose to transfer fluid between the two. The bevel gear was fitted to a custom shaft which would utilize the existing ball bearing housing. The pedal shaft was turned, involving multiple steps to accommodate the bevel gear, bearings, and pedal cranks. Once finished turning, the left hand side of the shaft was threaded in order to tighten down the bevel gear and control the alignment to the pinion. The pedal bearing brackets were clamped and welded to the shaft to ensure bearings were fully engaged and there would be no movement of the sub-assembly within the frame. Pedal cranks were then press fit to the shaft.

Another design consideration is the placement of the reservoir to mitigate suction issues caused by low RPM input to the gear pump. The reservoir was redesigned to sit directly above the pump, allowing gravity to aid in the flow of fluid into the pump, and reduce the risk of cavitation. The hose linking the reservoir to the pump was also made as large a diameter as possible to increase volumetric flow rate. The new operating pressure rose significantly due to the smaller components, now at 2200 PSI. However, with the elimination of the geroler motor, the maximum pressure of the system rose to 3000 PSI, allowing for a higher setting on the pressure relief valve, which is currently set to 2800 PSI, with the additional 200 PSI cushion to absorb the effects of erratic pressure fluctuation near the maximum.

4.4 Mechanical Component Design/Assembly

As shown in the original design, the pump was mounted to a steel plate, contoured to the mounting face of the pump, and welded to the frame. The motor mount was had to be designed to serve multiple purposes. The first purpose of the rear mounting system is supporting the shaft. To achieve this while maintaining the free spinning motion and minimal resistance on the wheel, the shaft was fitted into two sleeve ball bearings, which transferred the load from the wheel to the frame. The load transfer takes place in the bearing housing plates, which were designed to press fit the bearing sleeves, and were welded directly to the back

Figure 13: Updated Concept Design with New Pump and Motor

portion of the frame, where the original wheel mount was located. The outermost plate of the bearing housing was also designed to match the bolt pattern of the Series 26 motor. The keyed shaft of the motor mates up with the wheel drive shaft by lining up the keyways and press-fitting the two together. The drive shaft mated to the wheel utilizing a two-inch bolt pattern matching the pattern on a small circular steel plate fixed to the spoke hub. The original rear wheel mounts were cut from the frame, and the new rear plates were welded to the existing frame in their place. The plates housed the shaft bearings and were press-fit to the shaft. The plates were moved back 3 inches to increase the amount of contact area for the welds and allow clearance for the larger diameter shaft that was to be used. The modification resulted in the need to replace the break lines with a longer protective sheath and brake line.

4.5 FEA Analysis

FEA analysis was conducted on two critical parts of the design, the frame and rear shaft. FEA on the frame allowed the team to design around and avoid modifying high stress points. The FEA was conducted as a static load of a 200 lb rider, and is pictured below in Figure 14. Analysis shows a max stress of 4978 PSI where the rear tubes meet the middle tube, well below the maximum yield strength of 50,00 PSI. It was determined that the occurrence of the frame welds failing was very unlikely due the amount of load this application requires.

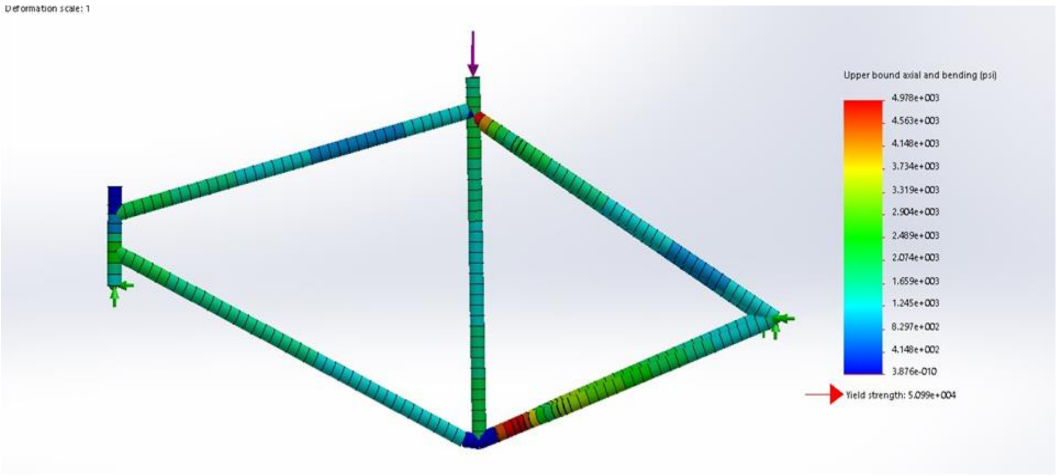


Figure 14: FEA of the Bike Frame

The second FEA conducted was on the rear shaft, which is considered the part of the design most likely to fail. A 200 lb static force was used to analyze the shaft, which is much higher than the expected static load, as 200 lbs almost approaches the total weight of the system and rider. The FEA, pictured below in Figure 15, revealed a max stress of 9270 PSI. The maximum stress point is at an expected location of a stress riser where the shaft reduces size. This stress point is well below the yield strength of 50,000 PSI.

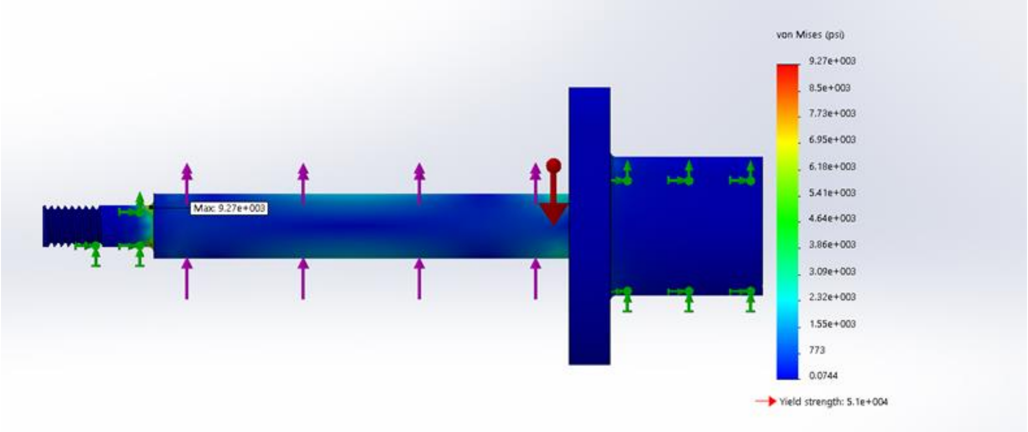


Figure 15: FEA of the Rear Shaft

5.0 DESIGN DRAWINGS

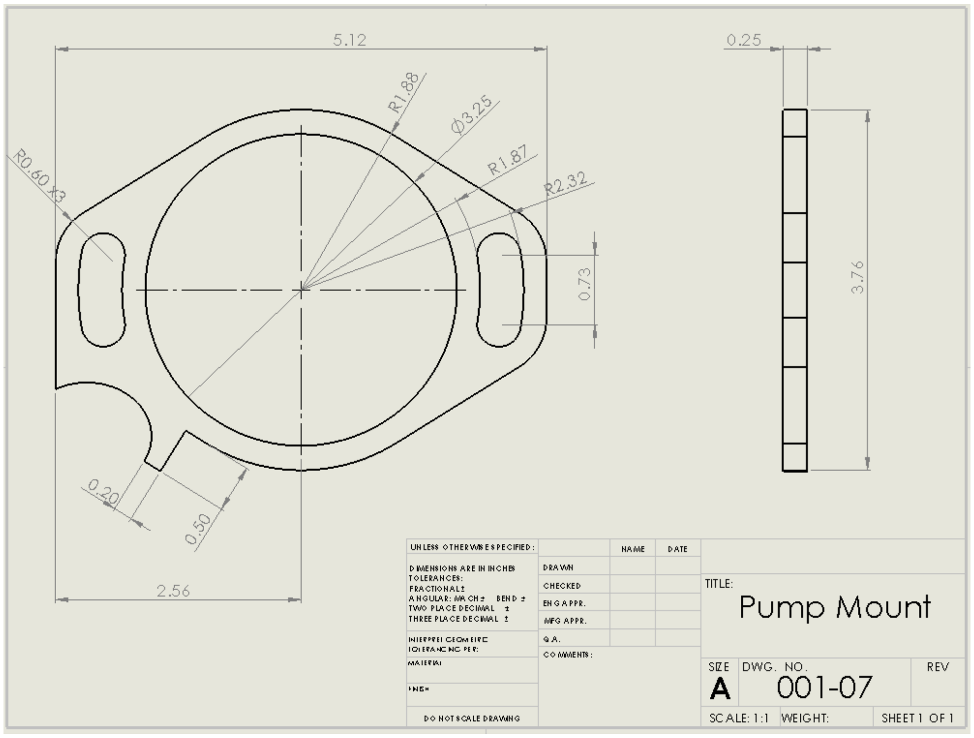


Figure 16: Pump Mount

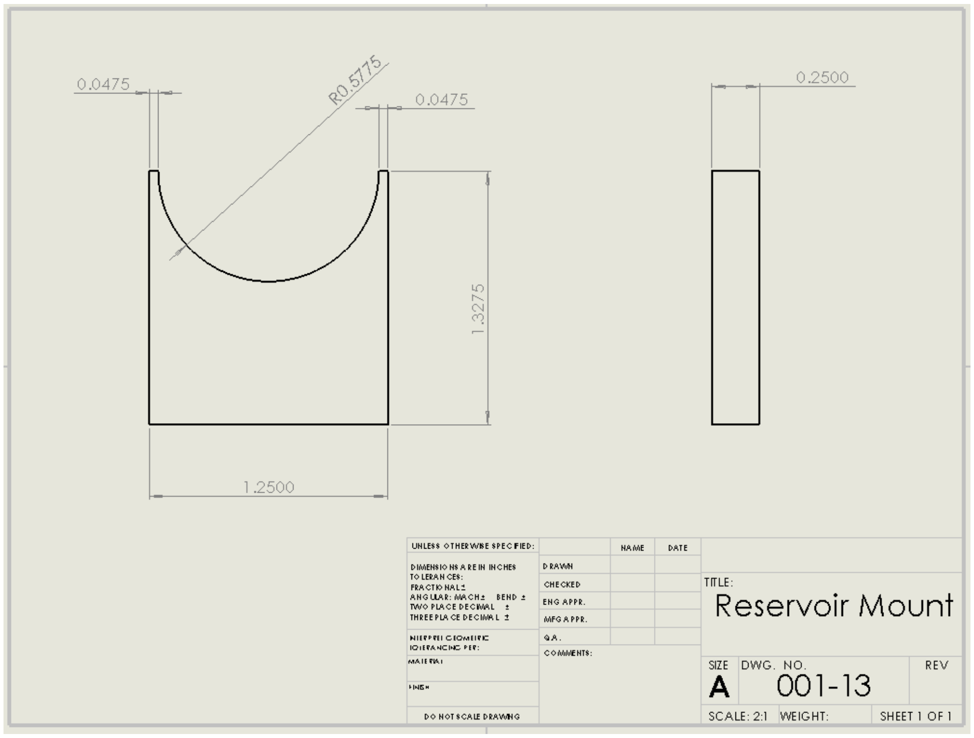


Figure 17: Reservoir Mount

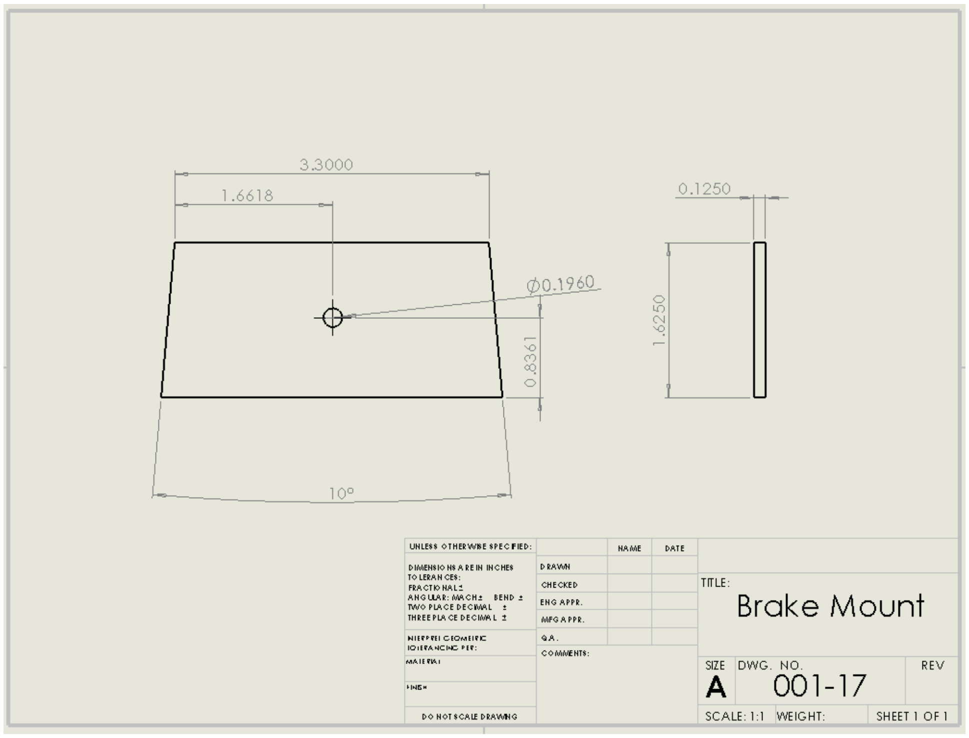


Figure 18: Brake Mount

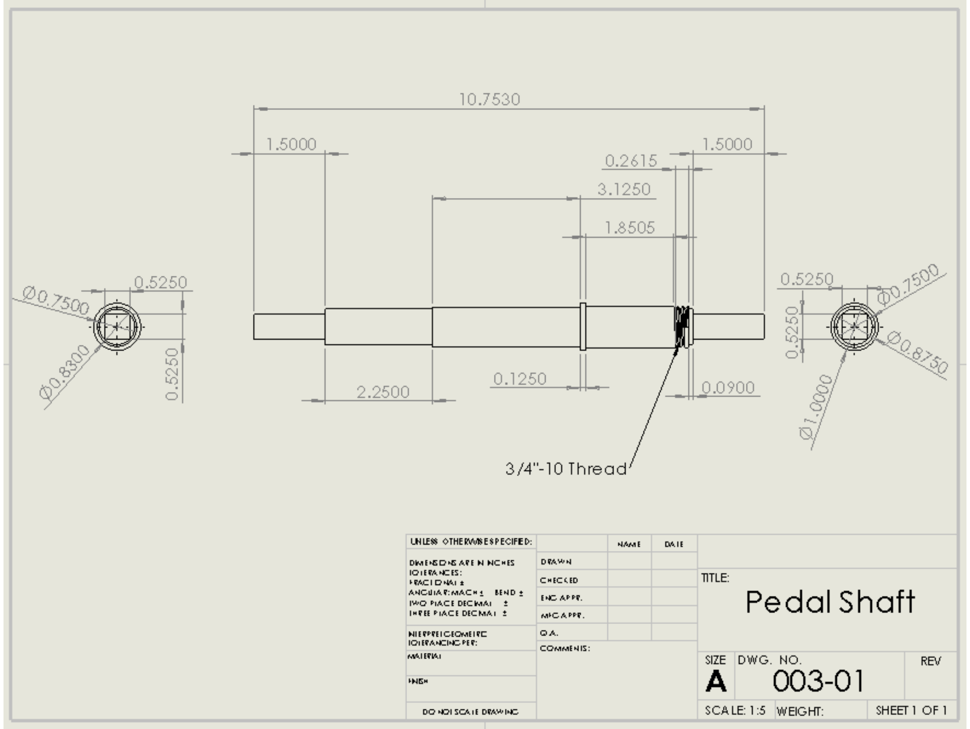


Figure 19: Pedal Shaft

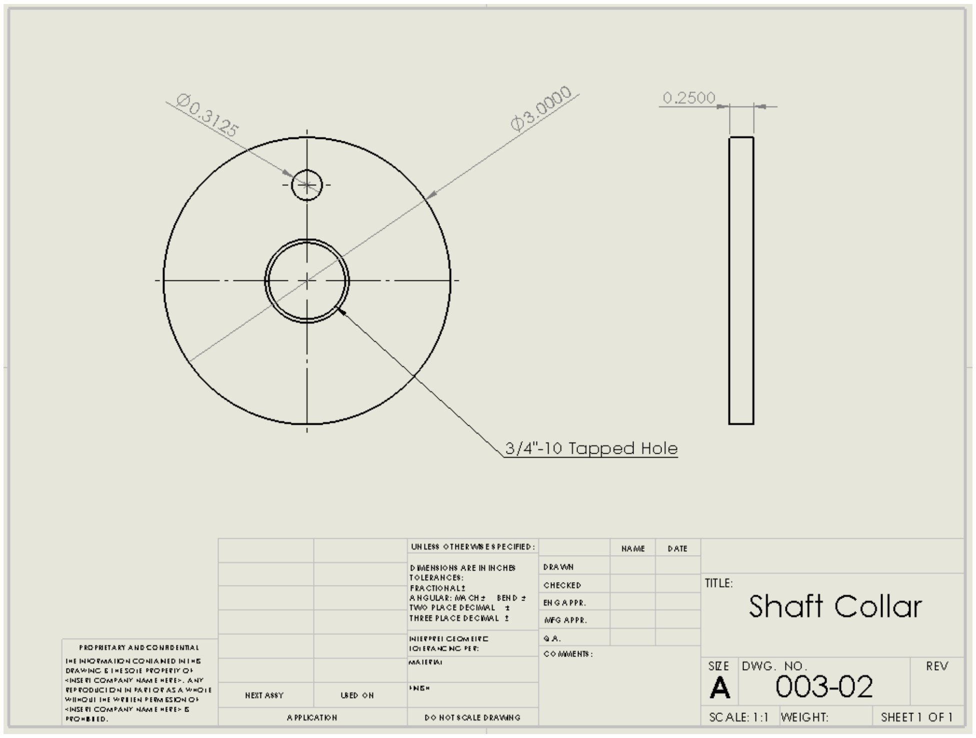


Figure 20: Shaft Collar

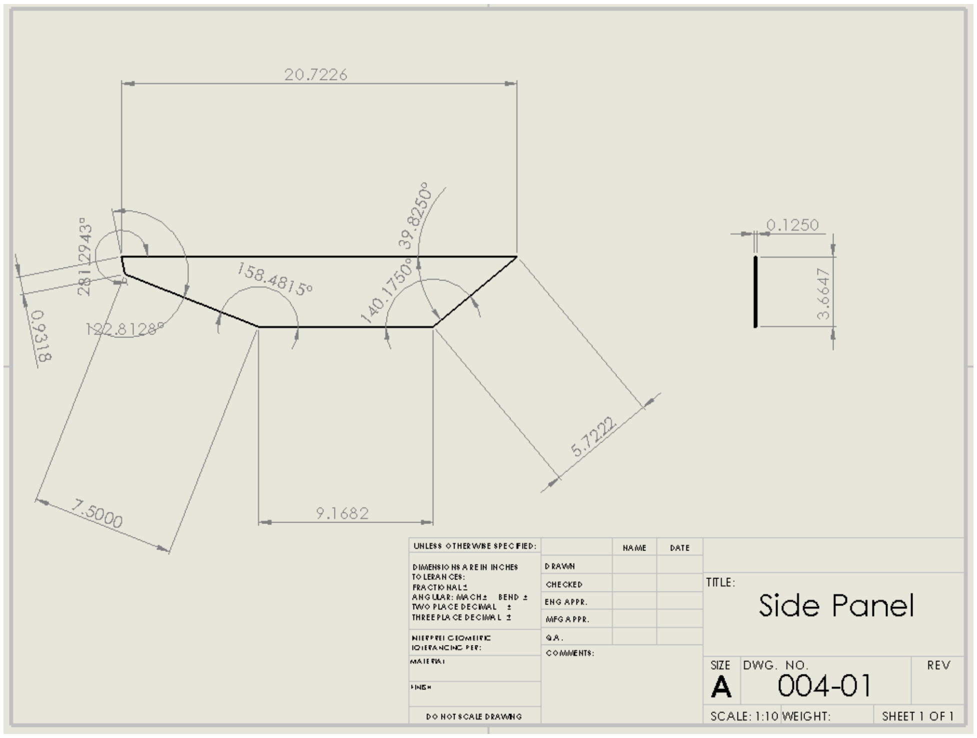


Figure 21: Reservoir Side Panel

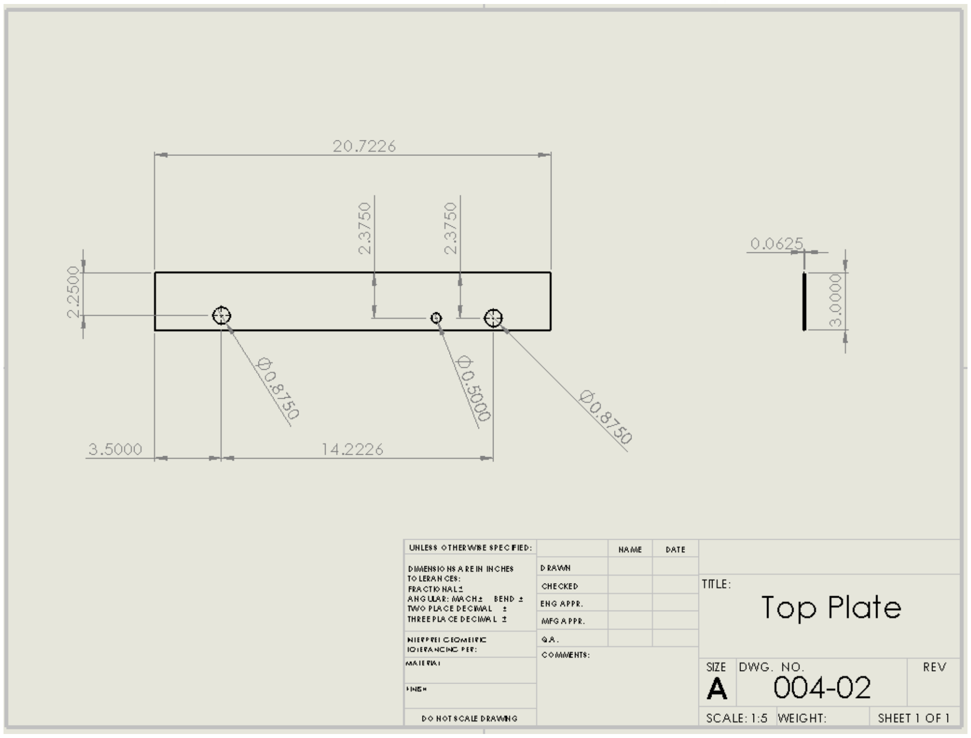


Figure 22: Reservoir Top Plate

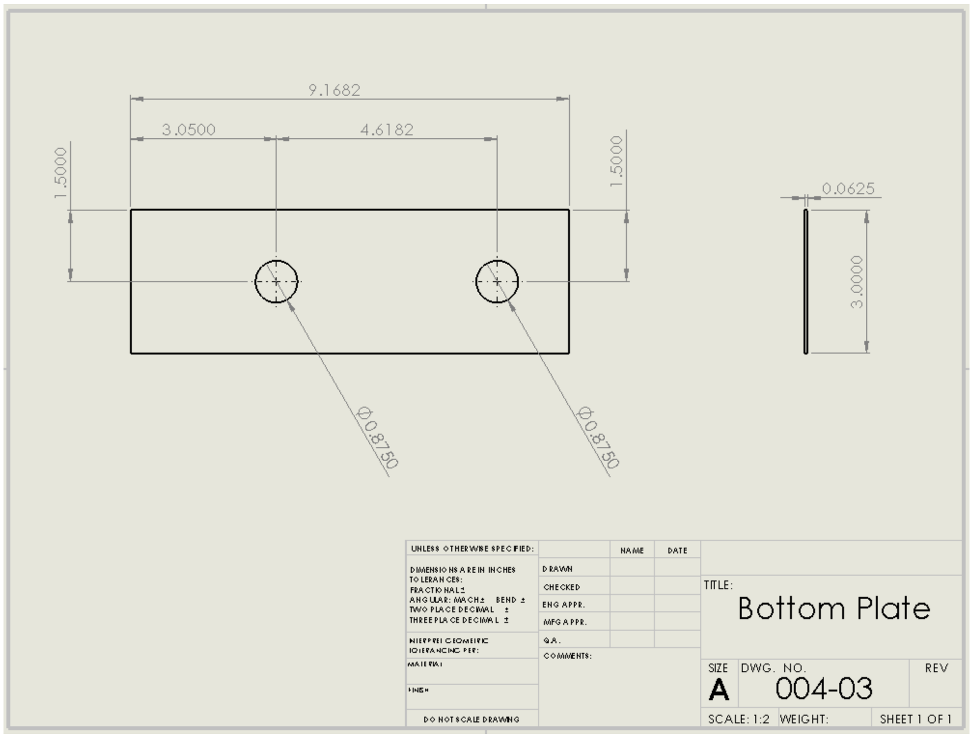


Figure 23: Reservoir Bottom Plate

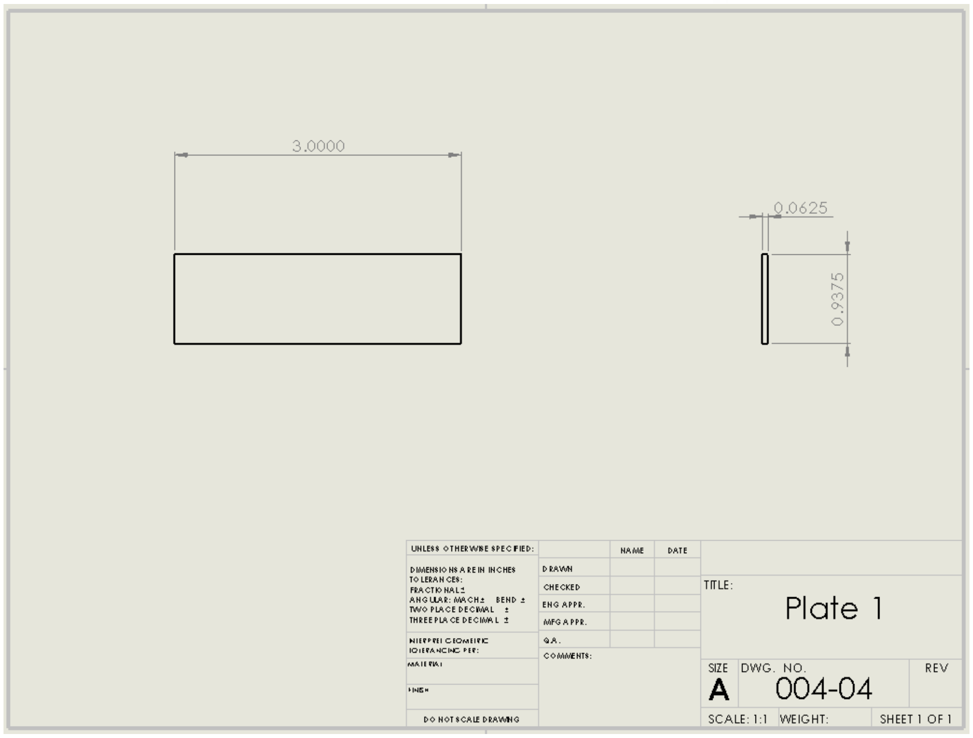


Figure 24: Reservoir Plate 1

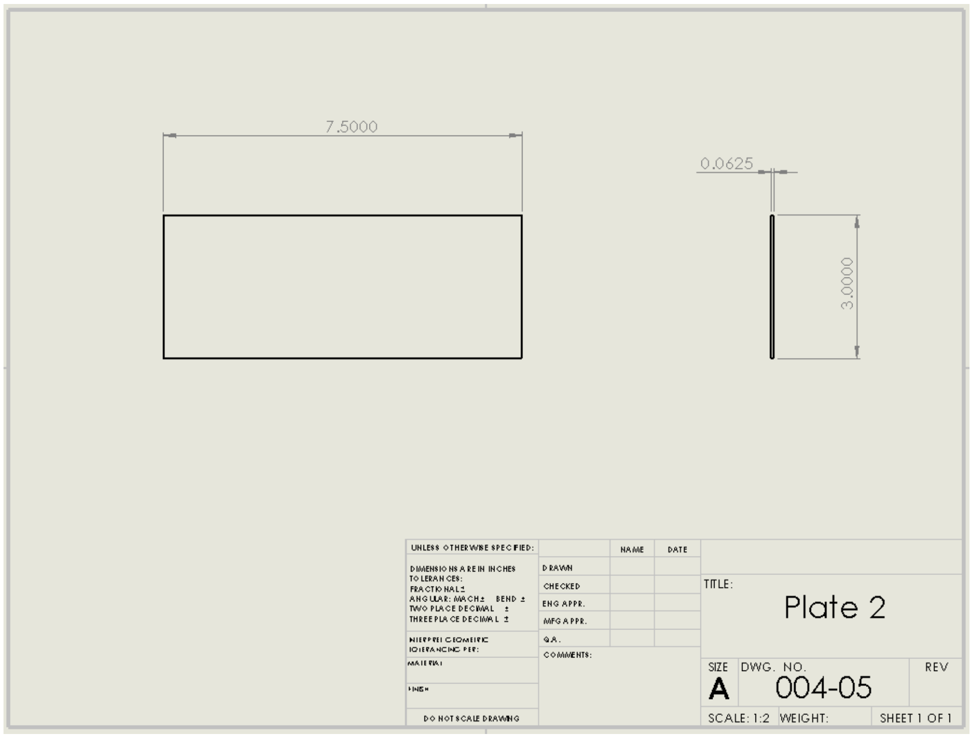


Figure 25: Reservoir Plate 2

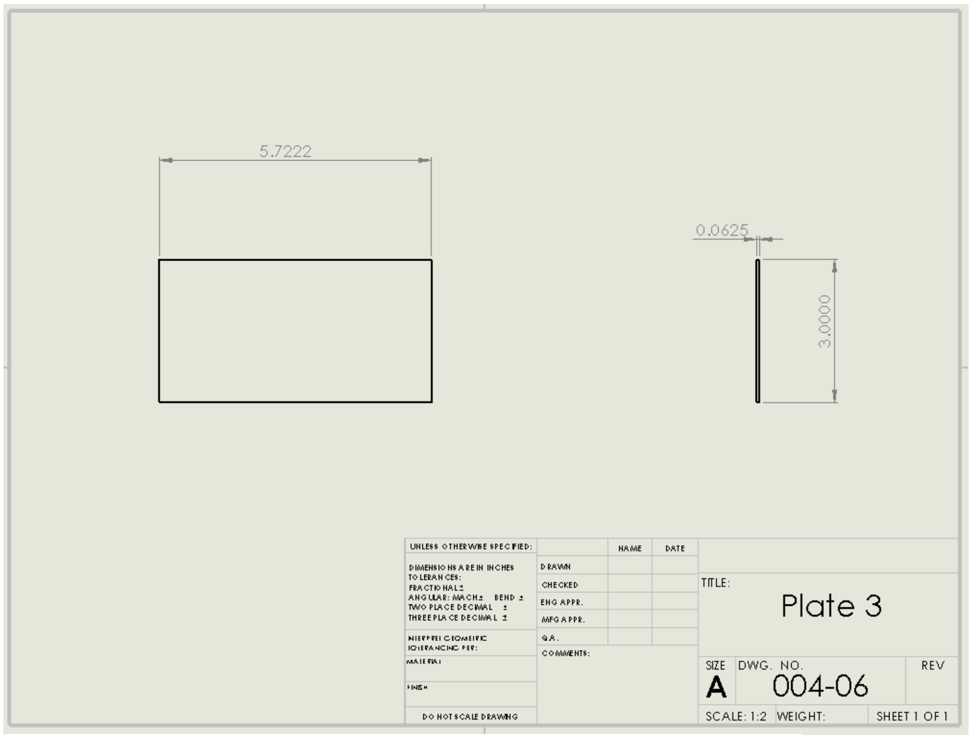


Figure 26: Reservoir Plate 3

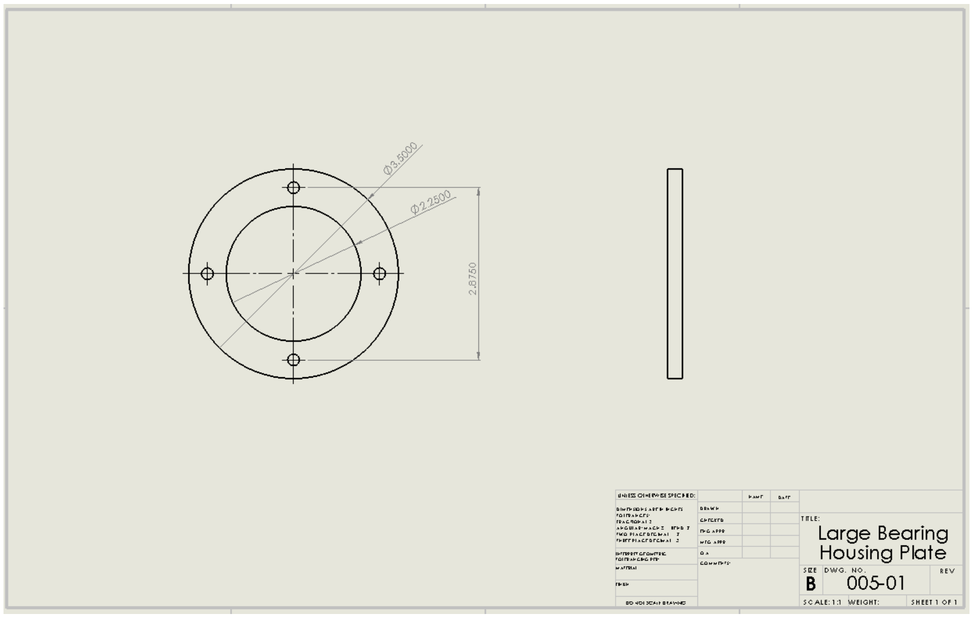


Figure 27: Large Bearing Hosing Plate

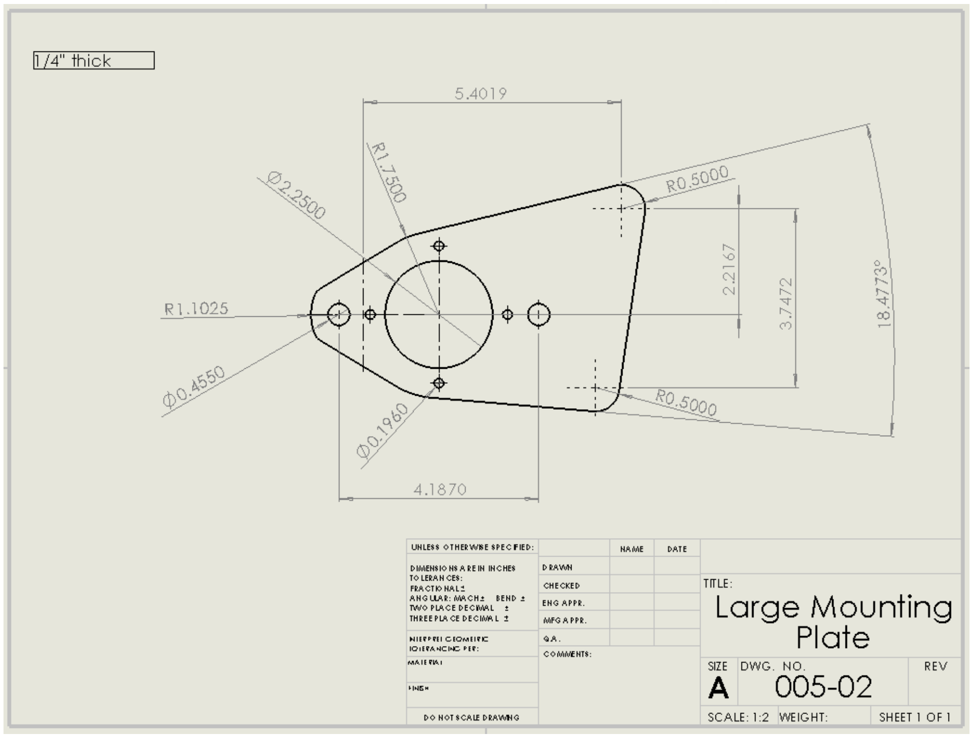


Figure 28: Large Mounting Plate

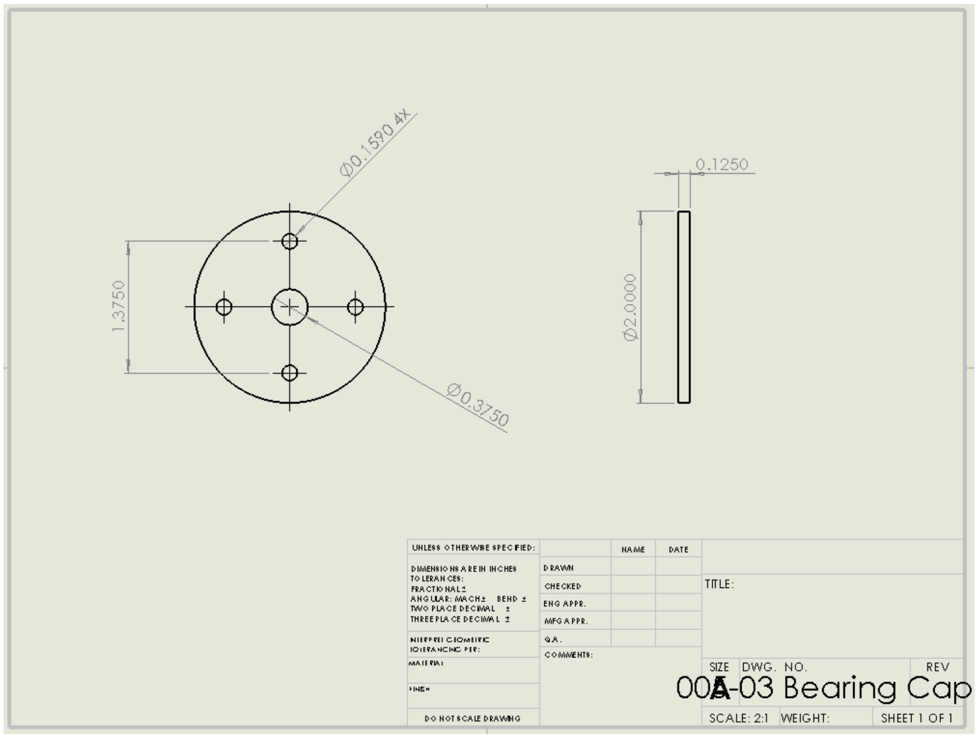


Figure 29: Bearing Cap

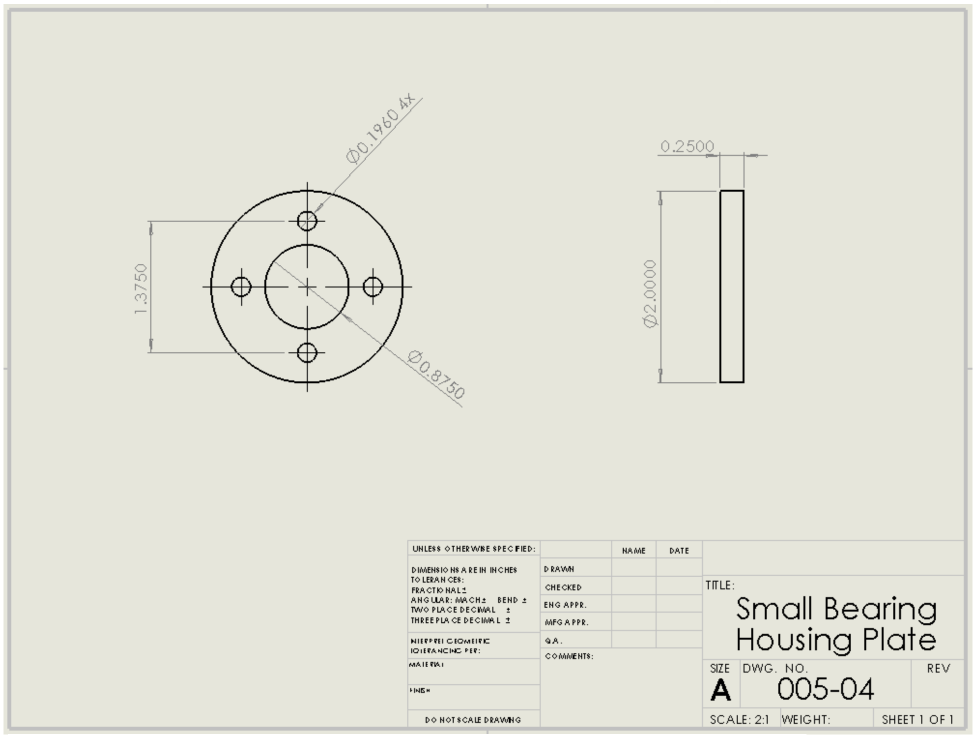


Figure 30: Small Bearing Housing Plate

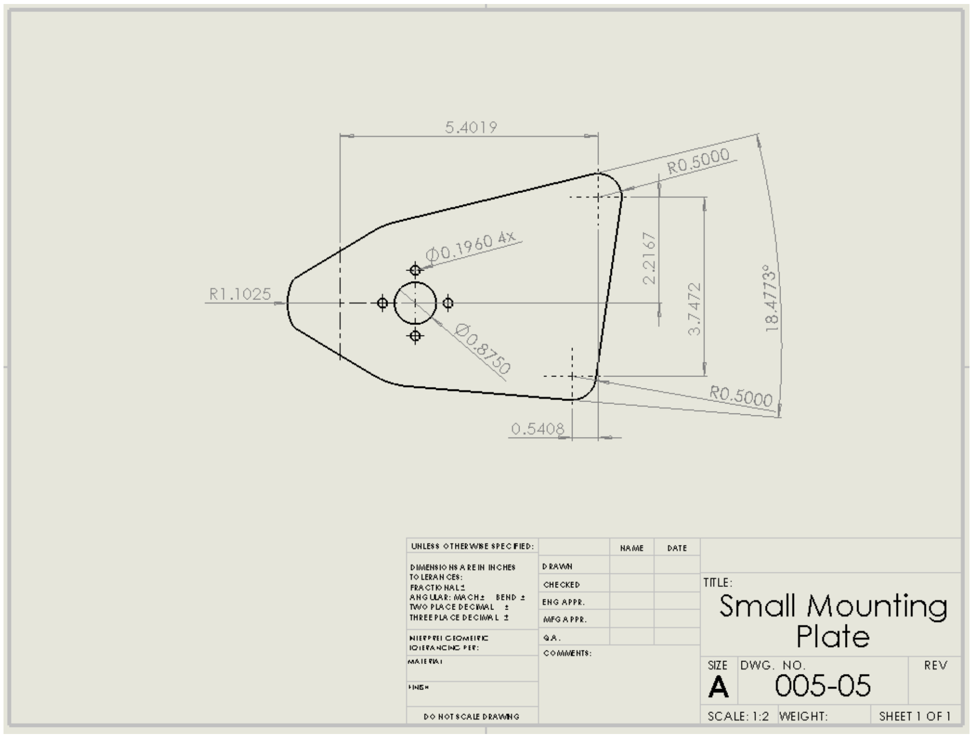


Figure 31: Small Mounting Plate

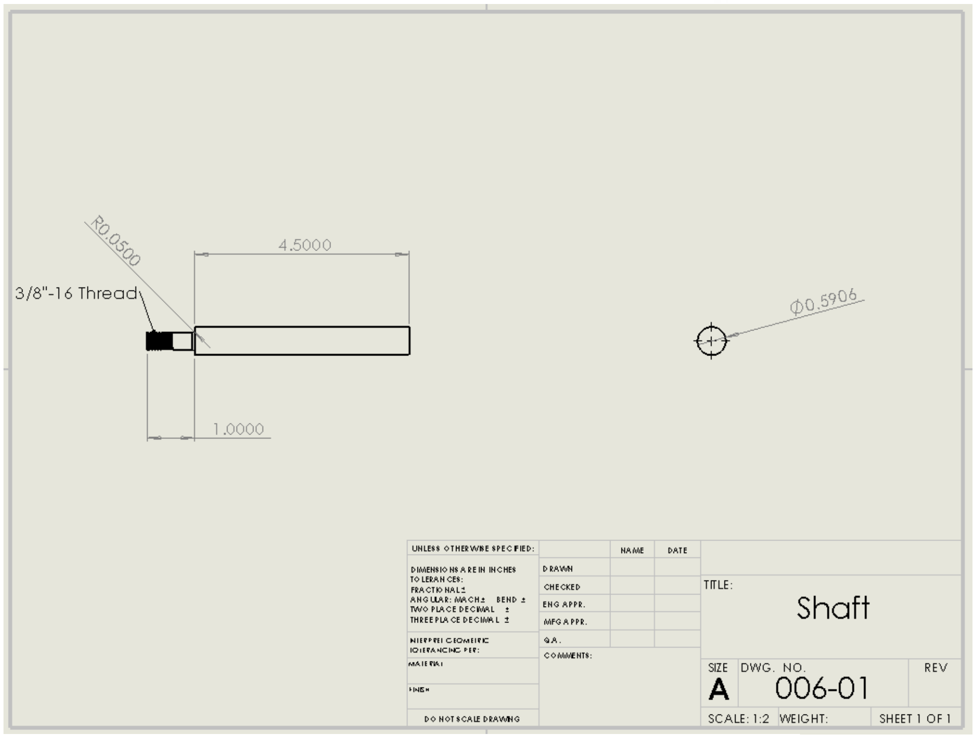


Figure 32: Rear Shaft

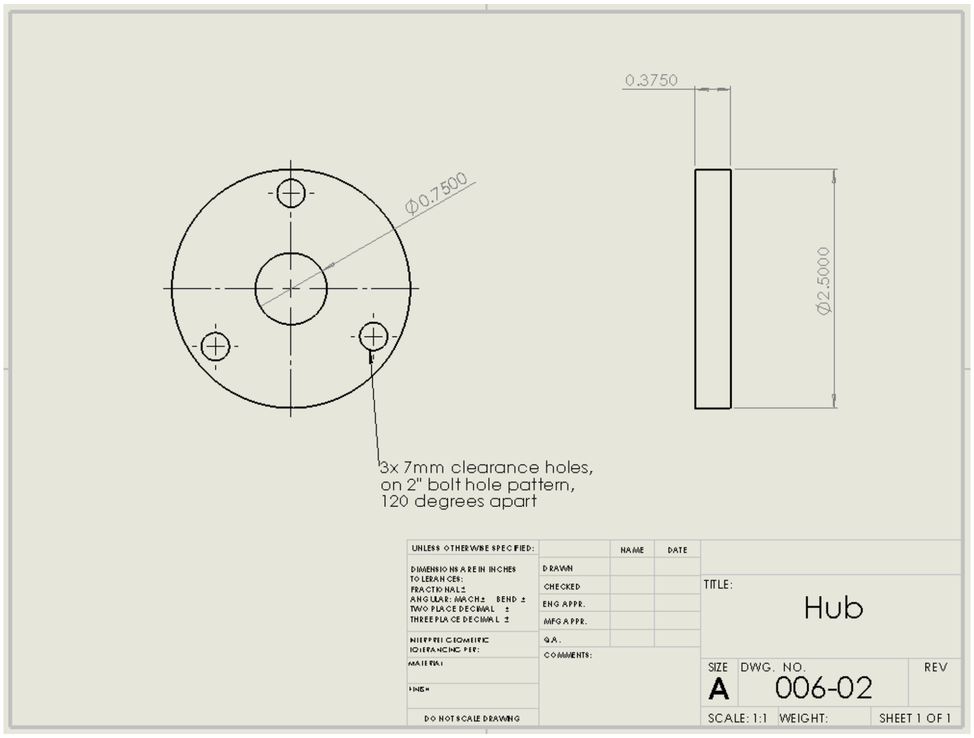


Figure 33: Rear Hub

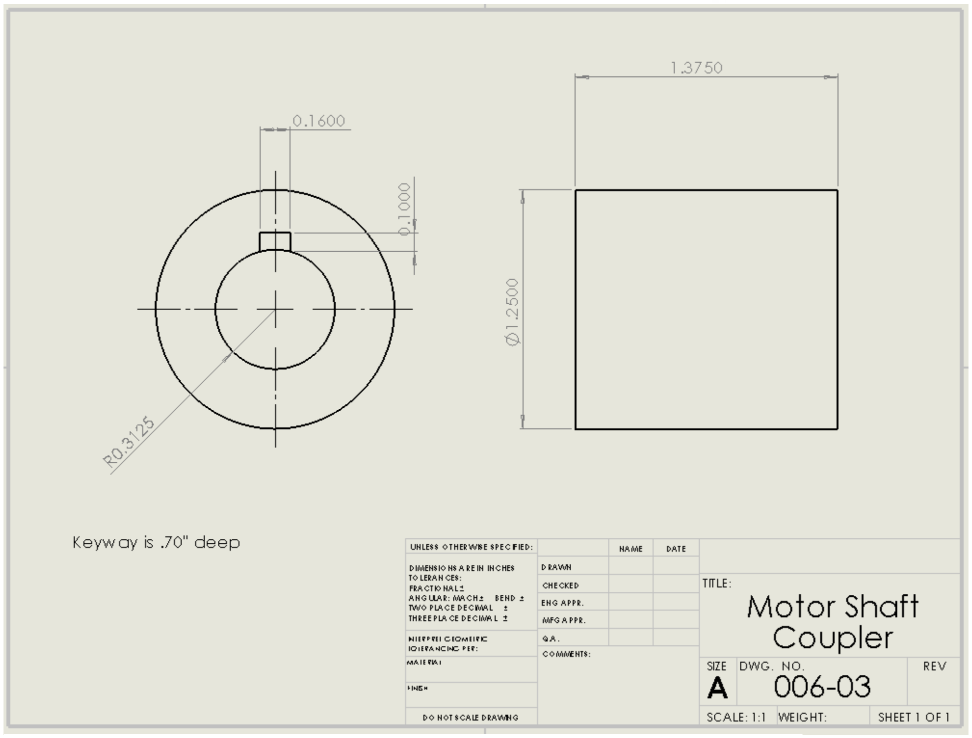
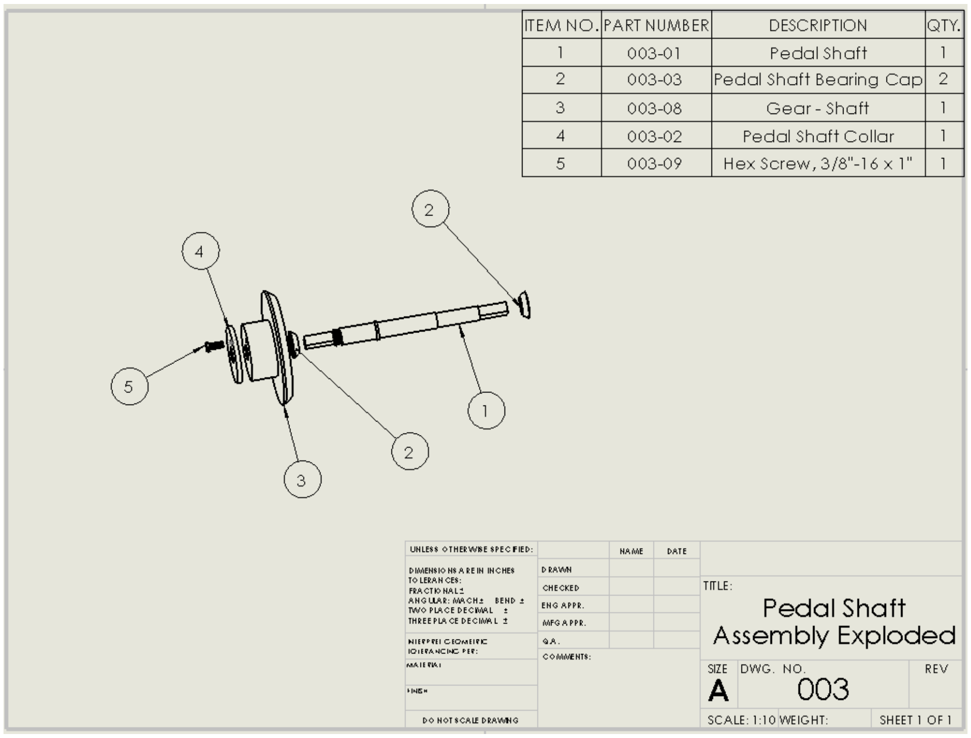
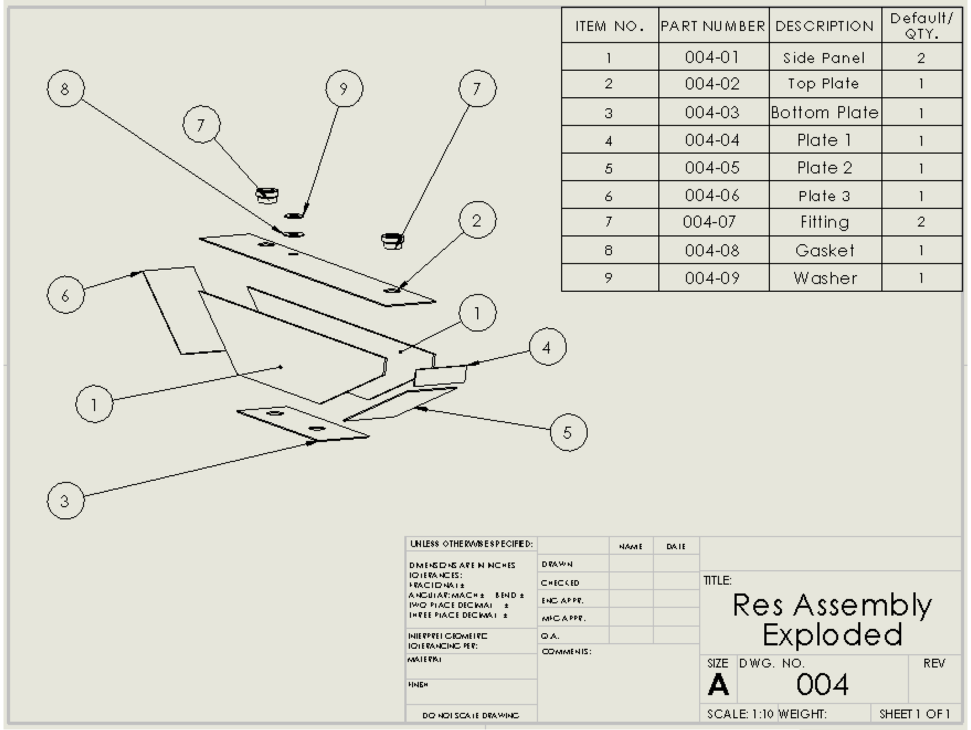


Figure 34: Rear Motor Shaft Coupler



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	003-01	Pedal Shaft	1
2	003-03	Pedal Shaft Bearing Cap	2
3	003-08	Gear - Shaft	1
4	003-02	Pedal Shaft Collar	1
5	003-09	Hex Screw, 3/8"-16 x 1"	1

Figure 35: Pedal Shaft Assembly Exploded View



ITEM NO.	PART NUMBER	DESCRIPTION	Default/ QTY.
1	004-01	Side Panel	2
2	004-02	Top Plate	1
3	004-03	Bottom Plate	1
4	004-04	Plate 1	1
5	004-05	Plate 2	1
6	004-06	Plate 3	1
7	004-07	Fitting	2
8	004-08	Gasket	1
9	004-09	Washer	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

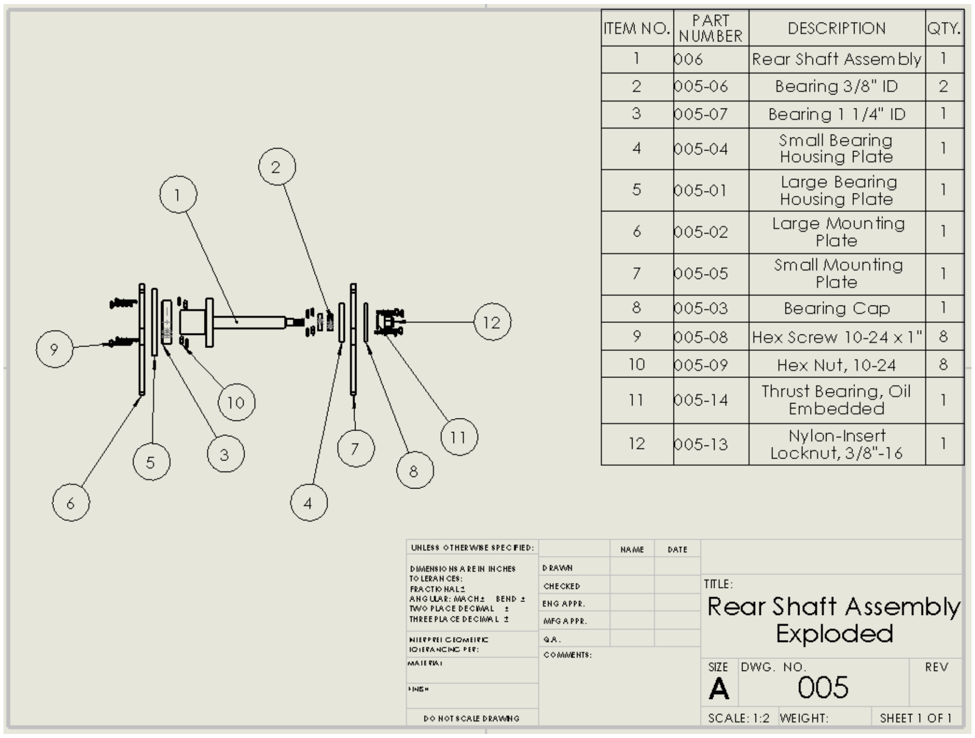
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
Res Assembly Exploded

SIZE A DWG. NO. 004 REV
SCALE: 1:10 WEIGHT: SHEET 1 OF 1

Figure 36: Reservoir Assembly Exploded



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	006	Rear Shaft Assembly	1
2	005-06	Bearing 3/8" ID	2
3	005-07	Bearing 1 1/4" ID	1
4	005-04	Small Bearing Housing Plate	1
5	005-01	Large Bearing Housing Plate	1
6	005-02	Large Mounting Plate	1
7	005-05	Small Mounting Plate	1
8	005-03	Bearing Cap	1
9	005-08	Hex Screw 10-24 x 1"	8
10	005-09	Hex Nut, 10-24	8
11	005-14	Thrust Bearing, Oil Embedded	1
12	005-13	Nylon-Insert Locknut, 3/8"-16	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
Rear Shaft Assembly Exploded

SIZE A DWG. NO. 005 REV
SCALE: 1:2 WEIGHT: SHEET 1 OF 1

Figure 37: Rear Shaft Assembly Exploded

6.0 COMPONENT LIST

Assembly	Asmbly #	Part #	Part Name	Quant	Ref #	Source
Bike Assembly	001	01	Frame	1		
	002	00	Hydraulic System Assembly	1	002	
	003	00	Pedal Shaft Assembly	1	003	
	004	00	Reservoir Assembly	1	004	
	005	00	Rear Shaft Assembly	1	005	
	001	06	Accumulator Clamps	2		
	001	07	Pump Mount	1		
	001	09	Hex Head Screw, 7/16"-20 x 1-1/4""	2	91286A293	Mcmaster
	001	10	Hex Nut, 7/16"-20	4	95036A037	Mcmaster
	001	11	Washer, 7/16" Screw Size	4	98023A032	Mcmaster
	001	12	Front Wheel	1		
	001	13	Reservoir Mount	2		
	001	14	Accumulator Brackets	2		
	001	15	Accumlator Bracket U-bolt	2		
	001	16	U-bolt 3/8"-16 Nut	4		
	001	17	Brake Mount	1		
lic System Assembly	002	01	Pump	1	ACNAL02ACA0040000000000A	Eaton
	002	02	Motor	1	ADMAD03AMA01AC0000000A0A	Eaton
	002	03	Accumulator	1	ACP08AA100E1KTC	Parker
	002	04	Hydraulic Hose, 3/8" NPT	1		
	002	05	Hydraulic Hose, 1/2" NPT	1		
	002	06	Ball Valve	1	AE2N11/4-11DB	Scott Industrial

Hydrau	002	07	Pressure Relief Valve	1	RV-4H	Scott Industrial
	002	08	Check Valve	1	C600SS-10BD	Parker
	002	09	Straight Thread 45 Deg P21T .1830	1	8V5OX-S	Cincinnati H & F
	002	10	Reducer Expande P21A .3500	1	16-8 F5OG5-S	Cincinnati H & F
	002	11	Crimp Fitting P22F .4000	2	10643-8-6	Cincinnati H & F
	002	12	Straight Thread Elbow P21T .3890	1	10 C5OX-S	Cincinnati H & F
	002	13	Crimp Fitting P22F .2500	1	10643-10-6	Cincinnati H & F
	002	14	Pipe Nipple P21A 0.1560	1	1/2X3/8 FF-S	Cincinnati H & F
	002	15	Male Elbow P21T .1720	1	4-6 CTX-S	Cincinnati H & F
	002	16	Male Connector P21T .0930	1	8-4 FTX-S	Cincinnati H & F
	002	17	Pipe Cross P21A .2500	1	1/4 KMMOO-S	Cincinnati H & F
	002	18	Male Elbow P21T .1860	2	4-4 CTX-S	Cincinnati H & F
	002	19	Male Elbow P21T .5520	2	8-8 CTX-S	Cincinnati H & F
	002	20	Crimp Fitting P22F .7440	4	10643-6-6	Cincinnati H & F
	002	21	Crimp Fitting P22F .2200	2	10643-4-4	Cincinnati H & F
	002	22	Crimp Fitting P22F .1100	1	13943-4-4	Cincinnati H & F
	002	23	Nut P21T .1610	1	12 BTX-S	Cincinnati H & F
	002	24	Tub End Reducer P21T .0740	1	12-4 TRTX-S	Cincinnati H & F
	002	25	Straight Thread P21T .7490	1	12 C5OX-S	Cincinnati H & F
	002	26	M-F Mini BL VLV P20V .1920	1	MV608-4	Cincinnati H & F
	002	27	0-5000psi Gauge N10G	1	T6O	Cincinnati H & F
	002	28	45 Deg Street E P21A .1250	1	1/4 CD45-S	Cincinnati H & F

Pedal Shaft Assembly	003	01	Pedal Shaft	1		
	003	02	Pedal Shaft Collar	1		
	003	03	Pedal Shaft Bearing Cap	2		
	003	04	Pedal Lever Arm	2	B005YO157O	Bikezilla Bike Shop
	003	05	Pedal	2		
	003	06	Ball Bearings	2		
	003	07	Gear - Pinion	1	PA6310Y-P	Boston Dynamics
	003	08	Gear - Shaft	1	PA6310Y-G	Boston Dynamics
	003	09	Hex Head Screw, 3/8"-16 x 1"	1	90201A314	Mcmaster
Reservoir Assembly	004	01	Side Panel	2		
	004	02	Top Plate	1		
	004	03	Bottom Plate	1		
	004	04	Plate 1	1		
	004	05	Plate 2	1		
	004	06	Plate 3	1		
	004	07	1/2" npt Fitting	1		Home Depot
	004	08	Gasket	1		
	004	09	Washer	1		

Rear Shaft Assembly	006	00	Rear Shaft Subassembly	1		
	005	01	Large Bearing Housing Plate	1		
	005	02	Large Mounting Plate	1		
	005	03	Rear Shaft Bearing Cap	1		
	005	04	Small Bearing Housing Plate	1		
	005	05	Small Mounting Plate	1		
	005	06	Bearing 3/8" ID	2	60355K504	Mcmaster
	005	07	Bearing 1 1/4" ID	1	60355K821	Mcmaster
	005	08	Hex Head Screw, 10-24 x 1""	8	92620A414	Mcmaster
	005	09	Hex Nut, 10-24	8	90480A011	Mcmaster
	005	10	Hex Screw, M7 x 1 mm Thread, 16mm	3	91280A412	Mcmaster
	005	11	Washer, M7 Screw Size	3	91166A260	Mcmaster
	005	12	Hex Nut, M7	3	90591A154	Mcmaster
	005	13	Nylon-Insert Locknut 3/8"-16	1	90630A121	Mcmaster
	005	14	Thrust Bearing, Oil Embedded	1	5906K511	Mcmaster
	005	15	Rear Wheel	1		
Rear Shaft Subassembly	006	01	Main Shaft	1		
	006	02	Hub	1		
	006	03	Motor Shaft Coupler	1		

7.0 ACTUAL TEST DATA COMPARED TO ANALYSIS

Upon completion of the build phase of the project, the first tests of the bike were run without any gas charge in the accumulator. The system ran better than expected, however continually pumping more fluid into the under-pressurized accumulator made for a slow ride with minimal fluid being pumped to the motor. After verifying that the circuit worked, a nitrogen tank was rented to begin testing at various pressures of precharge. It became apparent that the system was more over designed than intended. The bike achieved motion at far lower pressures than intended, as low as 500 PSI instead of the expected 2200 PSI. It should be noted that the design was intended to achieve motion at a 5% grade on rough, paved asphalt, and tests were done on level, smooth concrete. The system outperformed expectations, except in the ability to reach high pressures. The highest pressure that can be realistically achieved during the precharge process by a human pedaling is 2000 PSI which requires a high amount of exertion, and a particular technique involving short bursts of high-speed, forceful rotation. Following initial tests to verify the system worked, the gas bladder of the accumulator was charged to 2000 PSI, and three team members took turns making trial runs down the track. After each series of three trials, the bladder was bled out in increments of 100 PSI. Each test achieved more favorable results than the last, down to 1000 PSI.

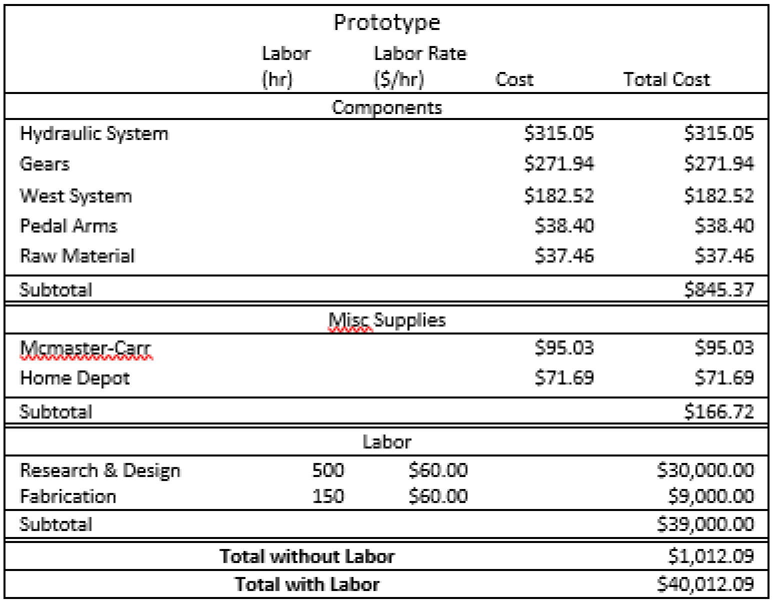
8.0 COST ANALYSIS

The cost analysis was completed using Design for Manufacturing Assembly Software by Boothroyd Dewhurst, Inc. DFMA utilizes concurrent engineering in which design, manufacturing, and other functions are integrated to give an estimate of the time and cost required to bring a new product to the market. It has helped identify, quantify, and eliminate inefficiency as much as possible in the product design.

Parameters were put in place as a guide through the costs for the overall fabrication of the bicycle. They are listed below:

- Labor: $60/hr
- Average Weight of Steel: $4.00/lb
- Efficiency of Production: 95%
- Yearly production: 500 units
- Life Volume: 5000 units

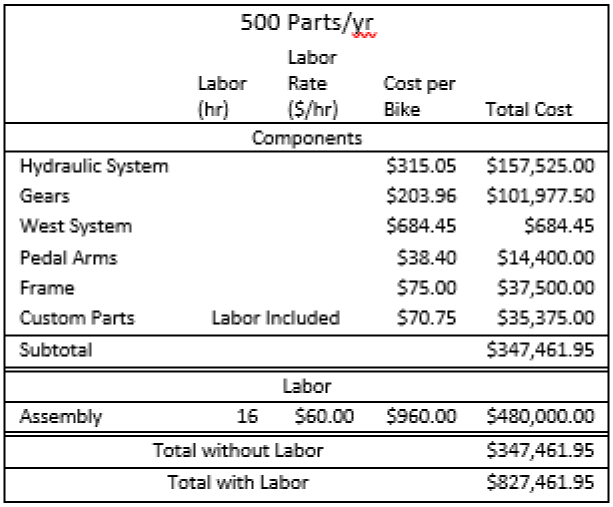
The total cost of the 2017 University of Cincinnati's prototype was $1012.09, close to half the budget, as seen below in Table 3. To save money the team was able to utilize fittings and valves from previous years' team, and a donated bike was used. Including labor costs, the total cost of the prototype is $40,012.



Prototype	Labor (hr)	Labor Rate ($/hr)	Cost	Total Cost
Components				
Hydraulic System			$315.05	$315.05
Gears			$271.94	$271.94
West System			$182.52	$182.52
Pedal Arms			$38.40	$38.40
Raw Material			$37.46	$37.46
Subtotal				$845.37
Misc Supplies				
Mcmaster-Carr			$95.03	$95.03
Home Depot			$71.69	$71.69
Subtotal				$166.72
Labor				
Research & Design	500	$60.00		$30,000.00
Fabrication	150	$60.00		$9,000.00
Subtotal				$39,000.00
Total without Labor				$1,012.09
Total with Labor				$40,012.09

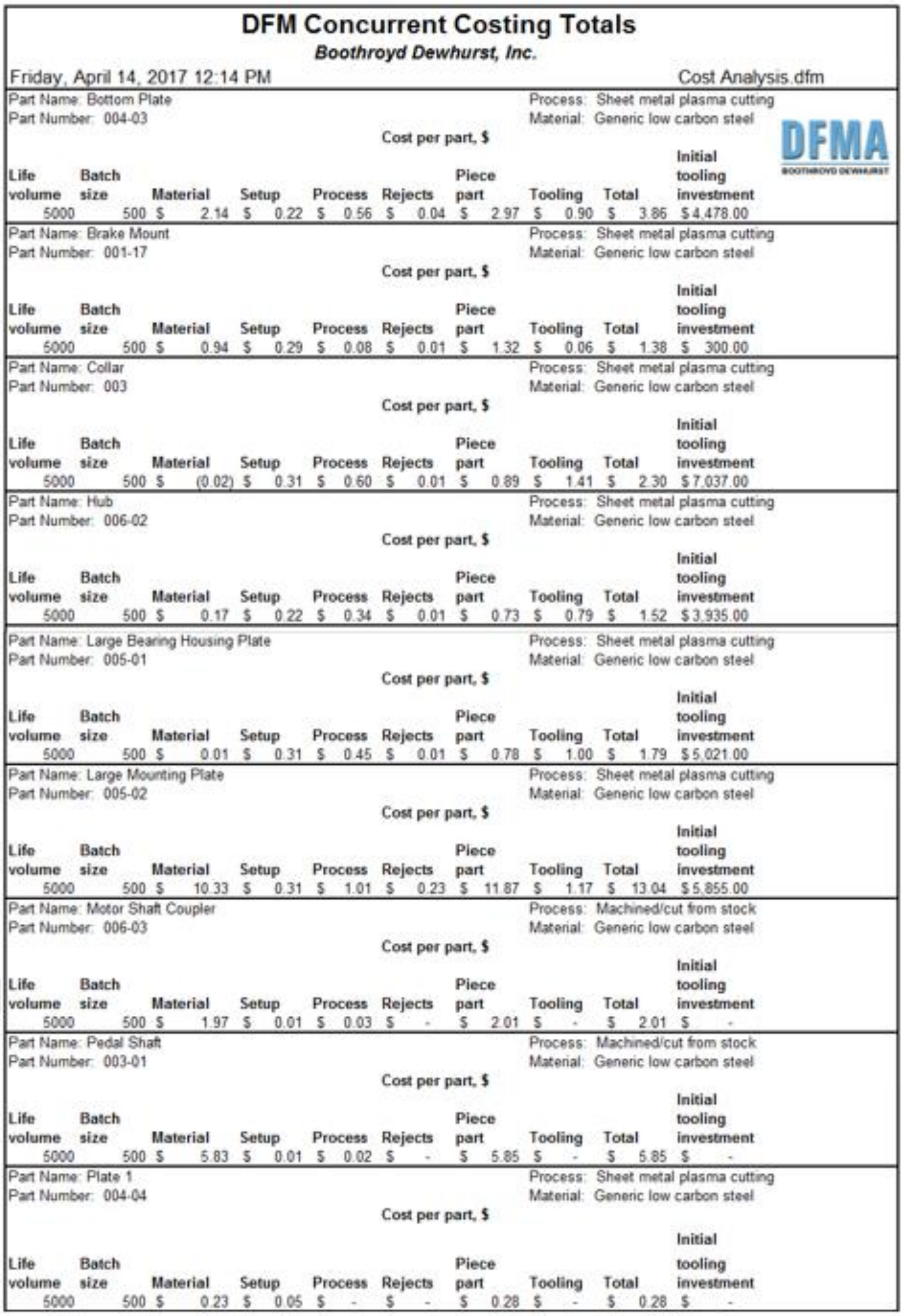
Table 3: Prototype Cost Analysis

The cost of producing 500 units a year is $347,461 without labor, $827,461 with labor. The cost can be seen below in Table 4. The breakdown of each individual custom made part is listed below in Figure 38.



500 Parts/yr	Labor (hr)	Labor Rate ($/hr)	Cost per Bike	Total Cost
Components				
Hydraulic System			$315.05	$157,525.00
Gears			$203.96	$101,977.50
West System			$684.45	$684.45
Pedal Arms			$38.40	$14,400.00
Frame			$75.00	$37,500.00
Custom Parts	Labor Included		$70.75	$35,375.00
Subtotal				$347,461.95
Labor				
Assembly	16	$60.00	$960.00	$480,000.00
Total without Labor				$347,461.95
Total with Labor				$827,461.95

Table 4: 500 Parts/ Year Cost Analysis



DFM Concurrent Costing Totals

Boothroyd Dewhurst, Inc.

Friday, April 14, 2017 12:14 PM
Cost Analysis.dfm

Part Name: Bottom Plate
Part Number: 004-03
Process: Sheet metal plasma cutting
Material: Generic low carbon steel

Cost per part, $

Life volume	Batch size	Material	Setup	Process	Rejects	Piece part	Tooling	Total	Initial tooling investment
5000	500	$ 2.14	$ 0.22	$ 0.56	$ 0.04	$ 2.97	$ 0.90	$ 3.86	$ 4,478.00

Part Name: Brake Mount
Part Number: 001-17
Process: Sheet metal plasma cutting
Material: Generic low carbon steel

Cost per part, $

Life volume	Batch size	Material	Setup	Process	Rejects	Piece part	Tooling	Total	Initial tooling investment
5000	500	$ 0.94	$ 0.29	$ 0.08	$ 0.01	$ 1.32	$ 0.06	$ 1.38	$ 300.00

Part Name: Collar
Part Number: 003
Process: Sheet metal plasma cutting
Material: Generic low carbon steel

Cost per part, $

Life volume	Batch size	Material	Setup	Process	Rejects	Piece part	Tooling	Total	Initial tooling investment
5000	500	$ (0.02)	$ 0.31	$ 0.60	$ 0.01	$ 0.89	$ 1.41	$ 2.30	$ 7,037.00

Part Name: Hub
Part Number: 006-02
Process: Sheet metal plasma cutting
Material: Generic low carbon steel

Cost per part, $

Life volume	Batch size	Material	Setup	Process	Rejects	Piece part	Tooling	Total	Initial tooling investment
5000	500	$ 0.17	$ 0.22	$ 0.34	$ 0.01	$ 0.73	$ 0.79	$ 1.52	$ 3,935.00

Part Name: Large Bearing Housing Plate
Part Number: 005-01
Process: Sheet metal plasma cutting
Material: Generic low carbon steel

Cost per part, $

Life volume	Batch size	Material	Setup	Process	Rejects	Piece part	Tooling	Total	Initial tooling investment
5000	500	$ 0.01	$ 0.31	$ 0.45	$ 0.01	$ 0.78	$ 1.00	$ 1.79	$ 5,021.00

Part Name: Large Mounting Plate
Part Number: 005-02
Process: Sheet metal plasma cutting
Material: Generic low carbon steel

Cost per part, $

Life volume	Batch size	Material	Setup	Process	Rejects	Piece part	Tooling	Total	Initial tooling investment
5000	500	$ 10.33	$ 0.31	$ 1.01	$ 0.23	$ 11.87	$ 1.17	$ 13.04	$ 5,855.00

Part Name: Motor Shaft Coupler
Part Number: 006-03
Process: Machined/cut from stock
Material: Generic low carbon steel

Cost per part, $

Life volume	Batch size	Material	Setup	Process	Rejects	Piece part	Tooling	Total	Initial tooling investment
5000	500	$ 1.97	$ 0.01	$ 0.03	$ -	$ 2.01	$ -	$ 2.01	$ -

Part Name: Pedal Shaft
Part Number: 003-01
Process: Machined/cut from stock
Material: Generic low carbon steel

Cost per part, $

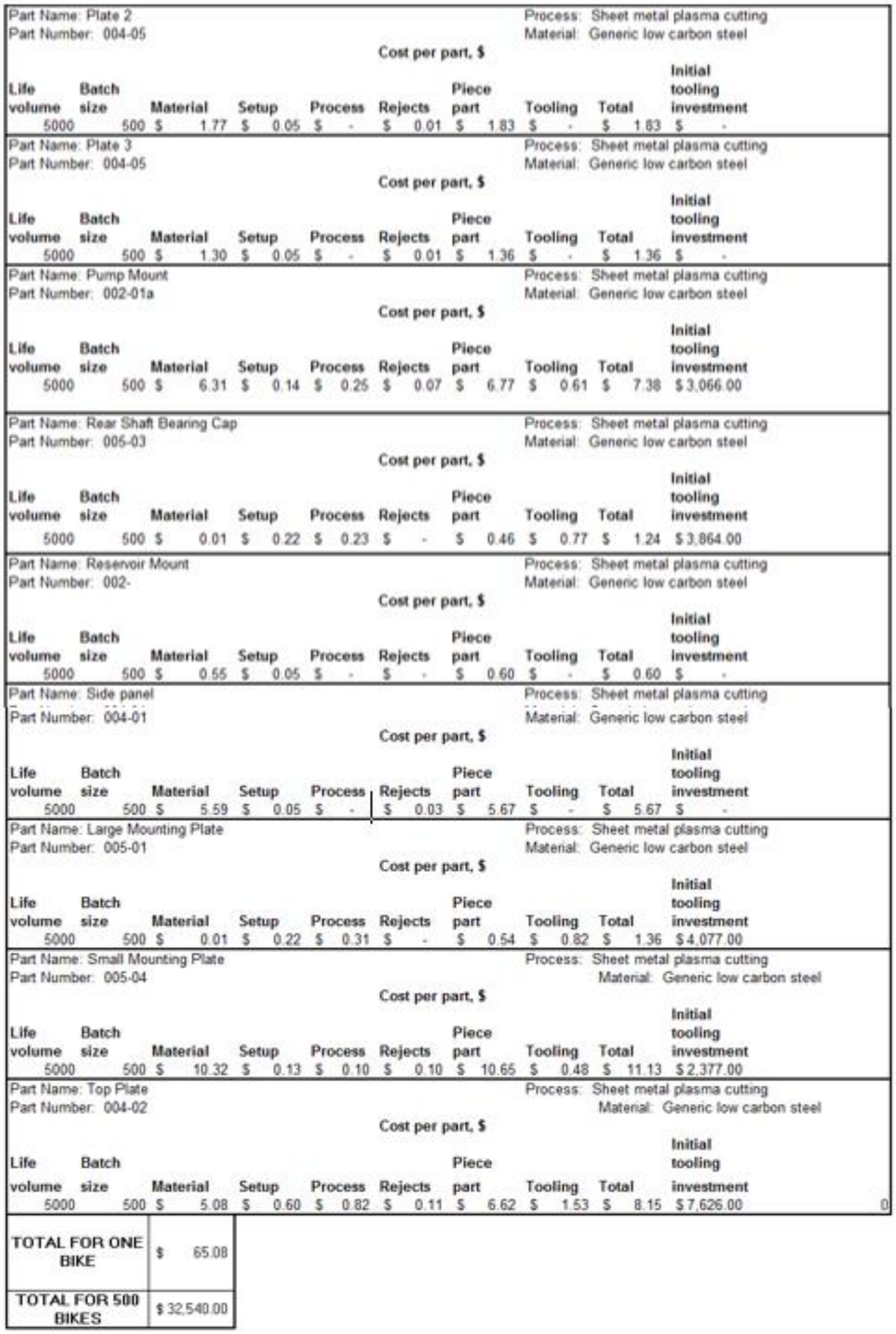
Life volume	Batch size	Material	Setup	Process	Rejects	Piece part	Tooling	Total	Initial tooling investment
5000	500	$ 5.83	$ 0.01	$ 0.02	$ -	$ 5.85	$ -	$ 5.85	$ -

Part Name: Plate 1
Part Number: 004-04
Process: Sheet metal plasma cutting
Material: Generic low carbon steel

Cost per part, $

Life volume	Batch size	Material	Setup	Process	Rejects	Piece part	Tooling	Total	Initial tooling investment
5000	500	$ 0.23	$ 0.05	$ -	$ -	$ 0.28	$ -	$ 0.28	$ -

Figure 38: DFM Concurrent Costing Totals – Part 1



Part Name: Plate 2
Part Number: 004-05
Process: Sheet metal plasma cutting
Material: Generic low carbon steel

Cost per part, $

Life volume	Batch size	Material	Setup	Process	Rejects	Piece part	Tooling	Total	Initial tooling investment
5000	500	$ 1.77	$ 0.05	$ -	$ 0.01	$ 1.83	$ -	$ 1.83	$ -

Part Name: Plate 3
Part Number: 004-05
Process: Sheet metal plasma cutting
Material: Generic low carbon steel

Cost per part, $

Life volume	Batch size	Material	Setup	Process	Rejects	Piece part	Tooling	Total	Initial tooling investment
5000	500	$ 1.30	$ 0.05	$ -	$ 0.01	$ 1.36	$ -	$ 1.36	$ -

Part Name: Pump Mount
Part Number: 002-01a
Process: Sheet metal plasma cutting
Material: Generic low carbon steel

Cost per part, $

Life volume	Batch size	Material	Setup	Process	Rejects	Piece part	Tooling	Total	Initial tooling investment
5000	500	$ 6.31	$ 0.14	$ 0.25	$ 0.07	$ 6.77	$ 0.61	$ 7.38	$ 3,066.00

Part Name: Rear Shaft Bearing Cap
Part Number: 005-03
Process: Sheet metal plasma cutting
Material: Generic low carbon steel

Cost per part, $

Life volume	Batch size	Material	Setup	Process	Rejects	Piece part	Tooling	Total	Initial tooling investment
5000	500	$ 0.01	$ 0.22	$ 0.23	$ -	$ 0.46	$ 0.77	$ 1.24	$ 3,864.00

Part Name: Reservoir Mount
Part Number: 002-
Process: Sheet metal plasma cutting
Material: Generic low carbon steel

Cost per part, $

Life volume	Batch size	Material	Setup	Process	Rejects	Piece part	Tooling	Total	Initial tooling investment
5000	500	$ 0.55	$ 0.05	$ -	$ -	$ 0.60	$ -	$ 0.60	$ -

Part Name: Side panel
Part Number: 004-01
Process: Sheet metal plasma cutting
Material: Generic low carbon steel

Cost per part, $

Life volume	Batch size	Material	Setup	Process	Rejects	Piece part	Tooling	Total	Initial tooling investment
5000	500	$ 5.59	$ 0.05	$ -	$ 0.03	$ 5.67	$ -	$ 5.67	$ -

Part Name: Large Mounting Plate
Part Number: 005-01
Process: Sheet metal plasma cutting
Material: Generic low carbon steel

Cost per part, $

Life volume	Batch size	Material	Setup	Process	Rejects	Piece part	Tooling	Total	Initial tooling investment
5000	500	$ 0.01	$ 0.22	$ 0.31	$ -	$ 0.54	$ 0.82	$ 1.36	$ 4,077.00

Part Name: Small Mounting Plate
Part Number: 005-04
Process: Sheet metal plasma cutting
Material: Generic low carbon steel

Cost per part, $

Life volume	Batch size	Material	Setup	Process	Rejects	Piece part	Tooling	Total	Initial tooling investment
5000	500	$ 10.32	$ 0.13	$ 0.10	$ 0.10	$ 10.65	$ 0.48	$ 11.13	$ 2,377.00

Part Name: Top Plate
Part Number: 004-02
Process: Sheet metal plasma cutting
Material: Generic low carbon steel

Cost per part, $

Life volume	Batch size	Material	Setup	Process	Rejects	Piece part	Tooling	Total	Initial tooling investment	
5000	500	$ 5.08	$ 0.60	$ 0.82	$ 0.11	$ 6.62	$ 1.53	$ 8.15	$ 7,626.00	0

TOTAL FOR ONE BIKE	$ 65.08
TOTAL FOR 500 BIKES	$ 32,540.00

Figure 38: DFM Concurrent Costing Totals – Part 2

9.0 LESSONS LEARNED

The following are personal perspectives offered by the University of Cincinnati team members, relaying their own experiences, lessons, and knowledge taken away from the FPVC competition design process.

Dorian Durant

> "Being a part of UC's FPVC team was an amazing experience. I not only gained a better understanding of the underlying concepts of hydraulics and its applicability, but I also have built a great relationship with my teammates. I'm very impressed by the knowledge each one of us has gained over the course of the project. I personally enjoyed the fabrication process and the techniques applied to making the designs a reality. From my prior fabrication experience, I knew that for every particular part would require a specialized approach. I re-learned some old and new machining methods that helped tremendously in the fabrication process. There was definitely a lot of trial and error; dealing with redesigning along the process due to our pump and motor not being delivered until late, but we made it happen."

Raymond Frank

> "I had never designed a hydraulic circuit before. The logic used for the valves was similar to what I learned from working with pneumatic circuits during my previous co-op terms at Clippard. The pump, motor, and accumulator were the components I learned the most about. This experience also provided me with an opportunity to work with highly pressurized gas such as Nitrogen. Most of what I worked with prior to this experience was oxygen pressurized below 100 PSI. The folks at Airgas were very helpful with helping us getting our order right for our application when ordering a Nitrogen tank. This project also gave me an application for me to work on my manufacturing skills"

William Hayes

> "I learned a lot from this competition and being able to design something and build it myself. I am a lot more aware of possible ways to manufacture a part now that would have made fabrication of the bike a lot easier. I also learned almost everything I know about hydraulics from this competition; hydraulic applications are something we are not taught in school. The biggest lesson learned was having a backup plan, or a more flexible design to switch to quickly when there are logistical issues."

Tyler Tavalero

> “The hydraulics system design itself was what I took the most away from. None of us had much, if any, experience with hydraulics, and I ended up heading up the component selection process. Making the circuit was easy, but when it came time to finding the products in catalogues that would perform the required functions, things got much more difficult. There were so many more factors to consider in the components that were difficult to match up with the design calculations, like continuous flow rating especially. Eventually I did manage to wrap my mind around most of the concepts, and feel very well versed in hydraulic design compared to before the competition.
>
> “The whole process was also a great refresher course in designing for manufacture. Working in such a small, close team made it very easy to get feedback from the team members that were machining the parts I designed. It offered a more challenging experience in some ways than designing parts on co-ops for companies that have much more robust manufacturing capabilities.”

Paige Weaver

> “The most important lesson I’ve taken away from this experience is attention to detail and problem-solving are invaluable skills to possess. Keeping in mind the end result, and paying attention to how much material is being removed, saves the time it would take to have to re-make a part. Having the ability to assess a situation (in the event something does go wrong), determine the root cause, provide a countermeasure, and successfully implement the countermeasure, allowed me to work through any problems which came about throughout the fabrication and assembly phase, while keeping a level-head and not making any rash decisions.
>
> “Overall, working closely with my team, and bringing the drawing they created to fruition, has been rewarding and helped prepare me for when I start my career in manufacturing.”

10.0 CONCLUSIONS

From start to finish, the original vision and principles of the design remained consistent. Minimal gearing and focus on keeping the pump as close to the pedal shaft as possible, and the motor directly driving to the rear wheel, made in-house fabrication possible, and reduced the amount of parts which needed to be special ordered, keeping costs low. The simplicity and reliability of all systems involved helped to streamline the build process, and made troubleshooting and tuning easier.