Final Report

ME450
Fall 2009
Chainless Challenge
Project 14

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ABSTRACT

We have been tasked to design, build, and test a bicycle which incorporates a hydraulic drivetrain to compete in the Chainless Challenge competition sponsored by Parker Hannifin Corporation. The student group, BLUElab, began this project and will remain involved through the completion. In conjunction with the hydraulic drivetrain, a fluid accumulator will allow the storage of energy, enabling regenerative braking and the release of energy when assistance in acceleration is needed. The use of regenerative braking gives our design a competitive edge by capturing normally wasted energy. We have emphasized drivetrain efficiency and safe functioning in order to create a fast, reliable bicycle, which are essential characteristics in meeting our goal of winning the competition.

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EXECUTIVE SUMMARY

The project started out as a coalition between ME 450 and the student group BLUElab, to produce a hydraulic bicycle to compete in the Chainless Challenge competition sponsored by Parker Hannifin. BLUElab began design work on the bicycle in September, 2008, and the ME 450 team is responsible for the design completion and prototype manufacturing. Although the competition is currently cancelled, progress on the bike has continued, with the goal of raising awareness about the energy saving potential of hydraulics in transportation. Talks of hosting a hydraulic bicycle exhibition to replace the completion have begun.

At the beginning of the design phase, we generated the following specifications:

Table 1: Summary of engineering specifications

Specification	Target value	Specification	Target value
Vehicle weight	< 30 kg	Energy release rate	400 W
Fluid pressure	< 21 MPa	Pedal speed	100 RPM
Pump displacement	1-8 cc/rev	Pedal torque	50 N-m
Pump motor efficiency	> 80 %	Front gear ratio	< 10:1
Energy storage capacity	30 kJ	Regenerative braking	Yes

Our design challenges primarily consisted of component selection and placement. The pump motors were chosen for their efficiency, while sprockets were selected as the most reliable means of power transmission. The final design incorporates two 1.5 cc/rev pump motors with a 9.61:1 front gear ratio and a 4.25:1 rear ratio. The front gear ratio created a need for a bearing plate to support some of the load on the front pump. A single fixed gear rear wheel is used for normal riding which includes regenerative braking, while a wheel with an eight speed internal gear hub can be used to allow for fast acceleration, but not regenerative braking. A basket on the front handlebars holds the battery which will be connected to the switches and relays controlling the valves. The hydraulic subsystem is securely attached to a rack over the rear wheel, which utilizes a 3.5 gallon accumulator, which increases our energy storage capacity to 75 kJ. Finally, we chose solenoid poppet hydraulic valves to minimize pressure leakage leading to a compact, efficient, and safe overall system design.

Completing the prototype included several different manufacturing processes. All of the metal components were produced using the manual lathe, manual mill or the CNC mill. Components such as the frame and brackets were sandblasted before they were welded together and finally painted. The electrical connections required soldering, while the brackets for the switches were laser cut from Plexiglas. The hydraulic system was primarily assembled with wrenches, while some of the fasteners for the accumulator required holes to be drilled.

Once the prototype was fully assembled, we had to bleed the air out of the hydraulic lines and test each mode of operation. Although we have not fully completed this bleeding process due to time constraints, we have been able to demonstrate the functionality of each mode. Further bleeding should allow us to run the higher pressures which the system was designed for and store more energy in the accumulator.

PROBLEM DESCRIPTION

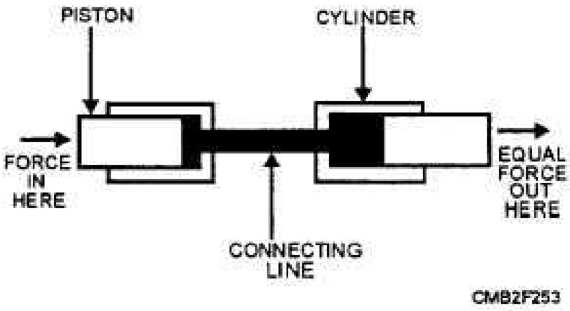
The Better Living Using Engineering Laboratory (BLUElab) at the University of Michigan is working to develop a bicycle with a hydraulic drive to race in Parker Hannifin Corporation's Chainless Challenge competition in March, 2010. The competition stipulates that power from the rider must be transferred hydraulically to the drive wheel. The bicycle may have chains, but they may not directly connect the pedals to the wheel. Previous ME 450 teams have built bicycle wheels capable of regenerative braking, but they were unable to enter the competition because they used chains as the primary connection between the pedals and the wheel. This semester, our sponsors, BLUElab and Professor Steven J. Skerlos, have come to ME 450 asking for our help with this project. BLUElab students have been doing some design work for approximately a year, selected possible components, communicated with Parker Hannifin, and procured a bicycle. At the beginning of the project, we were provided with preliminary specifications and the corresponding component research. The required hydraulic system comprising of all of the necessary components had been laid out in a schematic for both regenerative and non-regenerative designs. BLUElab had originally decided to use an accumulator to store energy for acceleration at the beginning of the Chainless Challenge race but not to collect energy from braking. However, we have decided that regenerative braking would give us the edge necessary to win the race and require few extra components. The ME 450 team must finish the design, order parts, and fabricate the prototype. In order to be a successful competitor in the race, the bicycle must be efficient, lightweight, reliable, and safe.

INFORMATION SOURCES

"They're still doing that project?" This is the typical response when discussing our ME 450 project with others. The hydraulic bike project, with its many variations, has been a staple of the ME 450 lineup for some time now, which has given us both a lot to learn from, and a lot to overcome. BLUElab started a new conceptual design and we will continue to design the system from the ground up. This has allowed for a lot of freedom, but conversely decreases the foregoing progress on our specific design. At its core, the hydraulic bike project is an innovative use of hydraulics, more specifically the hydrostatic drive principle. This widely used principle has been expanded upon in recent years for efficiency in transportation. We are not the first ME 450 team to do so. However, because we are starting with a completely new design, we are able to learn from the experiences of previous semesters to aid in our own design process. Research of the hydrostatic drive principle and its recent applications has given us a stronger understanding of our project, and review of old reports and discussions with previous teams has given us a peak at what to expect for this project.

The essence of a hydrostatic drive system is simple. It is used as a means of transmitting mechanical energy, but instead of using gears, levers, or other means of mechanical translation, it converts the mechanical energy to fluid pressure, which is then converted back to mechanical energy. This can be seen below in Figure 1.

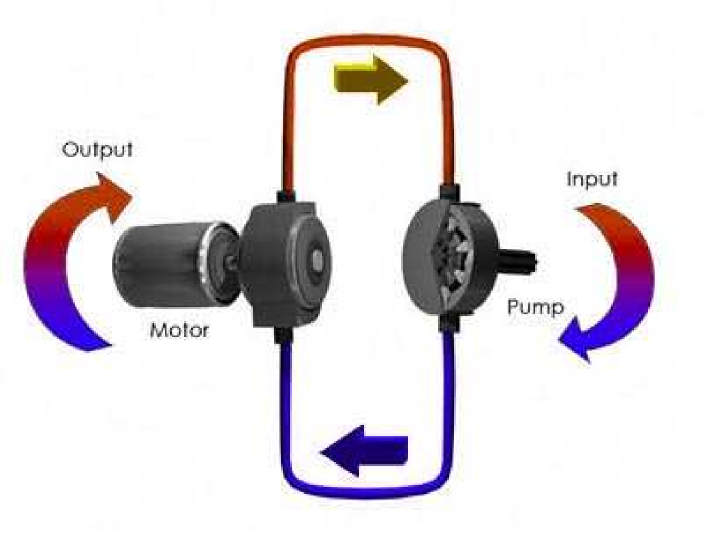
Figure 1: Basic Hydrostatic Principle [1]



Due to the incompressible characteristic of liquids, the input forces are directly translated into fluid pressure, which can then be turned directly back into output forces. The above figure shows the hydrostatic principle applied using pistons and cylinders. Similarly, the principle can be used with pumps and motors in place of the pistons and cylinders.

A pump is a machine that is responsible for converting rotational, mechanical energy into fluid pressure and flow. The input torque can be thought of in the same regard as the force seen above. Applying an input torque to a pump shaft will create low pressure fluid on one side of the pump and high pressure fluid on the other. This will then create a flow in the direction of the high pressure fluid. A torque in the opposite direction will also create flow in the opposite direction. Conversely, if a pump receives a high pressure flow without any input torque, it will create an output torque on the shaft and a pressure drop over the pump. At this point, the pump is now considered a motor, as it is converting fluid pressure to rotational, mechanical energy instead of vice versa. This path of input torque to output torque can be seen in the following figure.

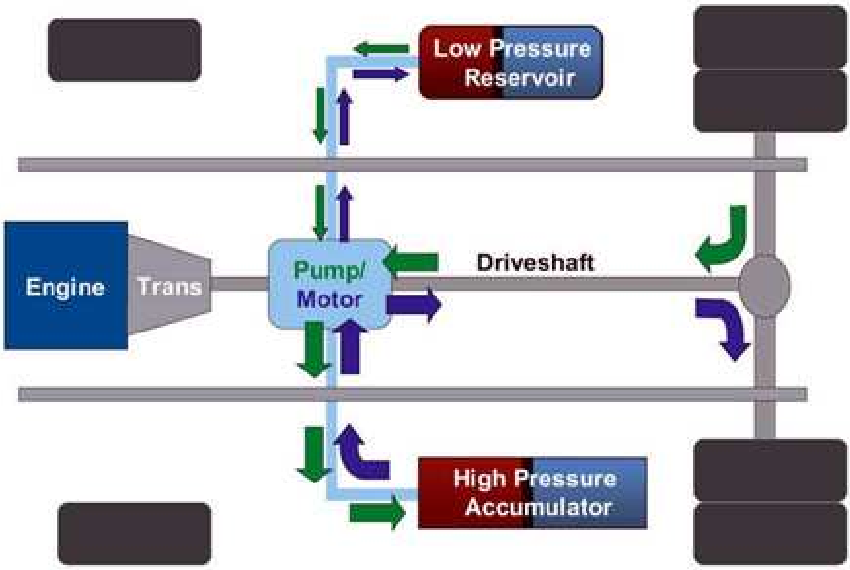
Figure 2: Hydrostatic Pump Motor System [2]



The hydrostatic principle has been employed for centuries, but it is only recently being looked at in the world of transportation.

The EPA (Environmental Protection Agency), UPS and Eaton have improved on the hydrostatic drive by designing hydraulic hybrid regenerative braking systems in large, fuel-powered vehicles. The addition of an accumulator and reservoir have allowed for the storage of energy that is normally lost during braking. This new design can be seen below in Figure 3.

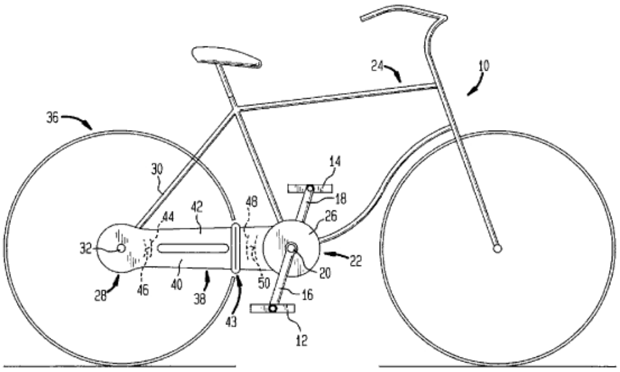
Figure 3: Hydraulic Hybrid Regenerative Braking System [3]



The accumulator is essentially a pressure vessel, but it has a bladder filled with nitrogen inside of it. As the vehicle slows down, the motor accepts the torque created by its kinetic energy, converting it to fluid pressure instead of wasting it as heat as in a vehicle with traditional friction brakes. This fluid is then routed to the accumulator, compressing the air in the bladder, leaving potential energy in the form of pressurized air to be used as a boost of acceleration or an assist during the launching of the vehicle. Because the fluid levels will vary inversely to the pressure levels in the accumulator, there will be a reservoir to store the excess fluid when the accumulator is not at maximum pressure. According to Eaton Corp., these innovations can give improvements in fuel economy around 15-30%, as well as allowing for better acceleration when used in conjunction with a running engine. The UPS teamed up with the EPA to design a truck with a different drive cycle, yet still employing a hydrostatic regenerative system that touts a fuel economy improvement of 60-70%. Both claim to recoup their costs at approximately 3 years, which the EPA claims to be approximately $7000. Although we have no fuel costs, this is a great representation of the energy savings possible [4],[5].

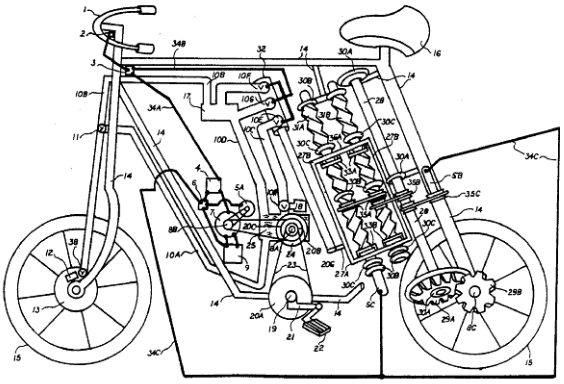
Although these are examples of hydrostatic drive systems being applied to trucks, it stands by many of the same principles as our hydrostatic bike design. A patent search for relevant technology has shown that ME 450 is not alone in its pursuit of this idea. Patent #5,772,225 describes a bike driven by a hydrostatic pump motor system as in Figure 2 [6]. This invention would fit the qualifications of the Chainless Challenge design, as the energy passes through a hydraulic gate between the pedals and the rear wheel. A drawing of the inventor's idea can be seen below in Figure 4.

Figure 4: Bike with Hydrostatic Drive system



Although this is completely embodied in our project, the idea of applying this to a bike has already been presented to us by the idea of the competition. Therefore, there was no useful knowledge to pull from this patent. Another patent (Patent #4,942,936) [7] was found, this time employing regenerative capabilities as well as a hydrostatic drive. But yet again, there was not much useful information to draw from the patent.

Figure 5: Electrohydraulic/Air Bike



As can be seen from the picture, this invention is incredibly complicated, but even with all of the possible information to draw from it, we learned nothing other than the fact that other people had invented a hydraulically regenerative bike in the past. Again, our design will incorporate many of the same features, but the patent, yet again, does not provide any useful knowledge. Our regenerative system had been designed by BLUElab and company before we started this project. These patents simply show us that other people are working on projects that are closely related to ours. Because they have not helped in our design process at all, they are really only relevant in a commercial scenario with issues of competition with other companies and patent infringement.

As previously stated, the hydraulic bike project has a fairly deep history with ME 450. There have been many projects with the intent of creating a hydraulically regenerative bike, but with a traditional drive system instead of the hydrostatic. There was even a team to strive for a hydrostatic bicycle just like ours, but no regenerative capabilities. Although our project this year is still a “hydraulic bike”, it is, in essence, a synthesis of the two previously stated design characteristics. We are setting out to create a hydrostatically driven bike with regenerative capabilities. This has allowed us to a) start with a fresh design, and b) view the entire bike as a system, instead of trying to fit the regenerative brakes inside of a wheel as many of the previous teams have done. The winter 2009 semester was a very successful team, and almost created a working prototype. However, the packaging became problematic when it came to fitting their entire system in the front wheel of the bike. Although we are not creating a hub-based design, the system components are still the same. We met with them early in the semester to discuss their project. Their design can be seen below in Figure 6.

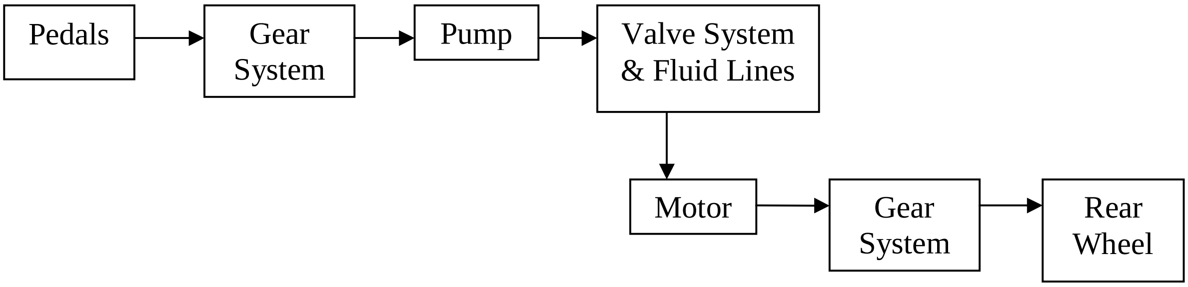
Figure 6: CAD Model of Winter 2009 Design [8]

The need for a high amount of precision was one of the largest obstacles this team had to overcome. Talking to this group has helped us understand what our largest challenges are going to be and how they are going to fit into our new design. We also learned that many of their difficulties were caused by the necessity to keep the components inside of the hub. Because we are not as constrained in size as they were, this will hopefully mean there will be less related problems for us. They also ran into problems with leaking fittings for their lines, which was a great warning for when we reach that point on our design [9].

FUNCTIONAL DECOMPOSITION

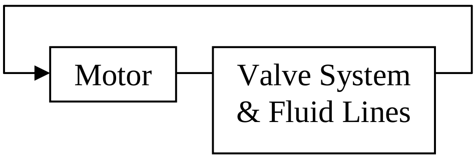
Due to the HRB design of our bike, it will employ the following five modes of operation: pedaling, coasting, accelerating, braking, and charging. During pedaling, the energy input from the rider’s feet will be directed as hydrostatic drive to the rear wheel. A flow chart of this energy transfer can be seen below in Figure 7.

Figure 7: Energy Flow During "Pedaling" Mode



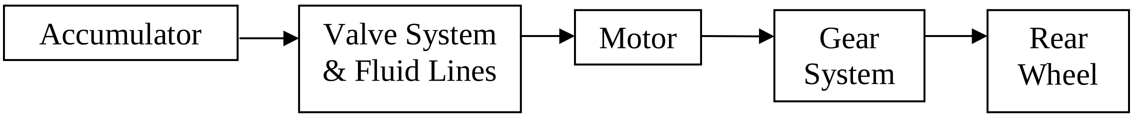
During coasting, there will be no energy transfer of any sort. Fluid will simply be circulated without any energy input, output or storage (neglecting fluid losses). This mode was created so that the rider will not have to be pedaling at all times. The circulation of the fluid without energy transfer emulates the "free-wheeling" feature that is possible on the average bike.

Figure 8: Energy Flow During "Coasting" Mode



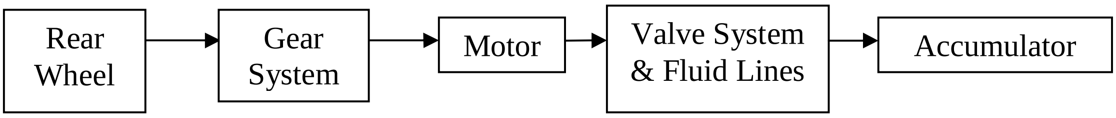
While accelerating, the energy stored in the accumulator will be released to accelerate the rider.

Figure 9: Energy Flow During "Accelerating" Mode



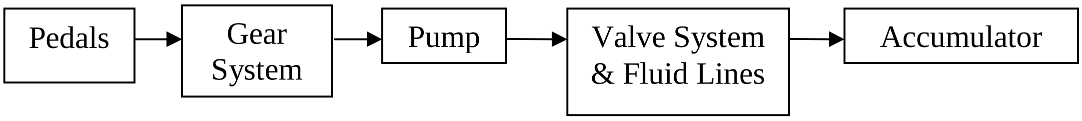
During braking, the rider's kinetic energy will be converted into fluid pressure, which will then be directed to the accumulator for storage.

Figure 10: Energy Flow During "Braking" Mode



Charging will also increase the amount of energy stored in the accumulator by the rider pedaling. This mode will normally be used while the bike is stationary.

Figure 11: Energy Flow During "Charging" Mode



As shown in Figures 12 and 13 below, multiple modes can operate at once. The system will also employ parallel functioning of accelerating/pedaling and braking/charging, allowing the rider to pedal at all times. Due to the design of our system – and for the convenience of the rider, there will be no required user signal to allow for these modes to function simultaneously. Don't understand what this means?

Figure 12: Parallel Energy Flow of "Accelerating" and "Pedalling" Modes

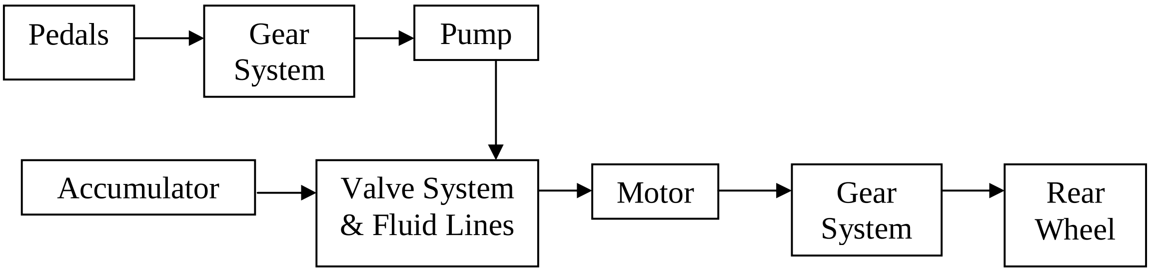
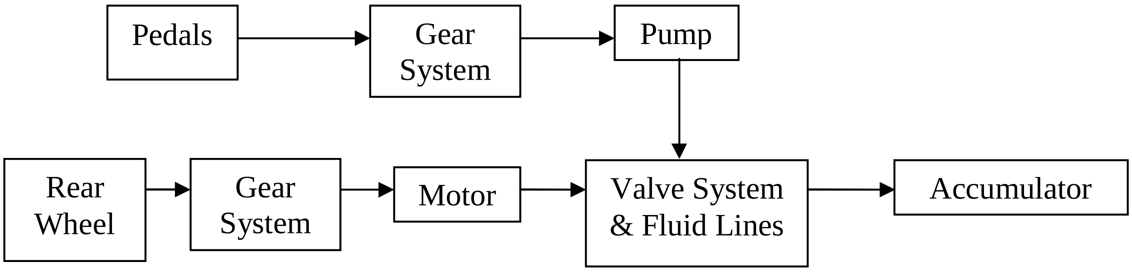


Figure 13: Parallel Energy Flow of "Braking" and "Charging" Modes



As you can see from the foregoing figures, the valve system and fluid lines are integral to each mode of operation, and will be responsible for making sure each mode functions correctly. The position of the valves (open vs. closed) will be dictated by a user-input driven control system. This will then direct the fluid pressures in the desired direction. The control system, valve positioning and resulting fluid pressures will be discussed in more detail in the Alpha Design and Final Design sections of this report.

THEORETICAL CALCULATIONS

Many of the components and subsystems are interrelated, meaning that the design and the specifications of one part are highly intertwined with another. In order to develop specifications and transform them into a final design, there needs to be a strong understanding of all of the theory surrounding each component.

Pump motors

The purpose of the pump is to convert mechanical energy to fluid energy, while the motor converts the fluid energy back to mechanical energy. If the pressure is reversed, a pump can become a motor. The equations for mechanical energy and fluid energy are given below in Equations 1 and 2, respectively.

$$\dot{W} = \tau * \omega \qquad \text{Eq. 1}$$

Where $\dot{W}$ is the power supplied by the rider (W), τ is the rider input torque at the pedals (N-m), and ω is the rotational speed of the pedal crank (rad/sec).

$$\dot{W} = \frac{P*d*\omega}{2\pi} \qquad \text{Eq. 2}$$

Where $\dot{W}$ is the power added to the fluid (W), P is the fluid pressure change through the pump (Pa), d is the displacement of the pump (m^3/rev), and ω is the rotational speed of the pump (rad/sec).

Assuming perfect efficiency, the power added by the driver would equal the fluid power which would then equal the power at the rear wheel. However, the pump motors are not 100% efficient and the relationship is shown below in Equation 3.

$$\eta = \frac{\dot{W}_{out}}{\dot{W}_{in}} \qquad \text{Eq. 3}$$

It is important to note that the rotational speed and torque at the pedals, pump motors, and the rear axle will be different because of gearing, although there is equal power transfer throughout them, neglecting efficiencies. For this reason we must also understand power transmission systems in order to pick the pump motors.

Mechanical power transmission

The mechanical power transmission systems between the pedals and the pump as well as between the motor and the wheels are used to convert the mechanical power into a torque and speed that is useable. The pump motors will typically operate best at speeds much higher than the pedals or the rear wheel spin and they also must handle much lower torques. Equation 4 below shows the relationship between these parameters. Once again this assumes perfect efficiency.

$$\frac{N_{teeth1}}{N_{teeth2}} = \frac{\tau_1}{\tau_2} = \frac{\omega_2}{\omega_1} \qquad \text{Eq. 4}$$

Where N is for the tooth count of the gears/sprockets, τ is the torques at the gears/sprockets, and ω is the rotational speed of each component. The units do not matter as long as they are consistent. This formula shows how these systems can be used to either reduce torque and increase speed, or reduce speed and increase torque.

Energy storage and transport

The energy will be stored in fluid form in the accumulator. Equation 5 is used to calculate the energy stored in the accumulator. We assume that the accumulator is large enough so that pressure can be approximated to be constant.

$$E = P * V \qquad \text{Eq. 5}$$

Where E is the energy stored (J), P is the pressure in the accumulator (Pa), and V is the volume of fluid stored in the accumulator (m^3).

This energy will then be converted to mechanical energy with the equations above and finally it will become kinetic energy.

SPECIFICATIONS

We determined the proper specifications for the chainless bicycle, based on parameters of the competition, and have listed them in Table 1. The QFD (located in Appendix A) allowed us to understand how the technical specifications satisfied the requirements of the sponsor. Since the bike is to be used in a racing competition scenario, it must be capable of handling aggressive driver inputs. It must be efficient and accelerate fast, while still being maneuverable and easy to ride.

Starting with these demands we had to determine how much force and at what speed the driver would pedal the bike. BLUElab conducted a survey of its members to determine the average torque and speed output of potential future riders. Using this data we set a target pedal torque capacity of 50 N-m. The pedal speed range was then set below 150 RPM, with the average speed at 100 RPM. Since the pumps typically run at much higher speeds, we decided to gear up the pedal input to the pump drive shaft. In order to use a chain/sprocket system we determined that the practical maximum gear ratio for a single chain setup could be no more than 5:1. From this limit we determined the target torque capacity of the pump to be at least 10 N-m. We set a target pump displacement of 5 to 10cc per revolution. We wanted the pump to be compact but not have a displacement so small that the pressure becomes unsafe.

The efficiency of the pump is also a major consideration. The pumps will be operating at speeds around 500 RPM, while the optimal operating range is typically between 1000-2000 RPM. This means that the efficiency may be lower than desired. From looking at some of the major components we expect the pump motors to be the limiting factor on the peak system pressure. We have set a target maximum pressure of 34 MPa. Lower pressures, however, will result in more fluid flow for the same amount of work. On this note, increasing pressures will reduce fluid losses (increase efficiency) at the expense of potential safety risks if the system were to burst. Therefore the system parameters are targeted while keeping in mind many tradeoffs.

The prototype will have regenerative braking that allows kinetic energy to be stored in an accumulator. The energy and power that the system must handle is directly related to the weight of the vehicle driver combination. We set the target bike weight to be less than 30 kg and the estimated combined weight with driver to be less than 110 kg. Then the kinetic energy at various speeds can be found, which resulted in our group setting the minimum energy storage at 30 kJ. Using this variable and the system pressure, we can determine the volume of the reservoir that is needed. We have determined that a volume of at least 2 liters is needed. However, a larger volume will ensure more consistent pressure as the fluid volume in the accumulator fluctuates.

To control the rate at which the bicycle accelerates and decelerates, we must control the rates at which fluid enters and exits the accumulator. This rate is essentially the power to the wheel, either in acceleration or deceleration. If the acceleration force at the back wheel is too great, the bike might lift the front wheel or lose traction, resulting in a loss of control. If the deceleration force is too great, the wheel will also lose traction causing a loss of control, as well as no power generation. It is difficult to have power saving and power delivery at different rates because the fluid will likely enter and exit the accumulator through the same restrictor valve. For this reason we have set the target power delivery and recovery rates to 0.4 kW. These parameters, along with our research of similar products and developments have given us a good starting point. We are currently working on finding components that meet the individual targets and integrate into the system well, meeting the overall goals.

The above specifications were initially developed prior to design review one, but as the alpha design was being developed, some of the specifications have evolved. Due to the limited availability of these relatively small pumps we have adjusted our target displacement range to between 1 to 8cc per revolution. We have also added an efficiency target for the pump motors to greater than 80 percent. The target maximum pressure has now been reduced to 21 MPa, because this is the maximum pressure rating of the accumulator Parker Hannifin has donated. In order to retain the same driver torque input we have now allowed for gear ratios of up to 10:1. These ratios may create other engineering challenges which will be discussed later in this paper.

CONCEPT GENERATION AND SELECTION

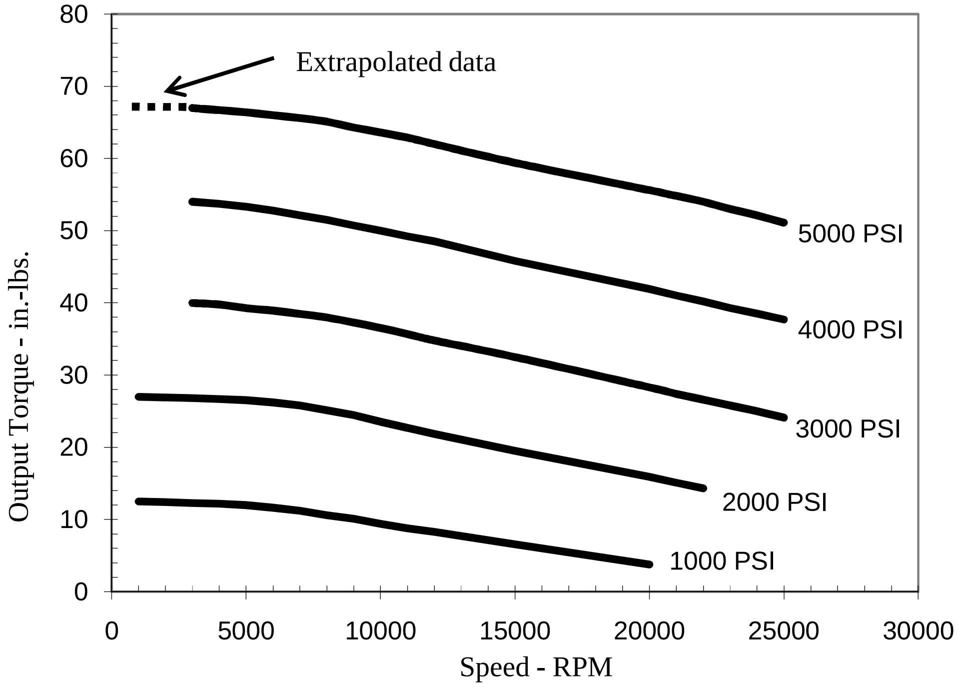
Pump motors

We need two pump motors: one to pressurize the fluid using power from the pedals and one attached to the rear wheel to supply power to the wheel during normal operation and pressurize the accumulator during regenerative braking.

The Parker 09 series pump motors are compact and efficient. A photo of these pump motors appears in Figure 14. Using data from the performance curves in Figure 15, we determined their efficiency to be 92% at 3000 rpm and 34MPa (5000psi). Although the accumulator Parker provides may force us to operate at 21 MPa, efficiency should be equally high at lower pressures. We used Equations 1-3 to calculate the efficiency of the pumps under our operating conditions. We assume that this efficiency will be the same at our lower operating speeds because the output torque of the motor should remain constant at lower speeds. However, these pump motors could easily pressurize the fluid beyond 34MPa, which would waste energy by opening the pressure relief valve.

Figure 14: Parker 09 series pump motors

Figure 15: Performance curves for Parker 09 series pump motor implies 92% efficiency



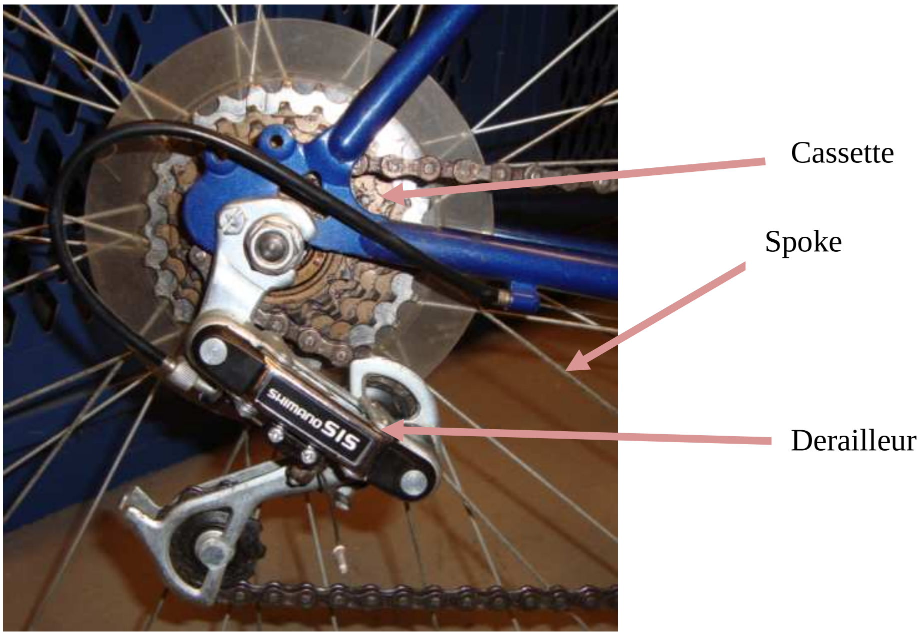
We also considered pumps such as the Parker 500 series with larger displacement which operate at lower pressure for a given torque. Using data from the performance curve in Appendix C, at 500 rpm and 27.5 MPa, these pumps are only 64% efficient.

We selected the Parker 09 series for their superior efficiency and compact size. Although larger pumps would be less likely to exceed the system's rated pressure and force the pressure relief valve to open, 64% efficiency is not high enough. We ordered the 09S-E-CK-P model which offers face mounting and a standard 19mm long keyed shaft.

Rear wheel hub

In a traditional bicycle (Figure 16 below), a hub in the rear wheel is necessary to transmit power from the cassette to the spokes and rim. It typically allows the rider to coast without pedaling by “freewheeling,” a ratcheting feature that allows the cassette to spin slower than the wheel. A fixed gear hub is less common and does not have the freewheeling feature, so the pedals spin whenever the bicycle is in motion.

Figure 16: Traditional Rear Bicycle Hub



Our needs are different from those of a traditional bicycle. A cassette is difficult to connect to a pump motor mounted above it. However, we want to have a variety of gear ratios to allow the rider to pedal at a comfortable speed. In order to determine the minimum number of gears, we assumed the bicycle would climb a maximum grade of .06 and descend a maximum grade of -.05. When changing gears, we wanted the slow pedal speed to be no less than .7 times the pedal speed in the faster gear. Thus, we determined at least six evenly spaced gears are necessary. For the bicycle to have regenerative braking, the hub must not freewheel because the wheel must be able to transmit a torque to the sprocket on the hub.

An internal gear hub provides the best packaging because it requires only one sprocket on its shaft and shifts gears internally. We selected the Shimano Nexus 8SG-8R36 because it offers eight speeds over a wide range (3.07 gear ratio total difference) and high efficiency. Although we received this product as a donation, its price of $190 is competitive with a cassette and derailleur combination. However, like all other internal gear hubs, it has the freewheel feature. We will need to disable freewheeling to have regenerative braking. Although we will have to modify an internal component of the gear hub to accomplish this, its advantages outweigh the difficulty of this modification. It has more than enough gears for the rider to maintain a comfortable cadence. It will be easier to connect the rear pump motor to a single sprocket on the gear hub than to a cassette using a chain because a cassette requires a derailleur.

Figure 17: Nexus 8 Gear Hub [11]

Mechanical connection of pedals to pump and motor to wheel

The shaft of one pump motor must be connected to the pedals, and the shaft of the other must be connected to the hub on the rear wheel. The connection to the pedals is the most challenging because it requires a gear ratio of 9.6:1. The gears may transmit a force of up 380 N from one to the other, so enough teeth must be engaged to prevent one of them from shearing off. The combination of pump and gear must be narrow enough to fit between the rider's legs.

We considered ring gears, spur gears, bevel gears, chains, and worm gears. Although worm gears are capable of large ratios, we ruled them out because the worm cannot drive the gear. The pros and cons of each other choice are summarized in the following table.

Table 2: Mechanical Transmission Selection

Connection type	Advantages	Disadvantages
Spur gears 	• Inexpensive • Easy to mount	• Misaligned gears transmit power poorly • Clothing may catch in between the two gears • Exposed sharp edges
Ring gears 	• More teeth are engaged than on spur gears, allowing more power transmission • Clothing is less likely to catch • No exposed sharp edges • Lighter than spur gears	• Misaligned gears transmit power poorly • Requires custom bracket to mount
Bevel gears 	• Allows pump assembly to be narrower by mounting pump parallel to the bicycle frame	• Misaligned gears transmit power poorly • Clothing may catch in between the two gears • Exposed sharp edges • Heavier than other gears
Chain and sprockets 	• High tolerance for misalignment • Easy to mount • Easy to change mounting of the pump by changing the length of chain	• Clothing may catch in between the two gears • Possible to shear off teeth on the small sprocket

Photos are courtesy of sdp-si.com.

We selected chain and sprockets because it will be easy to attach to the existing crank and wheel, and it allows for greater misalignment than the other gears. A guard can be used to prevent clothing from catching in the sprocket and chain, and a chain tensioner may engage more teeth to prevent shearing. Although the name of the competition is the “Chainless Challenge,” we are permitted to use chain as long as the pedals and wheel are connected hydraulically.

Valves

Three valves are necessary to control fluid flow during the three modes of operation: normal pedaling, regenerative braking, and assist. One must be normally closed, and two must be normally open. We considered ball, spool, and poppet valves. Although they are inexpensive and reliable, manual ball valves are not appropriate because our valves must be able to be actuated remotely. Spool valves are not ideal because their high leakage rate would decrease the system's efficiency. The valves must also be able to operate at a pressure of 34 MPa and a flow rate of 0.5 L/min.

We selected Eaton Vickers poppet solenoid valves SBV11-8-O-S6T-12DQP (normally open) and SBV11-8-C-S6T-12DQP (normally closed). Although they are only open or closed and do not have any capability to throttle, they have a low leakage rate of five drops per minute and are rated for 35 MPa and a flow rate of 60 L/min. We also considered Parker valves, but their price of $108 is higher than Eaton's price of $81, and Parker valves do not offer any extra features important to us.

Hose and Fittings

Parker has offered to donate and fittings to the team, but we must select the best model from their catalog. The hose needs to be rated for at least 34MPa and should have SAE 6 fittings. Two hose models meet these specifications: 471TC and 701. Both of these hoses are compatible with a variety of hydraulics fluids and are rated for use at temperatures from -40°C to 100°C. We selected the 471TC because it has a smaller minimum bend radius of 65mm which allows the hose to turn sharp corners. We also considered rigid tube, but alignment issues made this option problematic for the previous ME 450 team.

Electrical System

As mechanical engineers, we did not have the expertise to design the electrical system on our own. With the help of Andrew Richardson, an EECS major here at the university with extensive experience in controls, we were able to create a concept of how the system should be design.

When designing the electrical system, we needed to choose something that is capable of creating logical decisions based on mode priority (more on this can be found later in the Final Design section). This left us with the options of logic gates, a micro-controller, and a web of relays. The logic gates were chosen based on advice from Andrew. Relays would create an even more complicated – not to mention expensive – circuit than the logic gates, and the microcontroller would require additional research in programming while the logic gates only require an understanding of circuits.

We also had the choice of using perfboard or a printed circuit board (PCB) designed for our circuit. Due to time constraints, the perfboard was chosen, as the PCB would not be able to be printed in time. The perfboard also allows for modularity if changes need to be made to the circuit design.

We also needed to choose a proper battery for the system. Lead-acid, lithium-ion, and Nickel-Metal Hydride batteries were considered. Although the latter two offer lighter and smaller batteries, the lead-acid battery was chosen for its low price, and its ease of use. We knew that we had the correct charge available for a 12V lead-acid battery. We chose it to have 7Ah, because it would allow us to operate the bicycle for at least an hour at its highest current output of 6A.

ALPHA DESIGN

Figure 18: Placement of components on bike

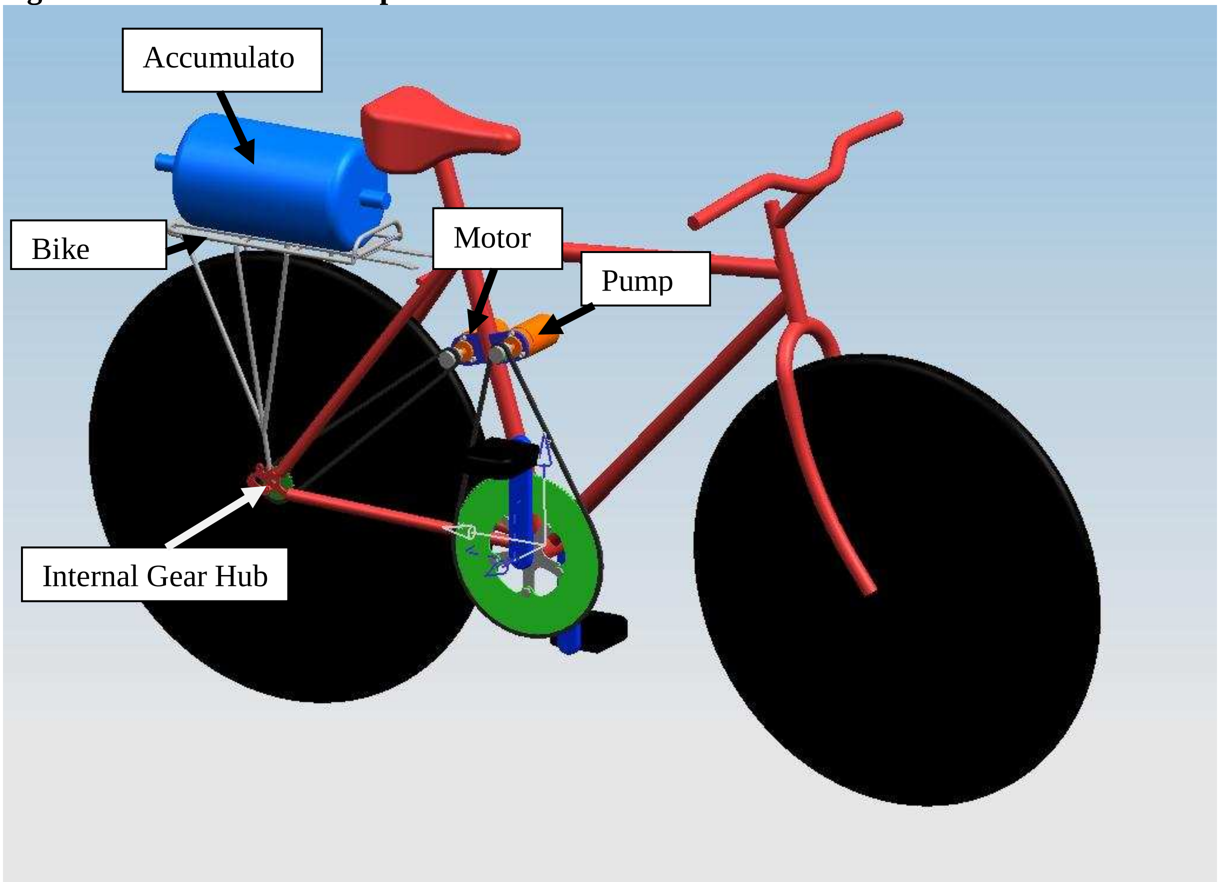
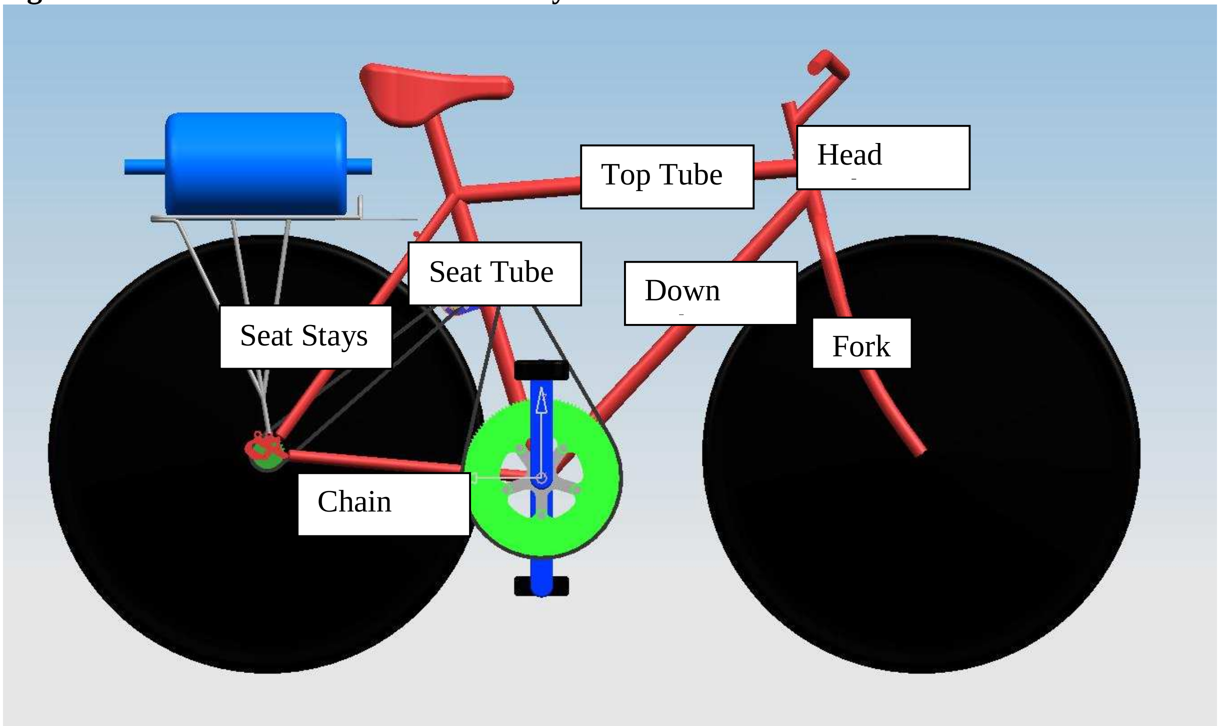
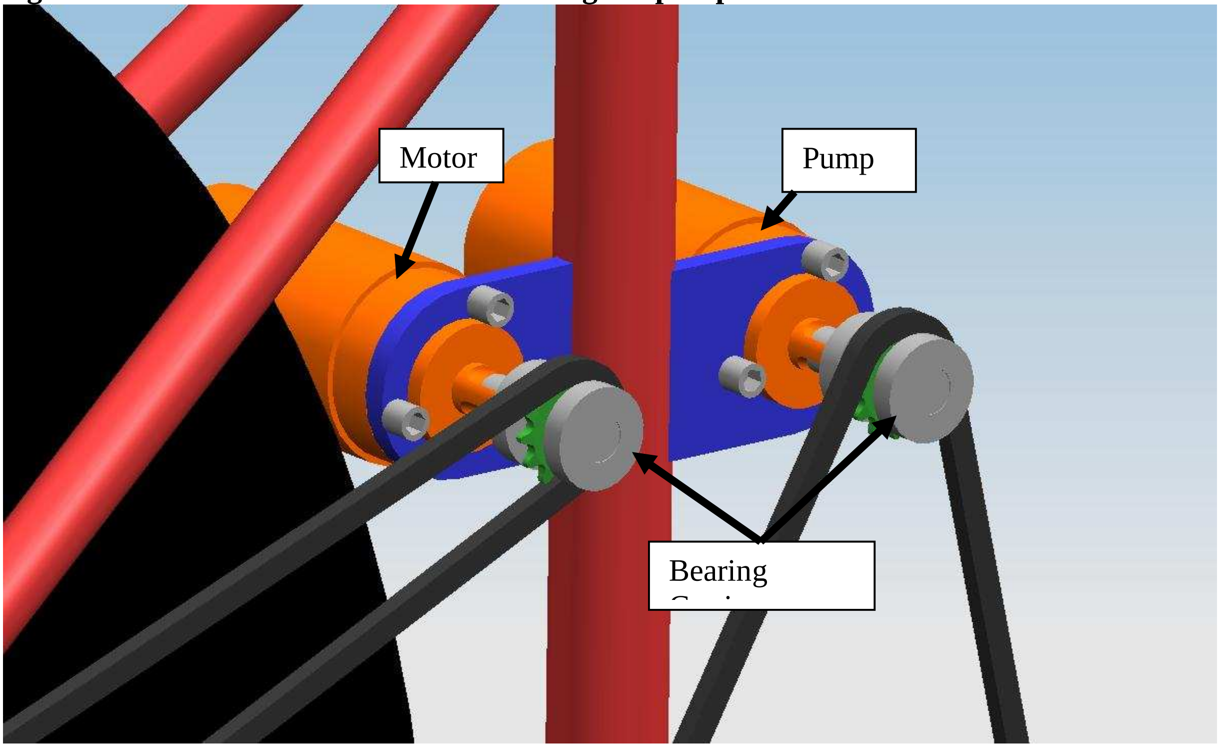


Figure 19: Technical tube names for a bicycle



Having chosen the 1.5cc/rev pumps, it was necessary to have a large gear ratio going from the pedals to the pump, as shown in Figure 18. This large gear ratio creates a large radial load on the pump shaft, so we are required to design a way to securely attach the pumps to the bike frame. Our design shows a mounting plate is to be welded to the seat tube of the bicycle. We will need to do some analysis on the seat tube to ensure the loads on it will not cause any structural problems to the frame. If there is concern of the seat tube not being strong enough to support the loads applied to it, we can reinforce it. This is easily done by taking the seat off and sliding a reinforcing tube inside of the seat tube and then welding them together.

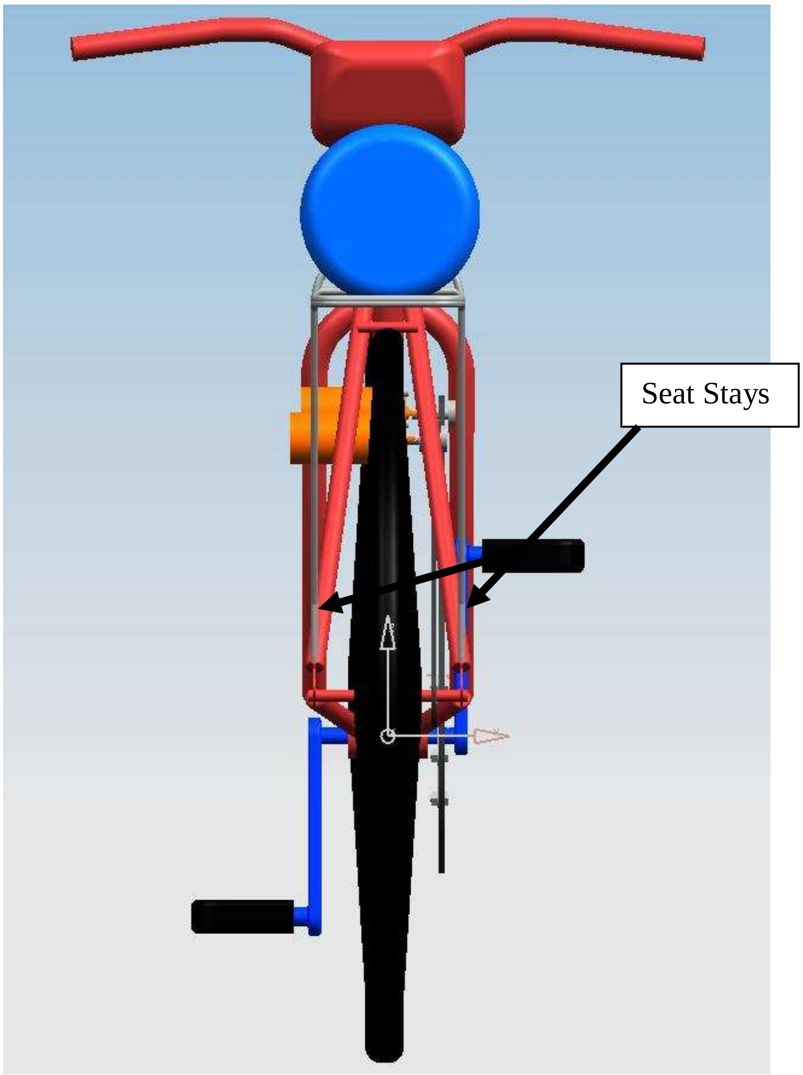
Figure 20: Location and method of mounting the pump and motor



The pumps are attached to the mounting plate using the face mount on the pumps and three bolts, as seen in Figure 20. Due to the large radial load on the pump shaft, it may be necessary to create a bearing carrier. Two bearings and a sprocket will be press fitted onto a shaft which will be connected to the shaft on the pump. Its purpose will be to take the loading off of the bearing on the pump and place it on the bearings of the bearing carrier.

The placement of the motor is limited by the seat stays angling towards each other, as shown in Figure 21. We cannot move the motor higher up the seat tube because the path of the chain will intersect with the seat stays. Ideally we would like to have both mounts be placed together so the reinforcing tube does not have to be very long (if we require a reinforcing tube). The bearing plate is easier to manufacture and stronger if one rather than two. However, the placement of the pump may have to be moved up to where the seat tube and top tube come together. There are several advantages to having the pump at this location: the mount can be welded to the top tube as well as the seat tube which would result in a stronger mount, the larger distance between the sprocket at the pedals and the pump would allow more tooth engagement at the pump, and the driver would be less likely to hit the pump and hoses with his or her legs when pedaling.

Figure 21: Back view of bike showing the seat stays angling towards each other as they approach the seat tube



Due to the large size of the accumulator in relation to the bike, there is isn't enough room to mount it directly to the bike frame. Therefore, we plan to use a bike rack over the rear wheel and mount the accumulator to it. Not pictured in these renderings is the reservoir. The reservoir is a low pressure holder of the hydraulic fluid and will be about the same size as the accumulator. There are two options for the location of the reservoir. It can either be placed at the front of the bike, mounted to the top, head, and down tubes. Alternatively, we could build another layer to the rack and mount the reservoir there, but we would prefer not to do that because that would raise the center of gravity of the bike. We may still tweak the locations of some of our components so we are holding off on showing the hose and valves until DR3. We also have not decided whether or not we will be using mechanical or electrical actuated valves, so the location of the battery and electrical lines are not shown.

In order to direct the hydraulic fluid to the right place, and in turn create the possibility of the 5 different modes, we will have to employ a rider-controlled system of valves and fluid lines. A schematic of our design can be seen below in Figure 22. V1, V2, and V3 are our solenoid valves that will be either open or closed depending on mode. The other valves pictured are check valves responsible for only allowing fluid flow in the correct direction (as indicated on diagram). All other components can be seen as labeled.

ENGINEERING ANALYSIS

Our current alpha design is only a rough concept, so further refinement and analysis on the design is necessary. We have many of the components already selected and ordered because of the lead times. These components, which include the pump motors and all of the control valves, cannot be changed. However, the other components such as the gears, accumulator, and the lines still must be finalized. Part of this finalization process will include more development on the control strategy for the different modes of operation described in the concept generation section. At the same time we must refine the CAD model to the level that is necessary to complete the manufacture and assembly of the prototype.

To complete the control strategy for the valves we will use knowledge of circuits and cable actuation. This will depend on the difficulty of converting the solenoid valves to mechanical actuation as well as the challenges in mechanically actuating different combinations of valves. If we decide that using the electric solenoids is the best strategy, we will need to design circuit to control all of these functions. Also, we will need to select and package a power source capable of operating the valves for the length of time that we determine.

Completing the CAD model will require knowledge of fluid mechanics to minimize the fluid losses in the hoses and fittings. This is done by strategic component placement, specifically the pumps and the accumulator. We already have the preliminary placement of these major components, but it may vary slightly due to mounting challenges. The pump motors will be the most difficult to mount because they will have high torques applied to them from the mechanical power transmission systems. The mount design for these pumps will primarily deal with solid mechanics. The mounting of the pumps also includes the mounting of the bearing plates that will most likely be needed to reduce the high radial loads that would otherwise be acting on the pumps. Another avenue we are considering is removing the bearing plates and transmitting the entire radial load to the pumps. At times the peak radial load on the pumps would exceed the manufacture recommended load rating, but these exceeded loads would be sustained for only several minutes or less. Typically, the manufacturer recommended radial load limit is for sustained load. This design change would eliminate the frictional losses added by the extra bearings, improving the overall vehicle efficiency. To make this change we will need to consult a technical specialist at Parker Hannifin and also do some solid mechanics analysis on our own.

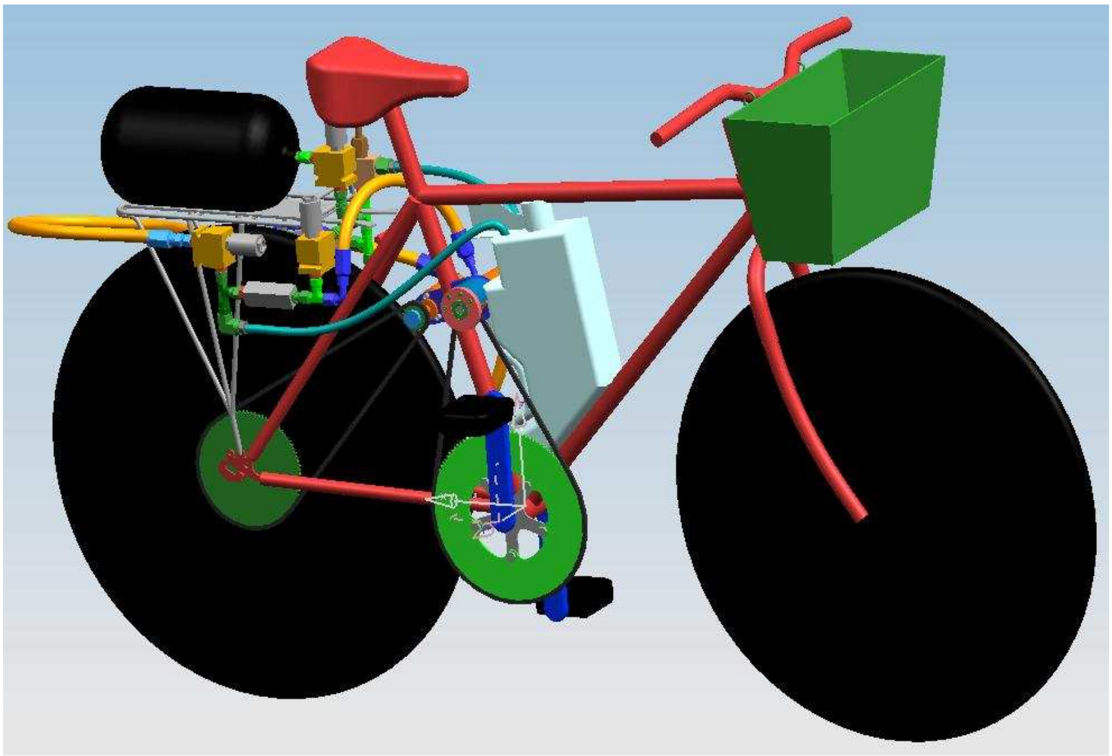
FINAL DESIGN AND PROTOTYPE DESCRIPTION

Because the intention of our bicycle is to compete in a race and not to enter mass production, our prototype is our final design. By the end of this course, the Chainless Challenge team should be able to use the final product in its competition. Although the team may choose to make some minor modifications, we intend to deliver a finished project that requires no extra work.

Overall design

Our design consists of three major subsystems: mechanical, hydraulic, and electrical. The mechanical subsystem transfers power to and from the hydraulic subsystem. The hydraulic subsystem transfers power from the pump to the motor and stores energy from braking in the accumulator hydraulically. The electrical subsystem receives an input from the user and sends voltage to the correct valves based on the desired mode of operation.

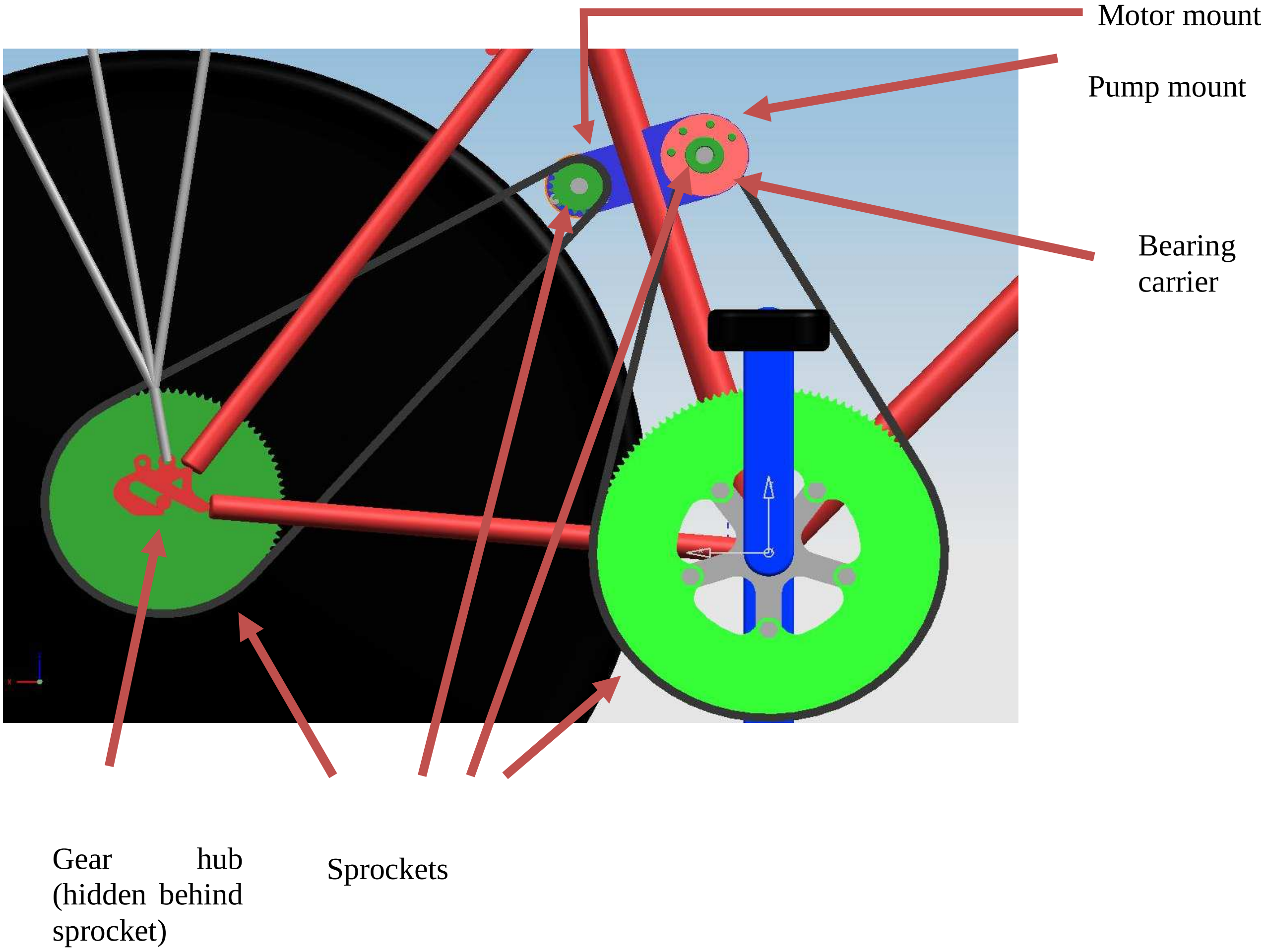
Figure 22: Overall design



Mechanical subsystem

The mechanical subsystem consists of chains, sprockets, the gear hub, a bearing carrier and mounts for the pump motors. A detailed description of each of these components appears in the Purchased Mechanical Components and the Manufactured Components sections. An overview of the mechanical subsystem appears in Figure 23.

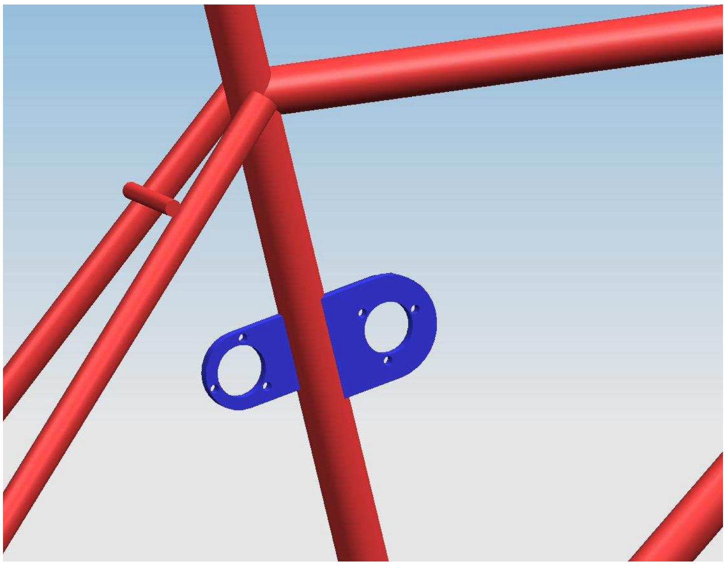
Figure 23: Mechanical components



Pump and motor mounts

Two separate mounts will connect the pump and the motor to the frame. They will be made out of ¼” steel plate and will be welded on to the seat tube. The faces of the pump motors will bolt to the mounts.

Figure 24: Pump and motor mounts



Bearing carrier

Because of the 400 N of tension in the pump's chain, we designed a bearing carrier to reduce the radial load on the pump's shaft. CAD models appear in Figures 25 and 26.

Figure 25: Bearing carrier

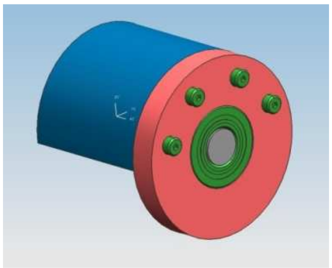
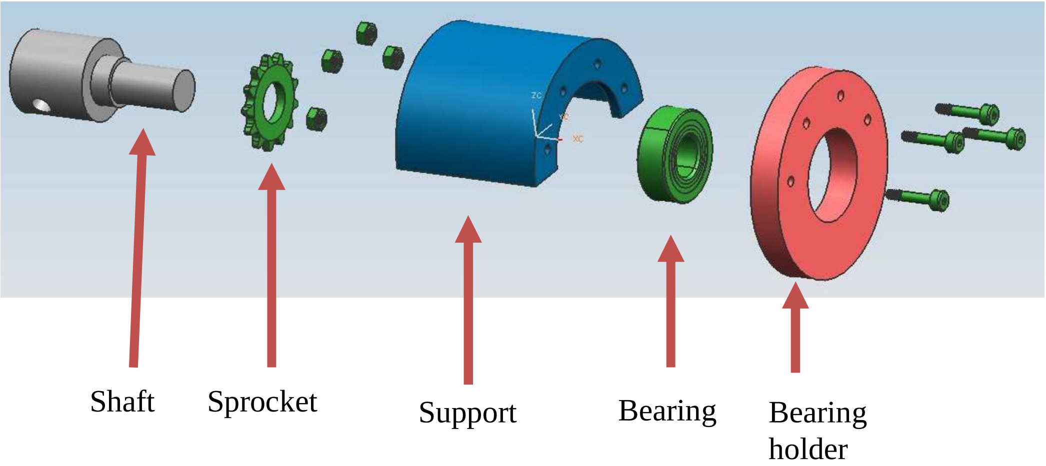


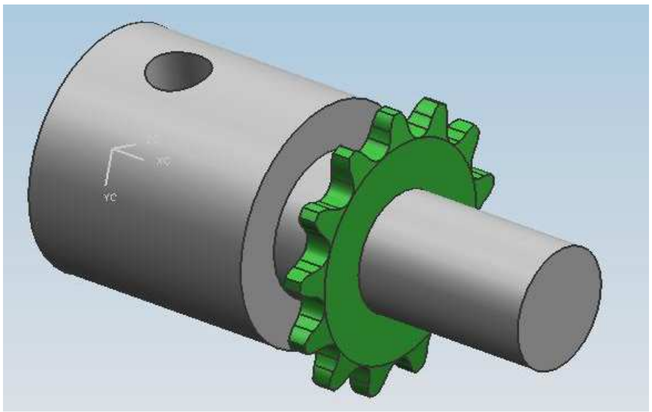
Figure 26: Bearing carrier exploded view



Shaft extensions

Loads on the motor are not as high as those on the pump, so the motor does not require a bearing. We will manufacture two shaft extensions, one for the motor and one for the pump, which will allow us to attach the sprockets to the pump and motor shafts. These will use a shoulder bolt through the shaft to transmit the torque. A CAD model of this part appears in Figure 27.

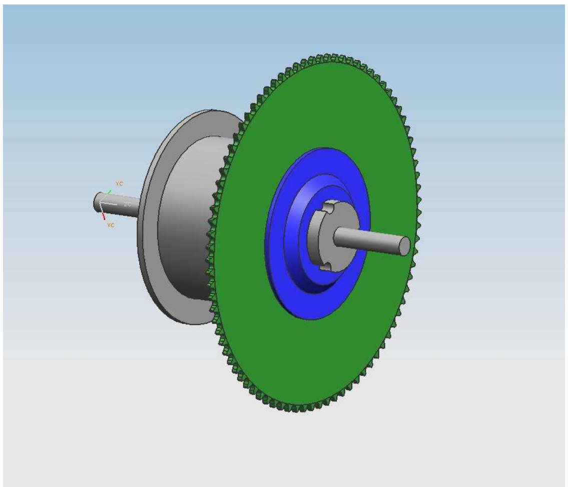
Figure 27: Shaft extension for motor and pump



Gear hub assembly

We will use the Shimano gear hub attached to an 85 tooth industrial sprocket. The industrial sprocket will be welded to the original bicycle sprocket designed to fit on the Shimano hub. A figure of this assembly appears in Figure 28.

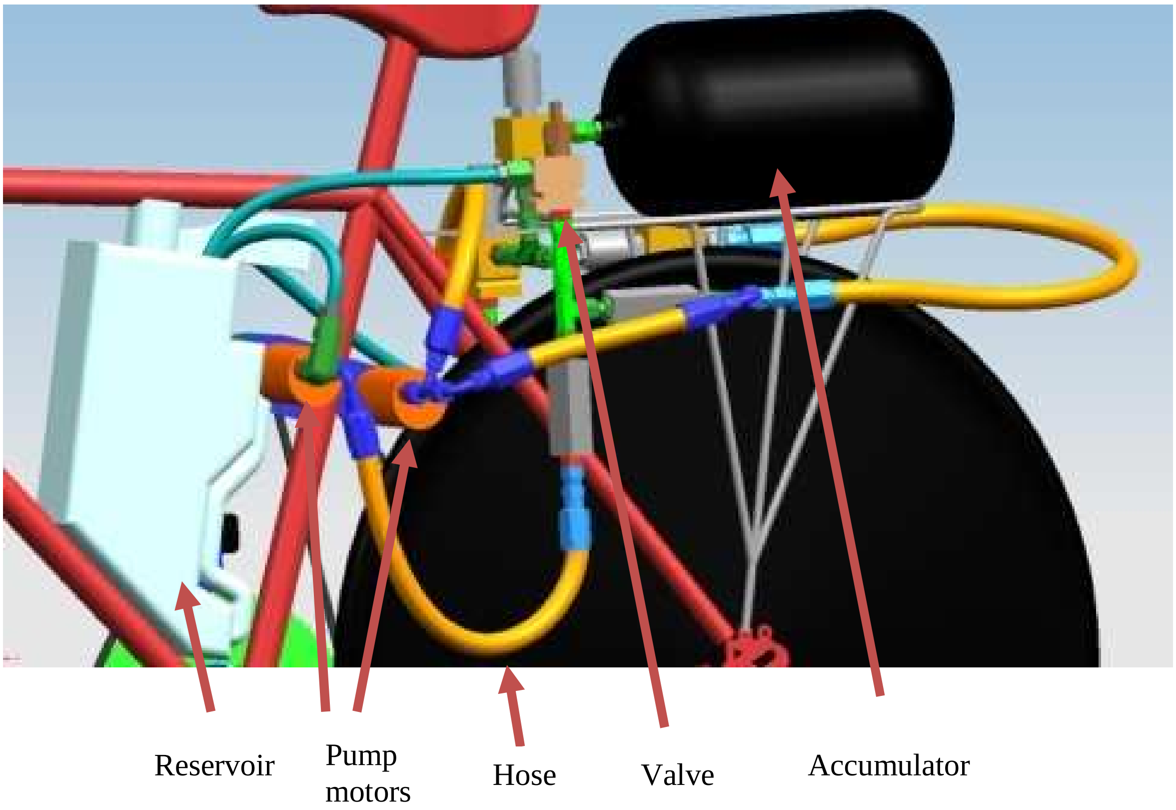
Figure 28: Shimano gear hub and industrial sprocket



Hydraulic subsystem

The hydraulic subsystem consists of pump motors, valves, an accumulator, a reservoir, and fittings. A detailed description of each of these components appears in the Purchased Hydraulic Components section. We have chosen a variety of fittings to convey the hydraulic fluid from one part to another: high pressure hose, tees, adapters, low pressure hose, and barb fittings. An overview CAD model of the hydraulic subsystem appears in Figure 29.

Figure 29: Overview of hydraulic subsystem



Hydraulic Schematic

In order to direct the hydraulic fluid to the right place, and in turn create the possibility of the 5 different modes, we will have to employ a rider-controlled system of valves and fluid lines. A schematic of our design can be seen in Figure 30. V1, V2, and V3 are our solenoid valves that will be either open or closed depending on mode. The other valves pictured are check valves responsible for only allowing fluid flow in the correct direction (as indicated on diagram). All other components can be seen as labeled.

Figure 30: Hydraulic Schematic of Our Valve System and Fluid Lines

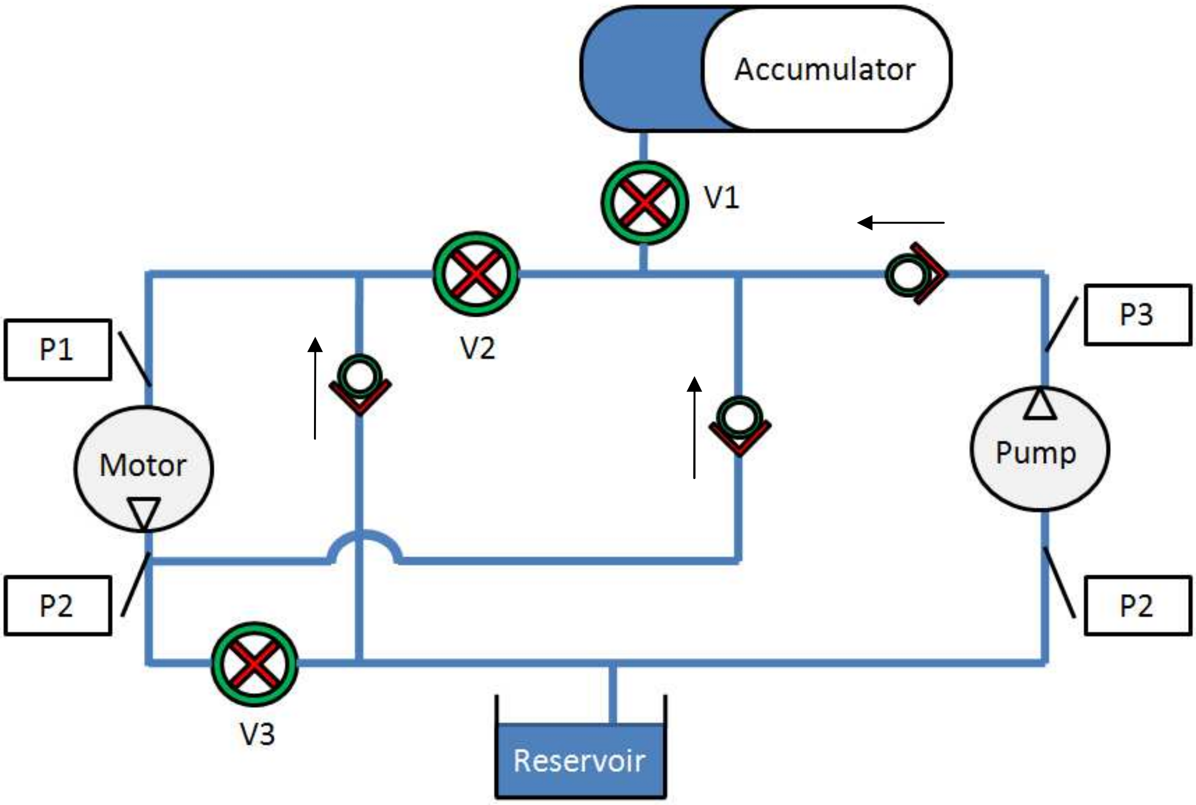


Table 3: Valve Positions and Resulting Pressures for Each Mode

	Valve Postition			Pressures			
Mode	V1	V2	V3	P1	P2	P3	P4
Pedaling	Closed	Open	Open	High	Low	High	Low
Coasting	Closed	Open	Closed	Constant	N/A	N/A	N/A
Accelerating	Open	Open	Open	High	Low	N/A	N/A
Braking	Open	Closed	Closed	Low	High	N/A	N/A
Charging	Open	Closed	Closed	N/A	N/A	High	Low

The position of the 3 solenoids in our fluid system will dictate the pressures on each side of our pump and motor, as well as where the resulting flows are directed. Depending on which side has a high pressure and which side has a low pressure will translate into which way torque is applied to the pump motor shaft. A difference in pressure over the pump or motor will indicate an energy transfer from mechanical energy to hydraulic pressure (or vice versa).

With the pump, it will only ever be able to input energy to the system, by means of the rider pedaling. This will result in a low pressure at P2, and a high pressure at P3, converting the rider's mechanical input into high pressure fluid that can directed to either the motor or the accumulator.

With the motor, a high pressure at P1 and a low pressure at P2 will result in an accelerating torque being applied to the rear wheel (by means of the motor gear system). A low pressure at P1 and a high pressure at P2 will mean a torque in the opposite direction, which will then cause the rider to slow down. The ability to apply torque in both directions is what gives our system its regenerative capability. This however, requires a rear hub that can apply torque as well, as explained in the Concept Generation section of this report. In order to emulate the "free-wheeling" ability of a normal bike, our motor will circulate the fluid in a closed loop with no energy transfer. This will create a constant pressure during circulation, and therefore there will be no torque on the motor shaft.

Some of these modes can also function simultaneously. While accelerating, the rider will also be able to pedal, creating a parallel functioning of the "accelerating" and "pedaling" modes. Similarly, the rider will also be able to pedal while braking, employ both modes "braking" and "charging". Both of these situations will require a large torque from the rider to overcome the high pressures involved, but the possibility of the parallel functioning exists nonetheless. A more comprehensive depiction of the different modes and their respective fluid flows can be seen in Appendix D.

Valve 1 is normally closed, and valves 2 and 3 are normally open. This gives a default mode of "pedaling". The other modes will be driver chosen, and executed by the electrical subsystem, which is described in the following section.

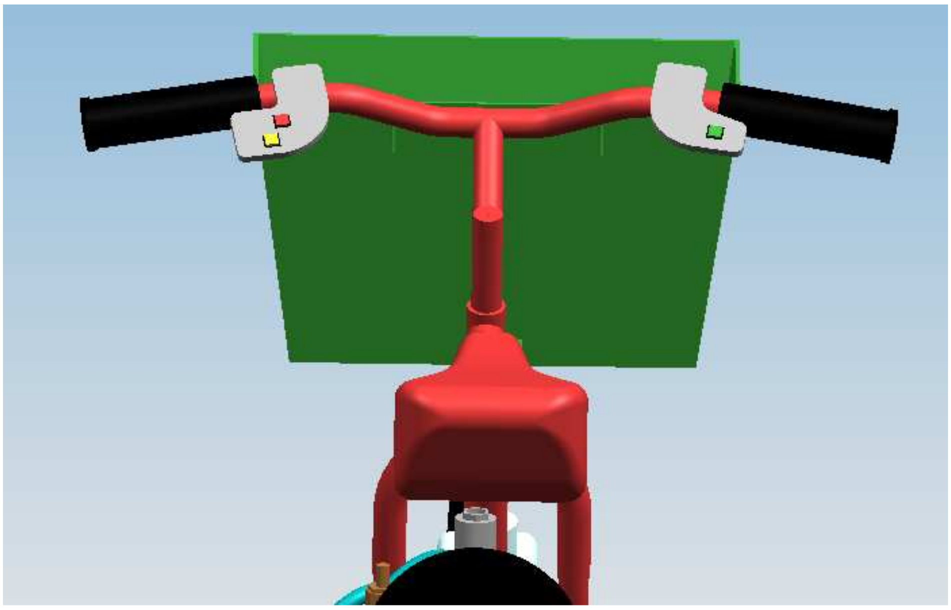
Electrical subsystem

The purpose of the electrical subsystem is to control the hydraulic solenoid valves. As stated before, the "pedal" mode is the default mode of the bike due to the valves' unpowered positions. The electrical subsystem is responsible for choosing any of the other modes of operation. It receives a signal from the user via switch, and in turn supplies power to the valves to create the desired mode as can be seen in the previous hydraulic schematic.

Acrylic Button Brackets

The buttons responsible for supplying the user input, will be mounted to the handlebars using acrylic brackets. These can be seen below in Figure 31.

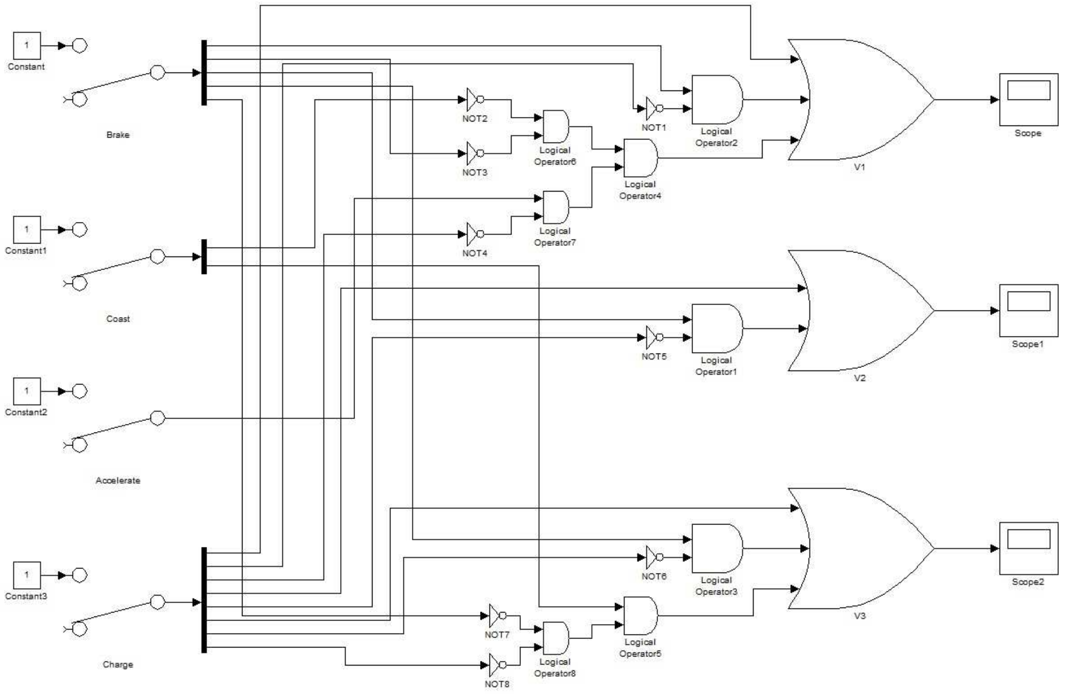
Figure 31: Acrylic button brackets mounted on handlebars



If the electrical subsystem receives more than one input from the user, it will output a safe valve selection. The electrical subsystem consists of a battery, a voltage regulator, switches, logic gates, relays, and wires. The subsystem will be mounted to acrylic, and attached to the basket that can be seen above in Figure 31.

The logic gates are used to ensure that the user is in both the desired mode, and at times of ambiguity, the safest mode. Protecting from things like accelerating at the wrong time is especially important in creating a safely functioning bicycle. Because of this, “charge” mode is given the highest priority with “braking”, “coasting”, and “accelerating” following respectively. This order has been chosen with an emphasis on safety, as can be seen by the order of the last three. The reasoning for putting “charging” mode first is also for safety, but will be explained later. Each mode is chosen by the user, by means of a switch, and if two are pressed at once, the system must choose whichever has higher priority. A logic schematic that was constructed in Simulink to make this choice of priority can be seen below in Figure 32.

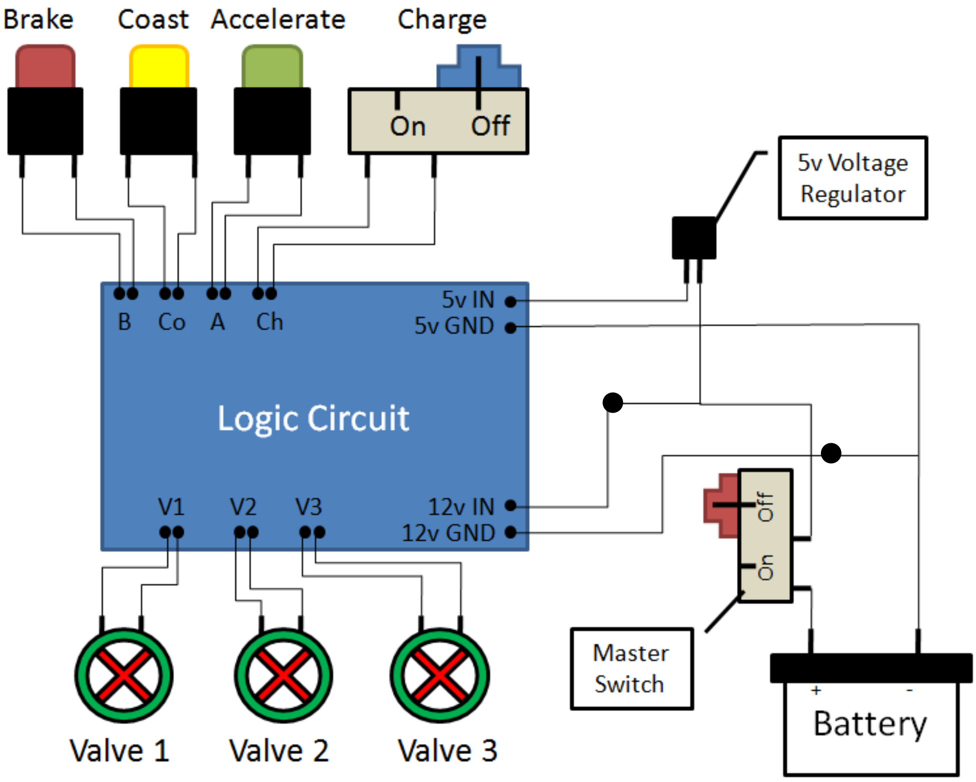
Figure 32: Logic Schematic of Control Circuit



The switches can be seen on the left side of the schematic. The “brake”, “coast” and “accelerate” switches will be pushbuttons that are normally open unless pressed. The “charge” switch will be a 2-position switch, allowing the user to stay in charge mode without holding down a button. This will be helpful as charging is done while the bike is stationary, and has the possibility to take a long time. Fittingly, “charge” mode was given the highest priority, as it would be unsafe for the other modes to engage while charging, by simply bumping a button.

Once these switches are closed, they will be sent a 5V signal through the network of AND gates, with the destination being the OR gates labeled “V1”, “V2” and “V3”, which are names for their respective valves. The purpose of this is to translate a mode-based signal into which valves should be powered during that mode. The AND gates are responsible for ensuring that if “accelerate” is pressed, the other modes of higher priority (“brake”, “coast” and “charge”) are not pressed. Once the AND gate network has done its job, the OR gates will get signals telling them whether or not to allow power to their respective valves. If any of their inputs provide 5V, they will pass that 5V through. The combination of having different switches closed, and their respective OR gate outputs can be seen in Appendix E. This 5V output will then switch a transistor, allowing the battery to provide 12V power to a relay, in turn allowing the battery to provide 12V at high current to the valves. A schematic of the entire electronic subsystem can be seen in Figure 33.

Figure 33: Diagram of Electronic Subsystem



The logic part of the control circuit from Figure 32 is embodied in the "Logic circuit" block, which also contains the transistors and relays for allowing power to the valves. (Note the terminals for switch inputs and the terminals for output to the valves). Because the logic circuit runs on 5V, there is a voltage regulator to step it down from the 12V battery, but also make sure it is a clean, non-noisy signal.

As you can also see from the diagram, there is a "Master Switch" located right next to the battery. This will allow us to turn the entire system off, preventing the battery from draining and eliminating any unwanted mode changes. Figure 31 is simply a figure to represent the general layout of the system, and not a wiring diagram. This can be found in Appendix L.

Purchased mechanical components

This section describes all purchased mechanical components. A detailed bill of materials with manufacturers, suppliers, and prices appears in Appendix F.

Sprockets

Model numbers: A 6C 7-25013, A 6C 7-25020, A 6C 7-25085, A 6C 7-25125

Description: These four sprockets are necessary to turn the chain which connects the pump motors to the pedals and the wheel. The crank will have a 125 tooth sprocket, and pump will have a 13 tooth sprocket, giving a 9.6:1 gear ratio. The motor will have a 20 tooth sprocket, and the rear wheel will have an 85 tooth sprocket, giving a 4.3:1 gear ratio. They are made of carbon steel. We will machine the inside of the 125 tooth sprocket so that we can attach it to the crank and weld the 85 tooth sprocket to a Shimano bicycle sprocket.

Chain

Model number: A 6Q 7-25

Description: Chain transmits a force between sprockets. It is made of carbon steel and can support a tensile load of 4115 N.

Internal gear hub

Model number: SG-8R36

Description: The gear hub connects the rear wheel to its sprocket. It offers eight different speeds without an external cassette. We will modify it to disable the freewheeling feature which allowed the rider to coast. This is necessary because we need the hub to apply torque to the motor under braking, when it would otherwise be coasting in an ordinary bicycle.

Bearing

Model number: McMaster-Carr 6384K49

Description: The bearing reduces the radial load on a shaft of a pump motor.

Racks

Description: The rear rack holds the accumulator above the rear wheel. The front rack holds the battery and electrical equipment that cannot be mounted on the handlebars.

Purchased hydraulic components

This section describes all purchased hydraulic components. A detailed bill of materials with manufacturers, suppliers, and prices appears in Appendix F.

Accumulator

Model number: SKC402921

Description: The accumulator stores energy hydraulically by compressing an internal nitrogen bladder with the fluid. It is necessary to allow us to store energy from braking and reuse it for acceleration. It is rated for 20.7 MPa and has a volume of 13.2 L (3.5 gallon). It is made of carbon fiber which is much lighter than the steel version (11.8 kg vs. 43 kg).

Pump motors

Model number: 09S-E-CK-P

Description: Pump motors convert a rotational torque on their shafts from the chain and sprockets to fluid pressure and back again into rotational torque. Fluid flows from the pump to the motor or into the accumulator during energy storage. These are rated for 34.5 MPa and have a displacement of 1.5 cc/rev.

Valves
Model numbers: SBV11-8-C-S6T-12DQP, SBV11-8-O-S6T-12DQP

Description: Valves control the direction of the fluid, directing it into the accumulator or into the pump motor on the wheel. They are normally fixed as specified, in either the open or closed position and they require a 12 V signal to activate the solenoid. We have purchased one normally closed valve to close off the accumulator and two normally open valves to use during regenerative braking and acceleration. They are rated for 34.5 MPa.

Check valves
Model numbers: C620S, C620S1

Description: Check valves allow fluid to flow in one direction only. They are rated for 34.5 MPa.

Relief valve
Model number: A02A2PZN-6T

Description: The relief valve prevents the system pressure from exceeding the rated pressure. When the pressure reaches the rated pressure, the relief valve opens and dumps fluid to the reservoir until the system pressure is below the rated pressure. It can be set to relieve any pressure below 34.5 MPa.

Reservoir
Type: Dodge Caravan coolant reservoir

Description: The reservoir holds fluid at atmospheric pressure, fills up as the accumulator empties, and provides a source of fluid for filling the accumulator. It is closed at the top to prevent splashing but has a small vent to ensure that the pressures inside and outside are equal.

Oil
Type: Automatic transmission fluid

Description: The system will use specially formulated hydraulic fluid, which is designed to handle the pressures, temperatures, and materials found in many hydraulic systems.

High pressure hose
Model number: Parker 302 series

Description: Provides a flexible and lightweight means for fluid transport. It is rated for 32.8 MPa and is compatible with field attachable fittings.

High pressure hose fittings
Model number: Parker 30 series

Description: Fittings attach to both ends of each high pressure hose and allow the hose to connect with other hydraulic fittings. These fittings are field attachable, which means that they use threads to secure the hose instead of crimps, allowing us to assemble the hose ourselves.

Hydraulic fittings

Description: Adapters are used to attach all of the necessary components as well as convert differing threads. These are necessary, for example, to allow us to attach our JIC hose fittings into the SAE fittings on our pump motors. Tees connect three hydraulic lines at one point, and elbows allow 90° bends. We are using SAE and JIC fittings for high pressure because they are readily available and leak free. We are using NPT fittings on the pressure gauge and on the low pressure side. We tried to avoid NPT fittings for high pressure because they are more difficult to seal and reuse. All high pressure fittings are rated for at least 34.5 MPa.

Pressure gauge

Model number: McMaster-Carr 3846K84

Description: The pressure gauge tells the rider the accumulator pressure, which indicates how much fluid and energy is in the accumulator.

Low pressure hose

Vendor: Carpenter Brothers

Description: 3/8” and 1/8” ID polyethylene lightweight hose for the low pressure lines, instead of the Parker hose used for high pressure. It carries fluid to and from the reservoir. It is rated for low pressures and is compatible with oil.

Barb fittings

Model numbers: Parker P6MCB6, P6MEB6, P3MCB2, P3TUB3

Description: Barb fittings connect low pressure hose to other ports. Low pressure hose slides over one end, and the other end has pipe thread to screw into another fitting. They are rated for low pressures and are compatible with oil.

Purchased Electrical components

This section describes all purchased electrical components. A detailed bill of materials with manufacturers, suppliers, and prices appears in Appendix F.

Battery

Model number: Newark 87F637

Description: A battery is necessary to provide electrical power to actuate the valves.

Prototyping board

Description: The prototyping board holds all of the components necessary to perform the logic needed to actuate the valves.

Buttons
Model numbers: Newark 46F1756

Description: The user depresses one of these pushbuttons to specify which mode to use: brake, coast, or accelerate. When no buttons are depressed, the bicycle is in pedal mode.

Rocker switches
Model number: Newark 01M9108

Description: There are two on/off two slide switches: one for charge mode and one master power switch. The master power switch disconnects the battery from the circuit when the bicycle is not in use. The charge switch is set to on to fill the accumulator by pedaling.

Logic gates
Model numbers: Newark 69K7675 (AND), 31C5904 (OR), 60K5154 (Inverter)
Description: The logic gates determine which valves receive a voltage based on which buttons the user has depressed. If the user pushes more than one button at the same time, the logic gates ensure that the valves remain in a safe mode of operation.

Voltage regulator
Model number: Newark 58K1803

The voltage regulator takes 12V from the battery and provides 5V to the logic gates.

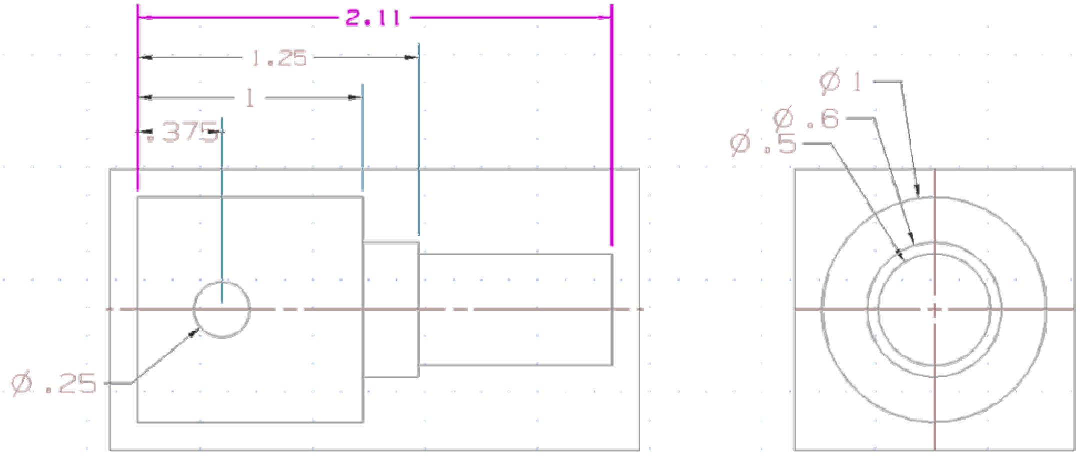
Transistors
Model number: IRL510PBF
Description: The logic gates cannot handle enough current to actuate the valves. If a transistor receives a signal voltage from the logic gates, it allows power to the relays. There are three transistors, one for each valve.

Relays
Model number: Newark G5LE-1-DC12
Description: The transistors allow 12V power to the relays. Once the relays have been switched, the high current loop is closed, and the associated valves are powered. There are three relays, one connected to each of the transistors.

Manufactured components
All manufactured components fall under the mechanical subsystem.

Shaft extensions
There will be two shaft extensions: one for the pump and one for the motor. They connect the shafts to the sprockets. The sprockets will be press fit on to the shaft extensions, and we will drill holes through the pump motor shafts and connect them to the shaft extensions with shoulder bolts. We will turn a 1” diameter steel rod on a lathe to manufacture the shaft extensions.

Figure 34: Shaft extension



Pump motor mounts

Two separate mounts will connect the pump and the motor to the frame. They will be made out of ¼” steel plate and will be welded on to the seat tube. The faces of the pump motors will bolt to the mounts.

Figure 35: Pump mount

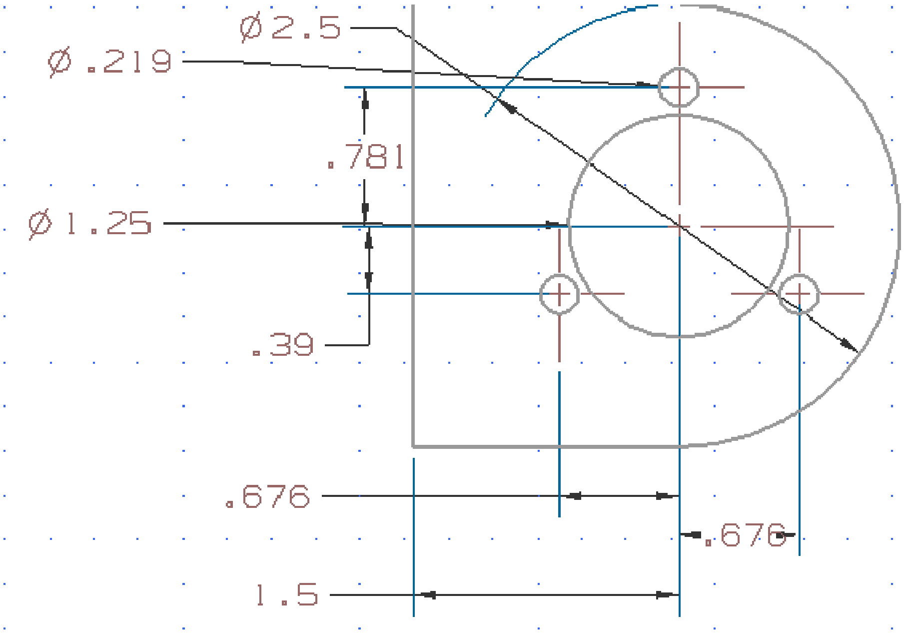
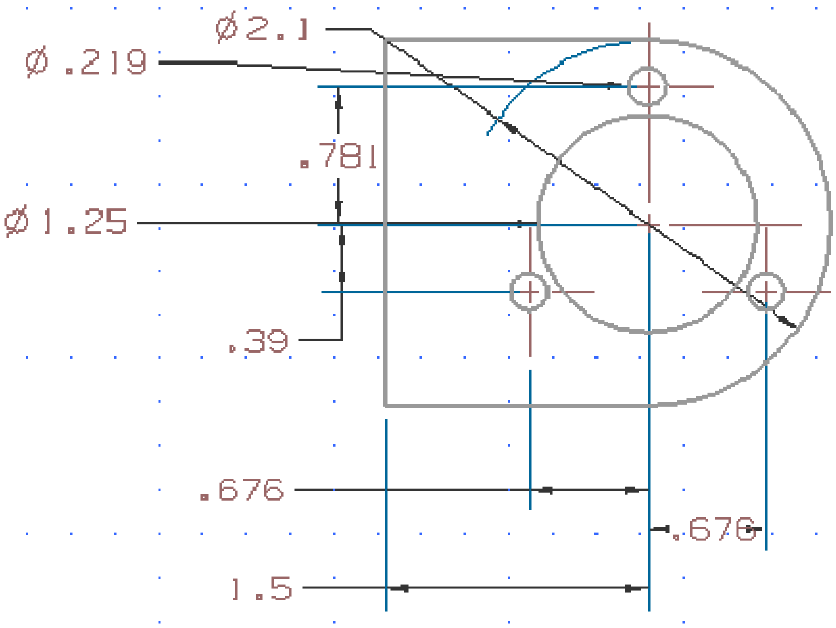


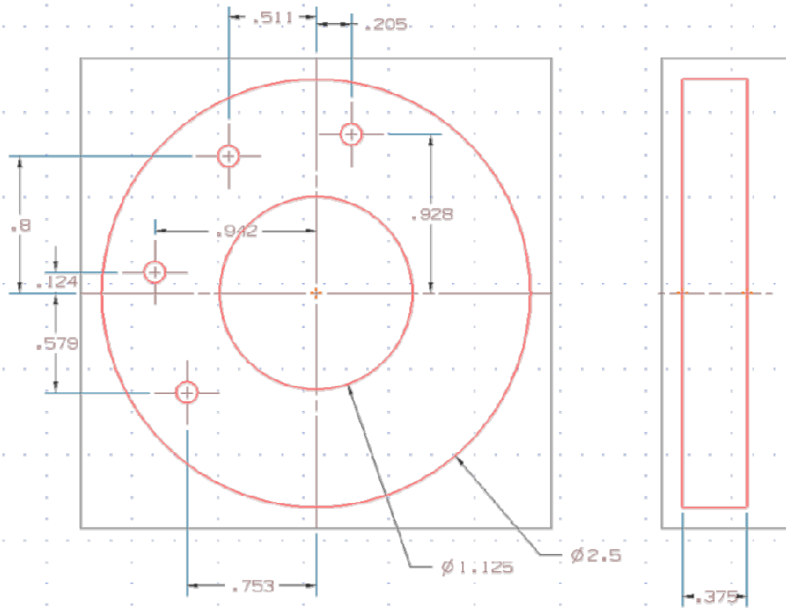
Figure 36: Motor mount



Bearing holder

The bearing holder holds the bearing that supports the shaft extension. It will be made from a ¼” thick steel plate.

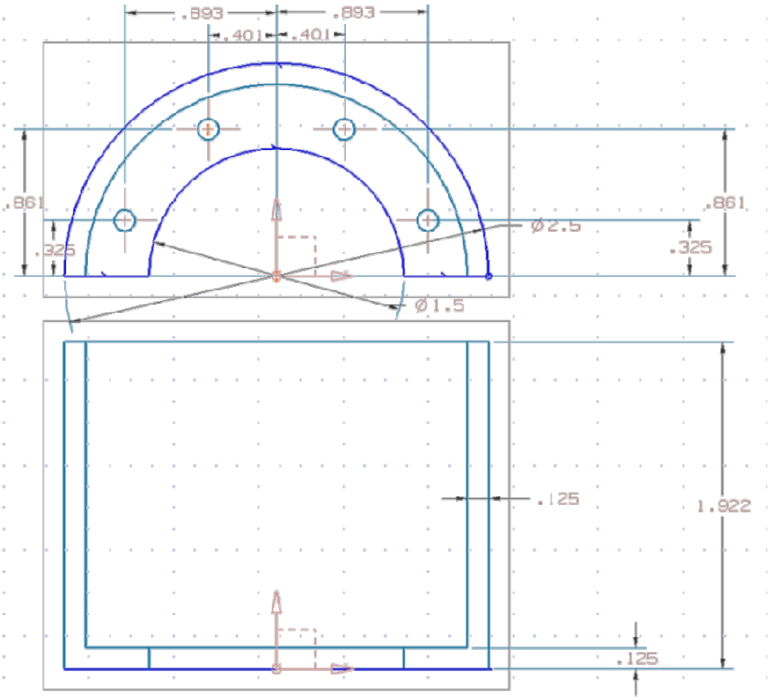
Figure 37: Bearing holder



Bearing carrier support

The bearing carrier support connects the bearing holder to the pump mount. It will be made of steel tube with the flange welded to the outer edge. The side opposite of the flange will be welded to the pump mount.

Figure 38: Bearing carrier support



Sprockets

Although we are purchasing sprockets, all of them will require machining operations. We will machine the center of the 125 tooth sprocket (Figure 39) to attach to the existing crank. We will bore a larger hole on the 85 tooth sprocket and weld it to the Shimano bicycle sprocket to attach to the gear hub. The 13 and 20 tooth sprockets will also require the centers to be bored out to allow them to be pressed on to the shaft extensions. Another 85 tooth sprocket has been designed to be attached to our original rear wheel for the bike. The profile can be seen in Figure 40. We will also need to machine spacers for its mounting that can be seen in Figure 41.

Figure 39: 125 tooth sprocket

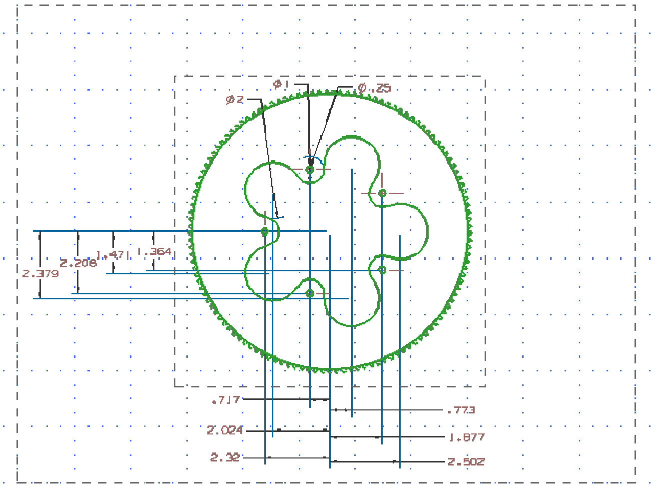


Figure 40: 85 tooth sprocket (single gear)

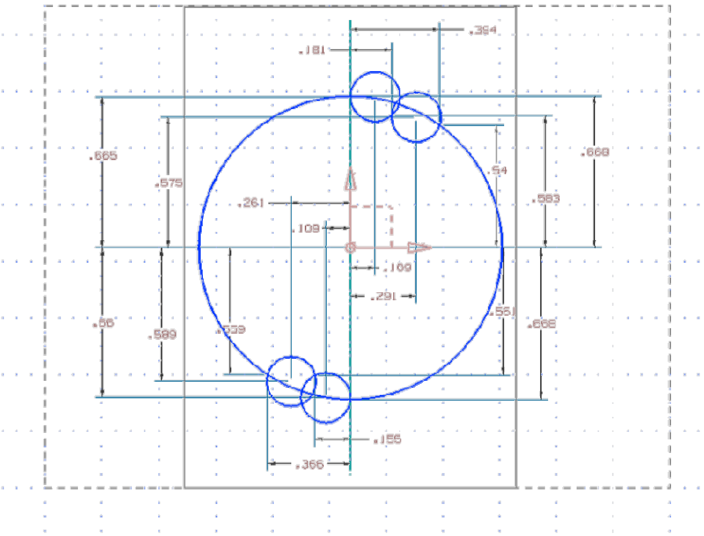
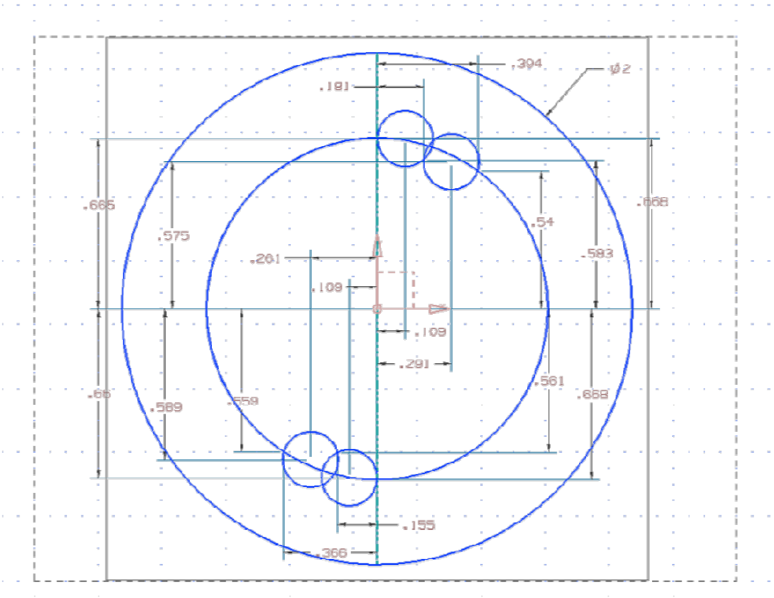


Figure 41: Single gear sprocket spacer



PARAMETER ANALYSIS

There are many complicated components on the bike, but we determined that only several required in depth analysis. These components include the shaft extension, bearing carrier, bearing support and bolts, torque transmitting shoulder bolt, and the stress at the pump and motor mount welds. The relevant equations surrounding this analysis can be found in Appendix G, along with the analysis on shrink fitting the sprockets onto the shaft extension. Other components were sized using engineering reason to ensure that the safety factors were sufficiently large.

To help us select and assess environmental impact of materials and identify safety risks, we used CES EduPack, SimaPro, and Designsafe software. A detailed report on our findings appears in Appendix H. We used CES EduPack to identify the best materials for the shaft extensions and safety shield. We identified carbon steel and cast iron as good candidates for the shaft extensions. We used SimaPro to compare the environmental impact of these two materials and found it is about the same for each. Aluminum and carbon fiber were candidates for the safety shield. Carbon fiber is lighter and has less environmental impact than aluminum but is more expensive.

Forces on bearing shaft extension

The peak torque acting on the pump is 45 lb*in. We are able to find the radial load on the sprocket by using

Eq. 6

Where T is the torque in lb*in, F is the radial force in lb, and r is the pitch radius in inches. We calculated the radial load to be 90lbs. This exceeds the recommended radial load on the pump shaft, so a bearing carrier was designed to lower the forces on the shaft. A simple force balance results in

$$\mathrm{F}_{\mathrm{radial}} = \mathrm{F}_{\mathrm{pump}} + \mathrm{F}_{\mathrm{bearing}} \qquad \text{Eq. 7}$$

The radial force on the bearing is determined to be 20lbs, which gives us a safety factor of 2.25. This will allow some misalignment when manufacturing.

Stress and deflection of bearing support

The bearing support will be welded to the mount and will behave as cantilevered beam, so it is necessary to analyze the bending stress at the weld and the deflection at the bearing. Due to the geometry, we are able to use beam theory to determine these values. The stress is found by using the following equation

$$\sigma = \frac{M*c}{I} \qquad \text{Eq. 8}$$

Where σ is the bending stress in psi, M is the bending moment in lb*in, c is the max distance from the neutral axis in inches, and I is the second moment of area in in^4. We determined that the bending stress was 230psi, giving a safety factor if 156 against yield. The deflection at the end of the support is found by using

$$\delta = \frac{-F_{bearing}*L^3}{3*E*I} \qquad \text{Eq. 9}$$

Where δ is the deflection at the end of the support in inches, L is the length of the support in inches, E is the Young's modulus in psi, and I is the second moment of area in in^4. We determined the deflection to be $1.77*10^{-5}$ in.

Shear stress in support bolts

The shear stress in the bolts connecting the bearing support and bearing holder can be calculated by use of the following formula

$$\tau = \frac{\mathrm{V*Q}}{\mathrm{I*t}} \qquad \text{Eq. 10}$$

Where τ is the shear stress in psi, V is the shear force in lbs, Q is the statical moment of area in in^3, I is the second moment of area in in^4, and t is the thickness in inches. With a diameter of 1/8", the shear stress in each bolt is 4900 psi. The tensile strength of each bolt is 144,000 psi and the shear strength can be approximated at 60% of the tensile strength. Therefore the bolts will be strong enough to transmit the load, with a safety factor of 17.

Shear stress in torque transmitter

The shoulder bolt that connects the pump shaft to the sprocket has to safely transmit the torque. The shear stress is the main concern in strength and can be found by using Equation 10. With a shear force of 90 lbs and a thickness of ¼” gives a shear stress of 458 psi which is well within the shear strength of 84,000 psi.

Stress at the weld of the pump mount

The radial load on the pump mount will cause a bending stress at the weld. This can be calculated in a similar manner as what was done for the bearing support, using Equation 8. With a height of 2.25in and a thickness of ¼”, the stress was found to be 1500 psi, which is well within the yield strength of 36,000 psi.

The radial load for the pump is larger than that of the motor, so the stresses are going to be less on the motor mount weld. Therefore, it was not necessary to calculate the stress at the weld of the motor mount since the pump mount proved to be strong enough. Also, the stress caused by torsion is very small in comparison to the bending stress, so it was neglected.

INITIAL FABRICATION PLAN

Because our final design is the same thing as our prototype, our initial fabrication plan will consist of manufacturing all of our parts we need to make and modify ourselves, as well as the assembly of all of our manufactured parts and purchased parts. Although our project is for ME 450, we are working in conjunction with the student group BLUElab. This has allowed us access to the Wilson Center, as it is for a student competition. Given this, we will be doing all of our machining and assembly at the Wilson Center. The majority of our bike’s components are parts acquired from outside suppliers, but we will have to machine some parts ourselves before the assembly process.

The following table describes the processes for the machining of our manufactured parts.

Table 4: Parts to be made and associated machining processes

Part	Machine	Material	Tool	Speed
Pump Mount	CNC Mill	Steel	½” End Mill / ¼” Drill	800 rpm / 1500 rpm
Motor Mount	CNC Mill	Steel	½” End Mill / ¼” Drill	800 rpm / 1500 rpm
Bearing Support Tube	Band Saw	Steel Tubing	N/A	Set @ Wilson Center
Bearing Support Flange	CNC Mill	Steel	½” End Mill / ¼” Drill	800 rpm
Bearing Holder	CNC Mill	Steel	½” End Mill / ¼” Drill	800 rpm
Shaft Extension (x2)	Lathe/Mill	Steel	Turning tool / ¼” Drill	1000-2000 rpm / 1500 rpm
Gear Hub Tabs	Mill and File	Steel	1/8” End Mill	2500 rpm
Reinforcement Tube	Band Saw	Steel	N/A	Set @ Wilson Center
Button Brackets	Laser Cutter	Acrylic	N/A	Set in Machine Shop
Electrical System Mount	Laser Cutter	Acrylic	N/A	Set in Machine Shop

The bearing support flange will then be TIG welded onto the end of the bearing support tube. With the shaft extensions, the cylindrical forms will be turned using a lathe, and the mill will be used to drill the holes for pin-mounting. The gear hub tabs will originally be milled for their general shape, but small modifications will be made by-hand using a file to give its functional, but not manufacturable characteristics. The following table describes our parts that need to be modified for our design.

Table 5: Parts to be modified and associated machining processes

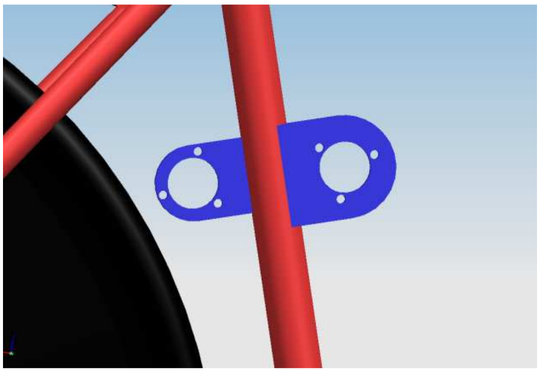
Part	Machine	Material	Tool	Speed
Pedal Sprocket	CNC Mill	Steel	½” End Mill / ¼” Drill	800 rpm / 1500 rpm
Pump Motor Sprocket (x2)	CNC Mill	Steel	¼” End Mill	1600 rpm
Rear Sprocket (Gear Hub)	CNC Mill	Steel	½” End Mill	800 rpm
Fluid Hoses	Chop Saw	Hose	N/A	N/A
Pump Motor Shaft (x2)	Mill	Steel	¼” Drill	1500 rpm
Rear Sprocket (Single Gear)	Mill	Steel	1/8” End Mill	2500 rpm
Sprocket Spacers	Mill	Steel	1/8” End Mill	2500 rpm

Before we begin the assembly process, we must first sandblast the bike. We will need to weld to the frame, but the paint and coating are in the way of getting to the steel frame itself. We will be sandblasting the entire frame, and it will be done at the Wilson Center using their sandblaster.

Once all of the parts have been machined, and the frame has been sandblasted, we will start the assembly process. There will be many processes using TIG welding, most importantly the pump and motor mounts. It will be important to pay careful attention to the alignment, because misalignment in the chain can reduce efficiency and cause premature failure. This will require an accurate and reliable jig to hold the parts in place. These jigs will be made as needed from spare materials sourced from the shop.

To begin, we will attach the pump and motor mounts to the seat tube on the bike. This will be done using a TIG welder, but will first need to have the steel reinforcement tube inserted inside of the seat tube. With the seat assembly removed, the reinforcement tube will be pressed in through the hole in the top of the frame. This will both strengthen the seat tube and provide more material for the welds on the pump and motor mounts as well. Once attached, the pump and motor mounts will look like the following figure.

Figure 42: Pump mount and motor mount attachment



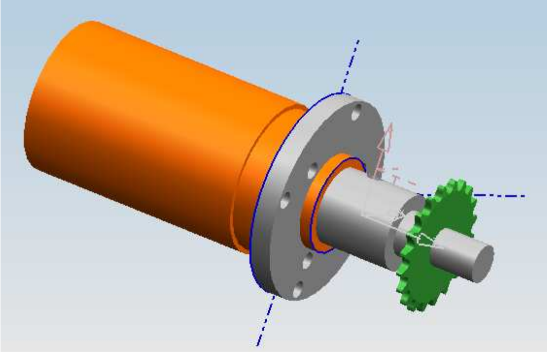
The jigging process for the welding of these mounts can be seen below in Figure 43.

Figure 43: Jig for pump mount

The sprockets for the pump motors will be attached to the shaft extension by means of a shrink fit. This will consist of heating the sprockets to 200 C, making their bores wider than the shaft extension. They will then be pressed onto the shaft extension and seated next to the step in the shaft. As they cool, they will create an interface pressure that will allow them to transmit torque.

After the sprockets are placed on the shaft extension, the shaft extension will be attached to the shaft of the pump motors. This will be done using a shoulder bolt, matching the hole on the pump shaft with the hole on the shaft extension. The foregoing processes will be done to both of the pump motors.

Figure 44: Pump motor with shaft extension and sprocket

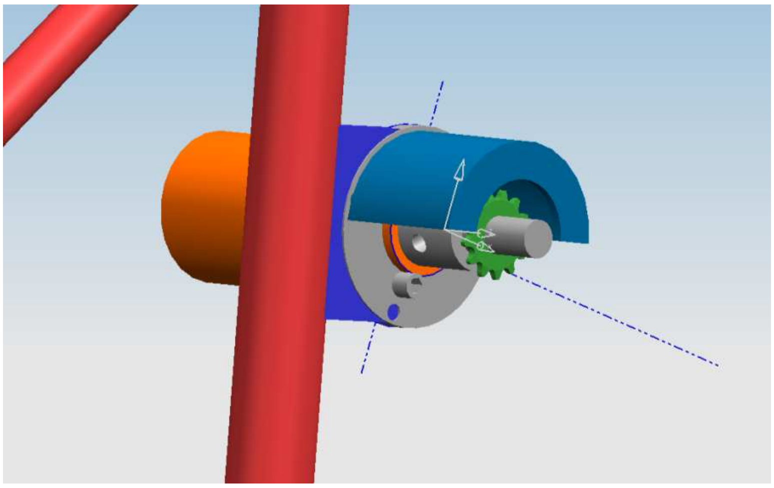


Next, we will assemble the bearing carrier. To begin, the bearing support flange and tube will be welded together in the same process as welding the bearing support tube to the pump mount.

This will hold the forces that will be applied to the bearing. The pump will then be placed inside of the pump mount and the bearing holder attached to the bearing support flange to ensure proper alignment. The jigging process for the welding process can be seen below in Figure 45. After which, the bearing holder will be taken off of the bearing support. This configuration can be seen in Figure 46. The motor will also be attached to the motor mount in the same fashion as the pump to the pump mount.

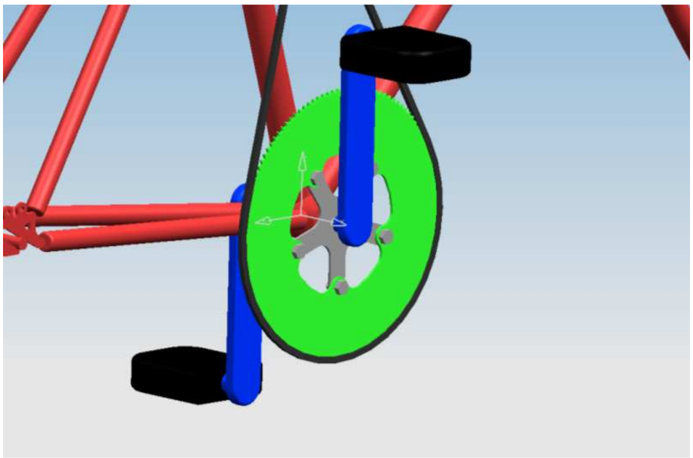
Figure 45: Jigging process for welding the bearing support tube and flange to pump mount

Figure 46: Attachment of pump and bearing support to pump mount



Before moving any further with the bearing carrier assembly, we must first attach the pedal sprocket to the pedals. This will be done using the original sprocket bracket that came with the bike. The sprocket will be bolted onto the bracket, which will then be attached to the pedal shaft. The assembly can be seen below.

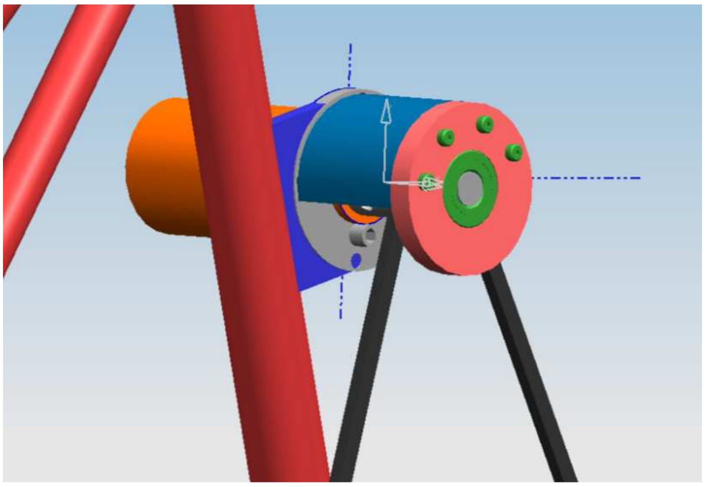
Figure 47: Pedal assembly



The chain will be set around the pump sprocket and pedal sprocket, creating a mechanical connection between the two.

The bearing must then be press fit into the bearing holder. The bearing holder will then be bolted to the bearing support, with the shaft extension going through the bore of the bearing, as seen below, completing the assembly of the bearing carrier.

Figure 48: Complete assembly of the bearing carrier and pump assembly

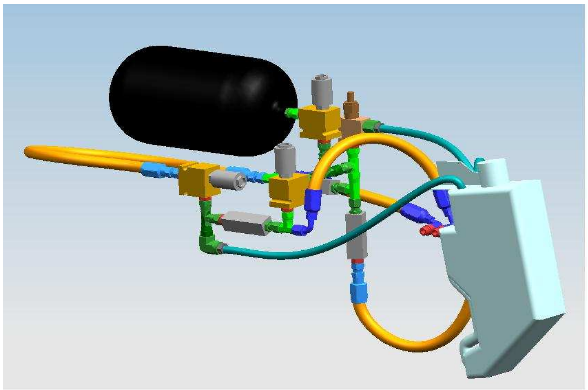


Next, the old gear hub tabs must be replaced with the new gear hub tabs. This will be done by disassembling the gear hub, and isolating the ratcheting piece. The old tabs are held on by e-clips, which can be taken off using a screwdriver. Once the new tabs are in place, the gear hub must be reassembled. At this time we will be attaching it to a new wheel. The attachment process will be done externally by BLUElab member Aidan Feldman.

After the rear wheel has been constructed, we must attach the rear sprocket. Because the hub has a very characteristic mounting of sprockets, we will be using the welding the old sprocket to our rear sprocket. This assembly will then be attached to the rear hub in the same fashion that the sprockets that came with the hub are attached. The wheel will be placed in the rear wheel holder on the frame. The chain will then be set around the motor sprocket and rear sprocket connecting the two parts mechanically.

The next subsystem up for assembly is the hydraulic subsystem. This will consist of attaching the hoses to the fittings, and the fittings to their respective valves, pump motors, pressure gauge and accumulator. This will be done using a wrench with an awareness of the proper torque levels for each fitting. The final assembly of this system can be seen in Figure 49.

Figure 49: Assembly of hydraulic subsystem



We must now attach the hydraulic subsystem to the bike itself. The low-pressure reservoir will be attached to the bike frame via cable ties. The accumulator and fittings will be resting on the rear rack of the bike, with the accumulator contained by a Coke rack designed to hold 24 20oz. plastic Coke-containing Coke bottles, but it could have Dr Pepper, depending on the geographic region. The Coke rack will be attached to the rear rack by means of steel bolts, and the accumulator will be strapped into the Coke rack thereafter. The valves, fitting, and hoses will be supported by the accumulator. To protect against vibration, we will be placing damping material beneath the accumulator.

Lastly, we must assemble the electrical subsystem. This will be placed in a basket hanging from the bikes handlebars, so that must first be attached using the instructions that have come with the basket. We must also construct the logic circuit that will be responsible for the controls. This will be done using wire-cutters and solder, and all components other than the valves, switches, and battery will be attached to perfboard. The wiring diagram for this can be seen in Appendix L. The valves have already been assembled as part of the hydraulic subsystem, the switches will be cable-tied to the handlebars, and the battery will be placed in the basket near the perfboard. The perfboard and battery will be strapped down to make sure that movement does not affect their connections/functioning. An electric speedometer will also be attached to the bike to monitor its speed. The mode-selecting buttons will be mounted to the handlebars using the acrylic button brackets, which will be mounted to the handlebars of the bike using bolts. The attachment of these brackets can be seen previously in the report in Figure

PROJECT PLAN

With the goal of entering the Chainless Challenge competition, we felt it would be good for us to research previous designs of vehicles with regenerative braking and launch assist features. Although their project was much different from ours, we met with last semester’s ME450 team to discuss what they learned from their project. We have also set up a meeting with David Swain at the EPA to inspect previous vehicles with regenerative braking and launch assist.

With our largest challenge on this project being the lead time on the components, our first and most important milestone is to nail down our design and engineering specifications. If parts are not ordered early it is a possibility we won’t receive them in time for the Design Expo. We will finish the specifications and order the pump, motor, and valves by September 30. The less specialized components in our design (hoses, fittings, etc.) do not have large lead times, so they can be ordered in late October.

In the time between ordering and receiving our parts we will be creating the CAD files and any numerical analysis that may be required. At this time we will also be creating the manufacturing plans and scheduling when each piece gets machined. This will allow us to begin machining the major components no later than November 6. With this timeframe we will be able to begin assembling on November 23. This allows us two and a half weeks to test, trouble shoot, re-machine, and fine tune before we present the final prototype at the design expo on December 10.

A summary of milestones appears in Table 6 below.

Table 6: Summary of Milestones

Milestone	Date
CAD fine tuned	10-31
Order hose and fitting	11-2
Purchase raw material	11-4
Begin machining	11-6
Decide mechanical or electrical valve	11-15
Gear hub fixed	11-22
Begin assembling	11-23
Valve actuation complete	12-5
Design Expo	12-10
Chainless Challenge competition (tentative)	3-25

A current major task is to finish the CAD model. We have drawn the bicycle and placed major components such as sprockets, pump motors, accumulator, and rack. We still need to add valves and route hose. Once CAD is complete, we will know hose lengths and end types. Although we previously had planned to finish CAD by November 5, we have decided to accelerate its completion to October 31 so that we can order hose and fittings on November 2. The CAD model will also help us decide what raw materials to purchase. We plan to purchase raw material by November 4 in order to begin machining November 6. Phil and Chris will complete the CAD, create a manufacturing plan, and purchase raw materials. Henry will order the hose and fitting.
We have determined the part to remanufacture to disable the freewheeling of the Shimano gear hub. By October 30, we will have created a CAD model and manufacturing plan for it. Andrew will be in charge of designing, manufacturing, and installing this part. We may decide to cut this part on a water jet. In this case, we have allowed ample time in advance of our November 22 deadline to gain access to the machine. We have set this deadline early enough to be able to install the hub in a new wheel in advance of the Design Expo.

Although the solenoid poppet valves may not arrive until December, we will have decided if we will actuate them mechanically or electrically by November 15. Following this decision, we will purchase either a battery and switches or cables and levers. Henry will conduct a preliminary investigation of the possibility of mechanical actuation. If he determines mechanical actuation is not practical, Andrew will design an electrical control system. The entire valve system will be installed by December 5.

We have ordered all major hydraulic parts. We still need to order hose, fittings, bicycle parts, chain and sprocket, and possibly electrical supplies for the valve. Phil will order the chain and sprocket, and Henry will order the hose and bicycle parts. Hose and fittings should take no more than four weeks to arrive, and the remaining supplies should take about a week.

Since Design Review 2, we have updated our schedule as shown in Table 7 to identify all major manufacturing operations.

We hope to be able to give the weekend of November 21 to a BLUElab member to assemble the rear gear hub and the wheel, which he has purchased. Henry and Phil will be able to access the Wilson Center during Thanksgiving break to machine the sprockets, shaft extensions, and the mounts for the pump motors and bearing. After these machining processes are complete, we will move on to assembly. Andrew will solder the circuit board, and Henry will prepare the accumulator for use and assemble hydraulic fittings. Phil will cut the hydraulic hose. Chris will be in charge of securing the accumulator to the rack and painting.

Table 7: Project plan with dates

Milestone	Date
Fix gear hub	11-20
Machine sprockets	11-20
Assemble gear hub on wheel	11-23
Turn bearing shaft	11-29
Machine and weld pump and bearing mounts	11-29
Press fitting	11-29
Circuit board and electrical assembly	12-3
Assemble hydraulic system	12-5
Design Expo	12-10

We have obtained all of the parts in the bill of materials except for those that will be bought at the local hardware store, the electronic components, one pump motor, and three poppet valves. The two normally open poppet valves are scheduled to ship November 24, and the normally closed poppet valve is scheduled to ship December 8. We have borrowed a valve from the EPA to use, in case ours does not arrive in time for prototype testing.

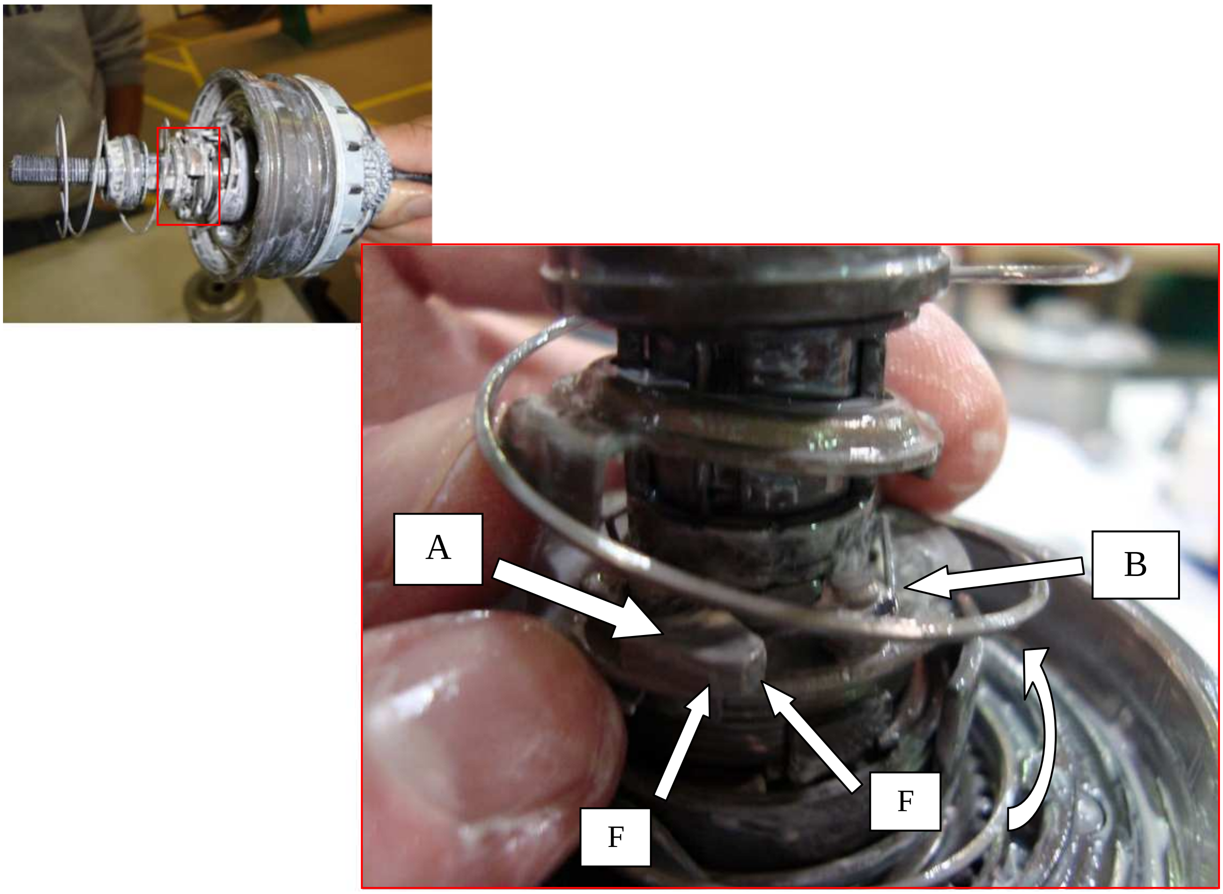
CHALLENGES

Aside from the difficulty of the engineering goal at hand, one of the largest and most evident challenges is the lead time on the components needed to construct the system. It is also important to find components, like the pump and motor, which are efficient and meet our desired specifications. The manufacturing time is also very limited and the complexity of the project will most likely require an above average allowance for manufacturing. Also, we want to make the bike reliable which is difficult to achieve in many first time prototyping scenarios. Similar projects have been attempted many times in the past, but they have not functioned reliably or even at all. Finally, safety is one of the most important parameters of this project. For this reason, the manufacturer recommendations and safety factors are taken very seriously. The high pressures in a very complex system can be a safety risk, but with proper safety precautions, the risk of injury can be greatly reduced. In order to overcome these challenges, we have set up a Gantt chart which will be strictly followed in order to keep the team on track towards the goal.

Rear wheel hub

As previously stated, we have intended to use the Shimano Nexus 8 as our rear gear system, but have run into the problem of disabling its freewheeling capabilities. In order to find which part of the hub causes the freewheeling, we have both taken the hub apart, and contacted the technical department at Shimano. The people at Shimano helped us by pointing us toward the proper components, and after some tinkering we have found that the components seen in Figure 50 are responsible for the freewheeling properties of the Nexus 8 gear hub.

Figure 50: Internal functioning of gear hub



On the internal assembly of the gear hub, there is a ratcheting system comprised of a mono-directional engagement piece, part “A” in Figure 50, and a torsion spring, part “B”. Face 1 (F1) engages when rotating in direction shown, and torque can be translated. However, when spinning in the opposite direction, the geometry of part A allows for the surrounding gear to pass over Face 2 (F2) and deflect the torsion spring. This allows for no torque to be translated and the hub “freely” spins around the internal assembly. Although we have identified the pieces of the system that are relevant to the hub’s free-wheeling, we are still in the process of developing a new design that will engage in both angular directions.

If we are unable to disable freewheeling on the internal gear hub, we may use two interchangeable wheels. One would have a fixed gear for use in events where regenerative braking is important, and the other would have the internal gear for events where being able to shift gears is important.

Integration of this hub into the bike will also be a challenge, albeit a small one. The Shimano hub will not fit on the current wheel, so we will need a new wheel built. We have found a vendor willing to do this for $100, or a BLUElab member has volunteered to do it. It may take several days or more to build the new wheel.

Radial load on pump motor shaft

The Parker pump motors are designed to support up to 222N of radial load on their shafts. With a large gear ratio and small sprocket on the pump’s shaft, we may exceed this force. Thus, bearings will be necessary to support the radial load. The challenge is to find bearings that are strong enough to support the extra force of 380 N yet small enough to mount on the pump’s 19mm long shaft. Additionally, mounting them without interfering with the sprocket will be difficult.

Competition currently cancelled

Parker has informed us that they are cancelling the 2010 Chainless Challenge competition because of a lack of commitment from other teams. This decision may affect our eligibility to receive donated product from Parker or other sponsors. We hope to be able to make Parker reconsider its decision or at least hold a scaled back competition and provide still donate what it has committed.

Valves

The Eaton Vickers solenoid valves we selected are designed to be either open or closed with no intermediate partially open position. They also require a supply of electricity to remain in one position. Converting these valves to be manually actuated via a cable would be ideal because it would allow the rider to throttle them open and would eliminate the need for a battery. However, this may not be possible to do safely.

Accumulator

Parker has offered to donate a carbon fiber accumulator rated for 21 MPa. However, we have been designing our system to operate at 34 MPa, so using this accumulator will require us to either reduce the system pressure or add an extra relief valve. We could purchase our own accumulator, but a steel accumulator rated for our pressures has a mass of 23kg.

Hose and Fittings

Parker has agreed to donate hose and fittings. We must specify the type and length hose in advance and must be careful to order the correct length because changing the hose length later will be costly.

Since Design Review 2, we have overcome many of the old challenges and some new challenges have emerged. We have developed a strategy for fixing the rear gear hub. We have designed a carrier bearing for the pump shaft to reduce the load and the motor gear ratio was modified to keep the loads low. We have decided that we will operate the valves electronically because of safety. The hoses and fittings have been drawn in CAD, ordered, and received.

The new challenges primarily consist of communication challenges with Parker. We sent Parker a letter about the status of the completion and we are currently working with them on possible solutions. This letter can be found in Appendix K. We hope to have the competition rescheduled or gain their support in a hydraulic bicycle exhibition which we would organize here in Ann Arbor. We have just received a 3.5 gallon accumulator from Parker, when we were expecting a 1 gallon accumulator. This is much larger than the one we currently have in our CAD model and therefore it may cause new mounting challenges. Also, we are still waiting to receive one pump motor from Parker.

Other challenges include receiving the valves, manufacturing with tight tolerances and safety considerations. As mentioned previously the poppet valve delivery times have been delayed. Many of the components will require careful machining as well as precise jigging for the welded parts. We are also considering possible safety issues that may arise during the testing of the bike and ways to prevent them.

TESTING PROCEDURES

Low Pressure Testing

Once our hydraulic assembly has been completed, we will fill our reservoir with the Pennzoil automatic transmission fluid, and pump it into the hydraulic system by spinning the pedals. The bike will be lifted and leaned to try and free the air from being trapped in the system. The bicycle will be placed on a bicycle trainer to allow for stationary pedaling of the bike. This will require no valve actuations, and will not reach pressures that could possibly cause harm during a failure. During the low pressure testing, we will only be able to employ our "pedal" mode of operation. This will demonstrate the hydrostatic drive capability of our system but not its regenerative or energy storage capabilities. These will be employed through our other modes of operation during high pressure testing.

High Pressure Testing

After the system has successfully been filled with fluid, and pedal mode has been validated, we will begin using different valve positions to achieve higher pressures. All subsequent tests will involve safety glasses and a keen awareness of the state of our system. High pressure failures can be catastrophic, so we will need to be very careful. The first part of these tests will still be done on the bicycle trainer. "Charge" mode will be employed, and the pedals will be turned, sending pressurized fluid to the accumulator. We will then release the stored energy of the accumulator by employing "accelerate" valve positions, and if the rear wheel spins, this will validate both the charge mode and the accelerate mode. To test "brake" mode, we will spin the rear wheel with the valves set in "brake" position, emulating the reverse torque applied to the motor when slowing down. We will then apply the accelerate mode again, and if the rear wheel spins, brake mode will be validated as well. At this point, the bicycle is ready for on-road testing. This will require dry weather and an open space. We are not planning on doing on-road testing for ME 450. This will need to be done next semester by BLUElab members.

VALIDATION RESULTS

Preliminary testing was done by attaching the bicycle to a stationary bicycle trainer. We were able to show that the hydrostatic pedaling mode worked. This was tested by having the rider simply turning the pedals while in "pedal" mode, which resulted in the rear wheel turning. However, when pedaled at lower speeds, the motor did not turn. We believe this is due to air in the lines because the pump should always displace a constant volume of fluid per rotation. Further bleeding of the lines will need to be done in order to fix this problem. We were also able to verify correct operation of valves in "charge" mode but were unable to store any fluid within the accumulator. When pedaling the pressure gauge showed pressure jumps of up to 13 MPa, but when the rider stopped pedaling the pressure quickly dropped. We believe this pressure is from air in the system being compressed, so again, further bleeding is necessary. Also, the torque the rider felt when pedaling at 13 MPa was moderate, validating that a rider could pedal at 21 MPa with the gear ratios chosen.

DISCUSSION (DESIGN CRITIQUE)

Figure 51: Team Members with Final Prototype

The key strengths of our design are the high efficiency pumps we have and the ability to recapture energy through regenerative braking. Previous hydraulic bicycles have much larger pumps whose efficiencies are typically around 60%, while our pumps operate at 92% efficiency. Physically, this means that much more of the work put into our system is returned as compared to previous teams' systems. Also, this is the first series hydraulic hybrid bicycle that we know of that incorporates regenerative braking.

The main weaknesses of our design are its complexity, rideability, and safety. Having the five modes of operation makes the hydraulic and electric control system complicated. This makes troubleshooting any problems with the bike difficult to locate and possibly hard to fix. The weight and placement of the accumulator makes the bicycle cumbersome. This will make it harder for the rider to stay upright when starting to pedal from a stop. Also, cornering will be difficult. In the event that the bicycle is in a crash there is concern for the rider's safety. Some of the fittings would impact with the road and they could fracture or develop a leak, which would expose the rider to fluid at pressures up to 21 MPa.

Given the opportunity to do this project again, we would have looked into a three wheeled bicycle. In our current design we have a heavy accumulator that is placed on a high spot on the bike. This is not ideal for a bike that is intended to be entered into a race. A three wheel bicycle would allow for the accumulator to be placed much lower on the frame and would have little effect on the center of gravity of the bike. A three wheeled bike would be better for packaging the rest of the hydraulic components and would better shield the rider from any high pressure leaks. A downside to this design is it would be heavier, have more rolling resistance, and be less aerodynamic.

RECOMMENDATIONS

We recommend that a bleeder valve be installed within the hydraulic system. This would make bleeding the lines of air easier and more effective. We also recommend that more research go into disabling the freewheel feature of the gear hub. Having a fixed gear hub would allow the rider to optimize accelerating and regenerative braking by simply changing the hub gears.

SUMMARY / CONCLUSIONS

Our team has set out with the goal of building a hydraulic bicycle capable of winning the Chainless Challenge competition sponsored by Parker Hannifin. Hydraulic bicycles have been experimented with extensively in ME 450, however our design will incorporate a complete hydraulic drive with regenerative braking. We began the design by calculating target specifications for our major components and outlining the timeframe for when objectives need to be completed by. We then fine tuned the specifications and evolved them into an alpha design, while remaining conscious of the accelerated deadlines. This alpha design has evolved into a final design from which the prototype was built. We were able to verify that all of the modes of operation function correctly, but the bicycle will still need further refinement to achieve its full potential. With further fluid bleeding, testing, and system refinement, we believe our prototype will be efficient, safe, and capable of winning the Chainless Challenge competition.

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ACKNOWLEDGEMENTS

Prof. Steven Skerlos – Advice and encouragement throughout this semester.

MRacing Formula SAE Team – Providing manufacturing assistance and use of its equipment.

Aidan Feldman – Consultation on bicycle components and building the wheel to house the internal gear hub.

Pete Washabaugh and Wilson Center Staff – Accommodating our presence in the Wilson Center.

David Swain, Dr. Andrew Moskalik and the rest of the people at the Ann Arbor EPA – Technical advice, services, and loaning parts.

Andrew Richardson – Provided electronics advice.

Winter ’09 ME 450 – Discussed practical experience with hydraulics.

Steve Hannon – Donated the bicycle used for project.

Amanda Gaytan – Administrative support.

Marvin Cressey – Assisted with laser cutter.

Parker Staff – Loaned accumulator and donated hose and fittings.

Shimano – Donated internal gear hub and provided support with disassembly.

BIOGRAPHIES

Andrew Berwald was born in Grand Haven, MI, on December 15, 1986. He lived there for his entire pre-college education, where his interests lied in math, science, art, history, and film-making. Upon reaching college, Andrew started out in LS&A here at the University of Michigan as a History major, but soon transferred into Mechanical Engineering. His hobbies and interests include skiing, skateboarding, music, product design and sustainability. After graduating from college, his short-term plans include film-making, music, skateboard production, while trying to ski as much as possible. As he gets older, he hopes to use his engineering degree in alternative energy and transportation, with the possibility of going to law school at some point.

Phillip Bonkoski, born on September 16, 1987, has lived in south eastern Michigan his entire life. At a young age he discovered his passion for all things mechanical. His parents have accused him of disassembling everything he could get his hands on from as young as five years old. As a child he loved to ride his bicycle, but soon he discovered how cool vehicles with motors on them could be. From then on he has had countless motorcycles, three wheelers and four wheelers. It was inevitable that he would fall in love with cars by the time he was sixteen. At an early age he also began helping out at the family automotive repair business. He continued working there through his first two years of college at Monroe County Community College. Then he transferred to the University of Michigan, College of Engineering, to pursue his degree in Mechanical Engineering. At Michigan he has been very involved with the Formula SAE team, where he has made contributions in the areas of engine subsystem development and general engine repair and assembly. Upon Graduation he hopes to work on development of internal combustion engines.

Henry grew up in Minneapolis, Minnesota. Although none of his family has a mechanical background, he has always enjoyed building and fixing things. In addition to being a founding member of the Chainless Challenge team with BLUElab, he previously participated in the Challenge X competition. Henry recently participated in the Research Experiences for Undergraduates program where he built a system to allow a pneumatic orthosis to become portable and function untethered. He also completed an internship working on reverse osmosis water filters at FilmTec Corporation and built pallets for a Coca-Cola bottler. After finishing school, he hopes to work in the fluid power industry.

Chris was born and raised in Grand Rapids, Michigan. As a child he was always involved with sports. You name it, he played it. Consequently, he didn't care much about his education, but he had a knack for math and physics while in high school. It wasn't until he was a freshman at Grand Rapids Community College that he began to take school seriously. His tennis coach, who is also an engineer and graduate of the University of Michigan, had many conversations with Chris about engineering and the quality of a U of M education. As Chris took pre-engineering classes he found that each one was better than the last, and took an interest in the field of mechanical engineering. Following the advice of his tennis coach, he transferred to U of M in the fall of 2007 and will graduate in December 2009. He is interested in getting a job involving the use of numerical analysis to solve either solid or fluid mechanics problems.

REFERENCES

[1] http://www.tpub.com/content/construction/14273/css/14273_219.htm

[2] http://www.duccutters.com/HydraulicInnovations-HydrostaticChopper/HydrostaticMotor.jpg

[3] http://jcwinnie.biz/wordpress/?p=1178

[4] Eaton Corp., 2008, Accessed: 9/22/2009, "Hydraulic Launch Assist: Refuse Truck". <http://www.eaton.com/ecm/groups/public/@pub/@eaton/@roadranger/documents/content/ct_168261.pdf>

[5] Bary, D., Fanning, C., 2007, Accessed: 9/22/2009, "EPA Unveils UPS Delivery Truck with 60 to 70 Percent Higher Fuel Economy". <http://yosemite.epa.gov/opa/admpress.nsf/bb53edc81304e30f852573590040b7f4/647f24072014856f852571b000613a97!OpenDocument>

[6] Patent #5,772,225, "Hydraulic Bicycle with Conjugate Drive Motors", as seen on http://www.google.com/patents.

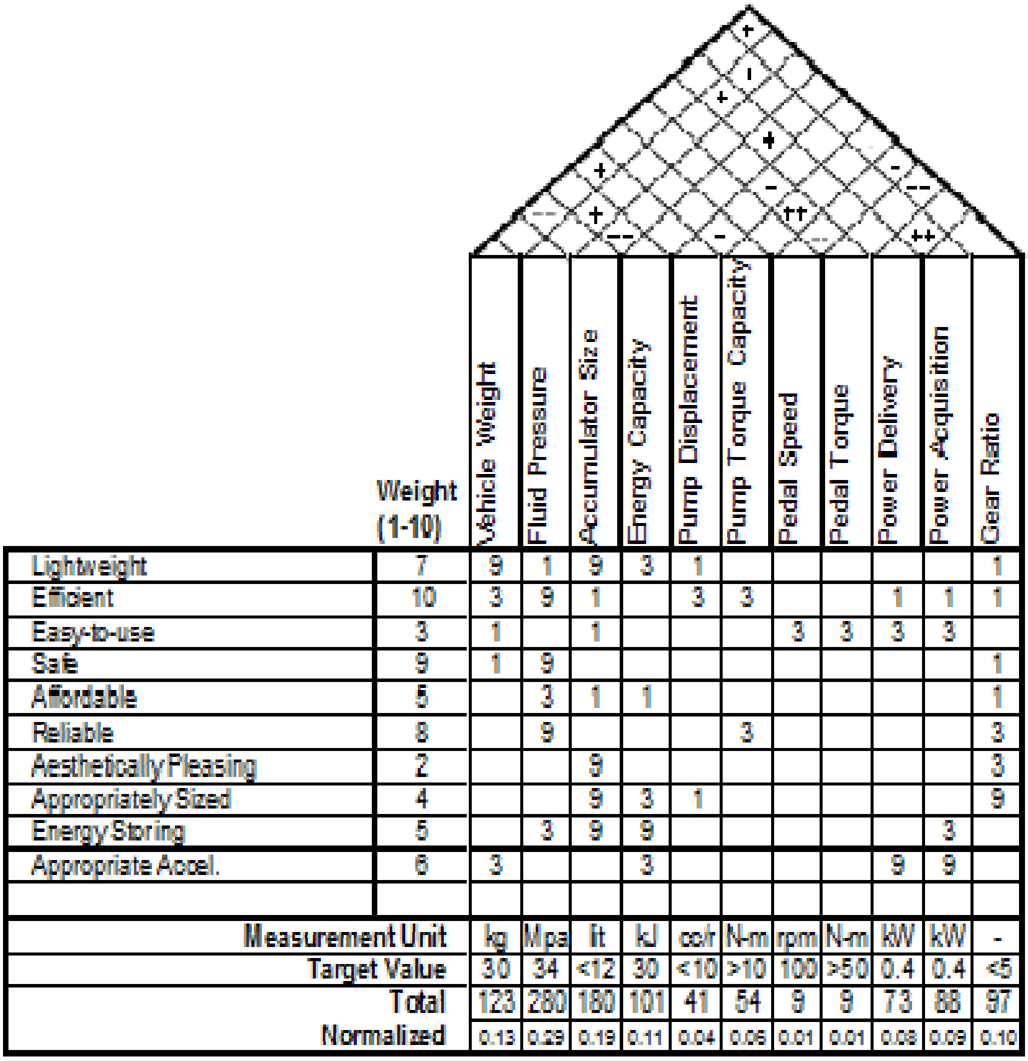
[7] Patent #4,942,963, "Electrohydraulic/Air Bike", as seen on http://www.google.com/patents.

[8] D'Souza, B., Kneifel, A., Singh, V., Williams, M., Winter Semester 2009, "Optimizing a Hydraulic Regenerative Braking System for a 20" Bicycle Wheel". <http://hdl.handle.net/2027.42/62476>

[9] Meeting with Winter 2009 team. 9/23/2009

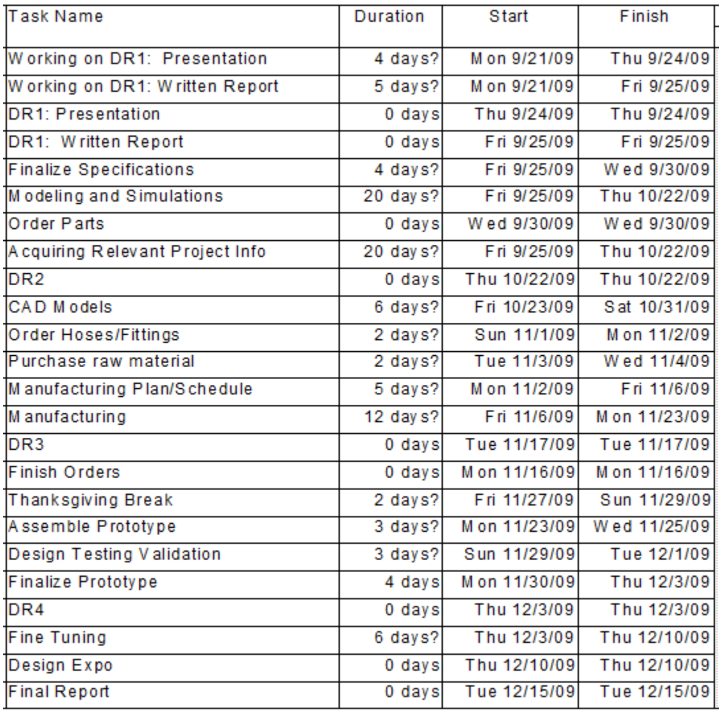
[10]http://bike.shimano.com/publish/content/global_cycle/en/us/index/products/0/nexus/product.-code-SG-8R36.-type-.html

APPENDIX A: QFD

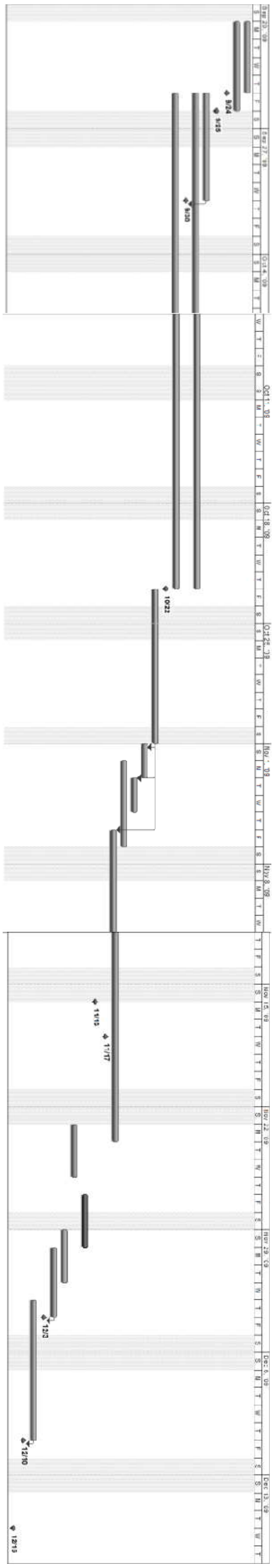


	Weight (1-10)	Vehicle Weight	Fluid Pressure	Accumulator Size	Energy Capacity	Pump Displacement	Pump Torque Capacity	Pedal Speed	Pedal Torque	Power Delivery	Power Acquisition	Gear Ratio
Lightweight	7	9	1	9	3	1						1
Efficient	10	3	9	1		3	3			1	1	1
Easy-to-use	3	1		1				3	3	3	3	
Safe	9	1	9									1
Affordable	5		3	1	1							1
Reliable	8		9				3					3
Aesthetically Pleasing	2			9								3
Appropriately Sized	4			9	3	1						9
Energy Storing	5		3	9	9						3	
Appropriate Accel.	6	3			3					9	9	
Measurement Unit		kg	Mpa	lit	kJ	cc/r	N-m	rpm	N-m	kW	kW	-
Target Value		30	34	<12	30	<10	>10	100	>50	0.4	0.4	<5
Total		123	280	180	101	41	54	9	9	73	88	97
Normalized		0.13	0.29	0.19	0.11	0.04	0.06	0.01	0.01	0.08	0.09	0.10

APPENDIX B: GANTT CHART



Task Name	Duration	Start	Finish
Working on DR1: Presentation	4 days?	Mon 9/21/09	Thu 9/24/09
Working on DR1: Written Report	5 days?	Mon 9/21/09	Fri 9/25/09
DR1: Presentation	0 days	Thu 9/24/09	Thu 9/24/09
DR1: Written Report	0 days	Fri 9/25/09	Fri 9/25/09
Finalize Specifications	4 days?	Fri 9/25/09	Wed 9/30/09
Modeling and Simulations	20 days?	Fri 9/25/09	Thu 10/22/09
Order Parts	0 days	Wed 9/30/09	Wed 9/30/09
Acquiring Relevant Project Info	20 days?	Fri 9/25/09	Thu 10/22/09
DR2	0 days	Thu 10/22/09	Thu 10/22/09
CAD Models	6 days?	Fri 10/23/09	Sat 10/31/09
Order Hoses/Fittings	2 days?	Sun 11/1/09	Mon 11/2/09
Purchase raw material	2 days?	Tue 11/3/09	Wed 11/4/09
Manufacturing Plan/Schedule	5 days?	Mon 11/2/09	Fri 11/6/09
Manufacturing	12 days?	Fri 11/6/09	Mon 11/23/09
DR3	0 days	Tue 11/17/09	Tue 11/17/09
Finish Orders	0 days	Mon 11/16/09	Mon 11/16/09
Thanksgiving Break	2 days?	Fri 11/27/09	Sun 11/29/09
Assemble Prototype	3 days?	Mon 11/23/09	Wed 11/25/09
Design Testing Validation	3 days?	Sun 11/29/09	Tue 12/1/09
Finalize Prototype	4 days	Mon 11/30/09	Thu 12/3/09
DR4	0 days	Thu 12/3/09	Thu 12/3/09
Fine Tuning	6 days?	Thu 12/3/09	Thu 12/10/09
Design Expo	0 days	Thu 12/10/09	Thu 12/10/09
Final Report	0 days	Tue 12/15/09	Tue 12/15/09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Sep 27, '09
Oct 4, '09
Oct 11, '09
Oct 18, '09
Oct 25, '09
Nov 1, '09
Nov 8, '09
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Nov 22, '09
Nov 29, '09
Dec 6, '09
Dec 13, '09
9/24
9/25
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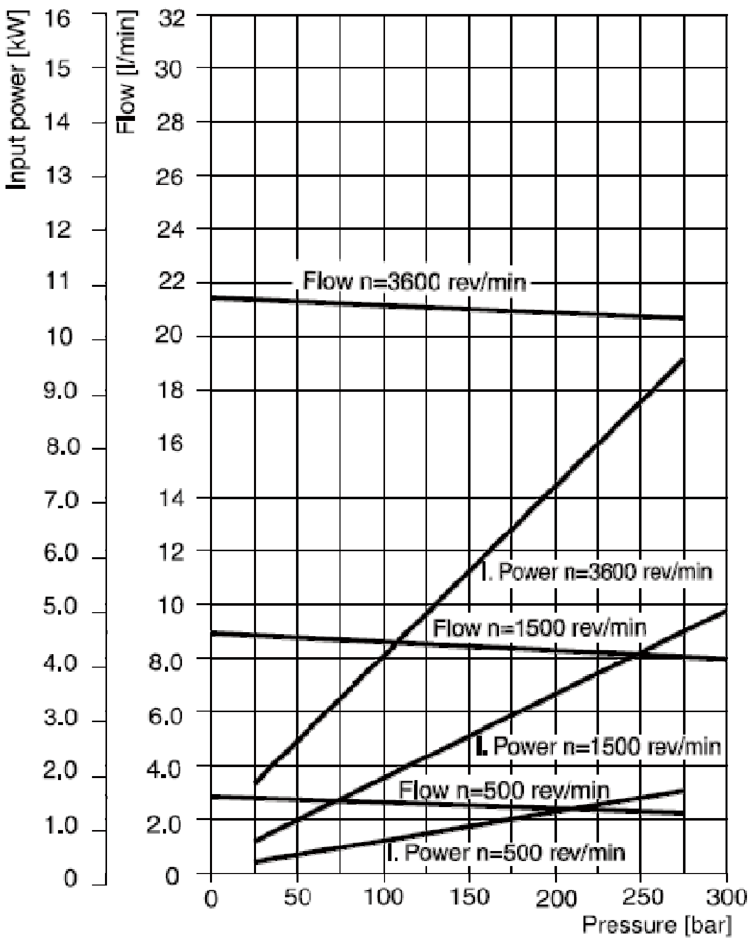
12/3
12/10
12/15

APPENDIX C: PERFORMACE CURVE FOR LARGER DISPLACEMENT PUMP

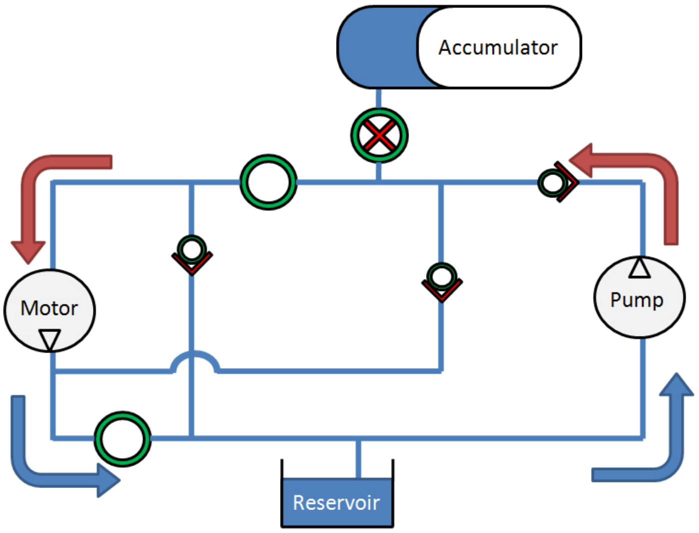


APPENDIX D: HYDRAULIC SCHEMATICS

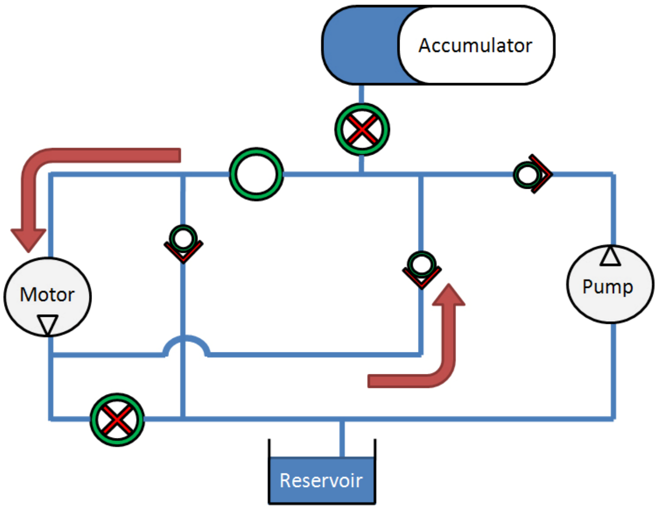
Hydraulic Schematic with Respective Fluid Flows/Pressure for Each Mode

In each of the diagrams, the following conventions can be used to understand what is pictured. A red arrow indicates high pressure flow, whereas the blue arrow indicates low pressure flow. A green circle with a red X indicates a closed valve, while the absence of the X indicates an open valve.

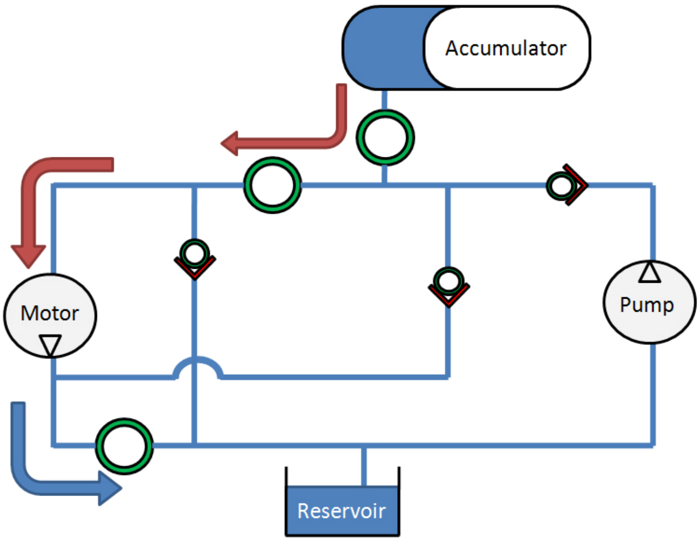
- **Pedaling**



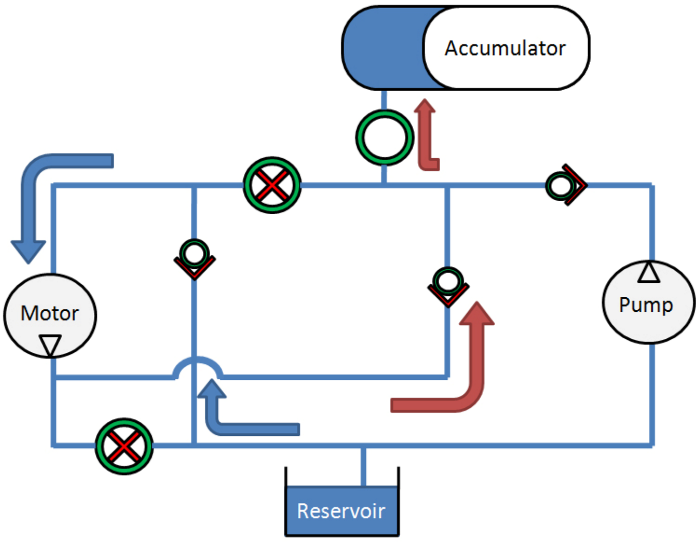
- **Coasting**



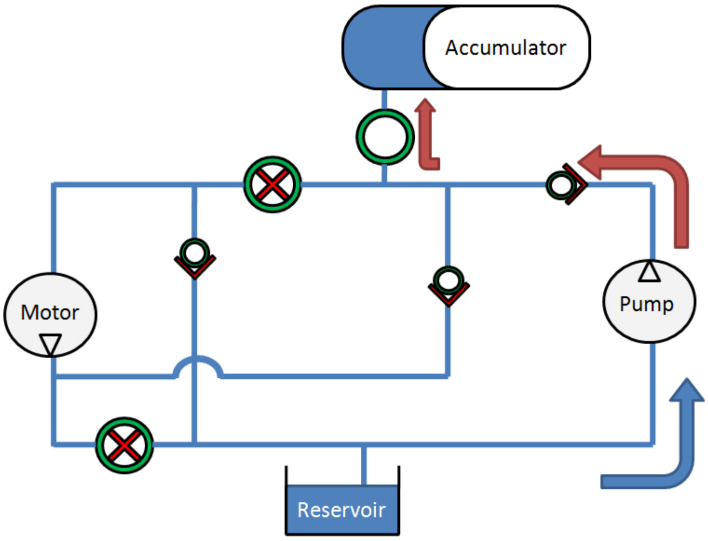
- **Accelerating**



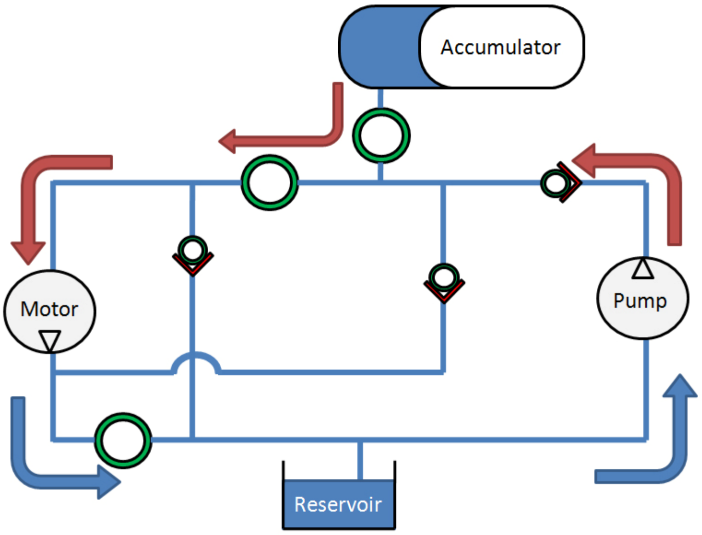
- **Braking**



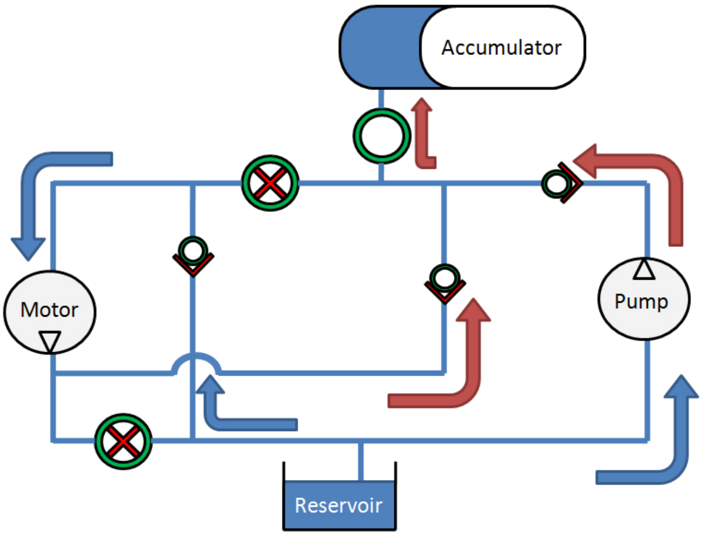
- **Charging**



- **Parallel Mode: Accelerating/Pedaling**



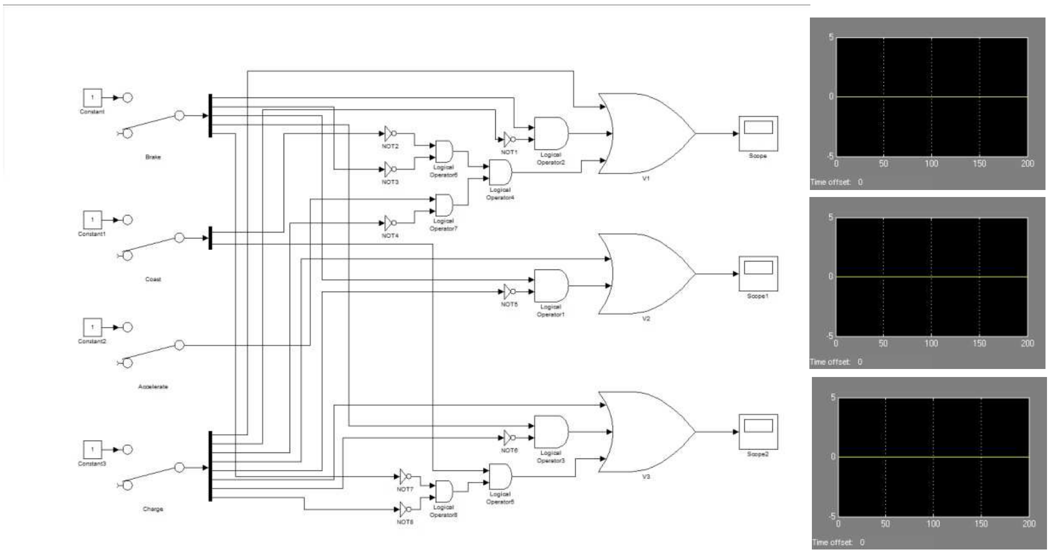
- **Parallel Mode: Braking/Charging**



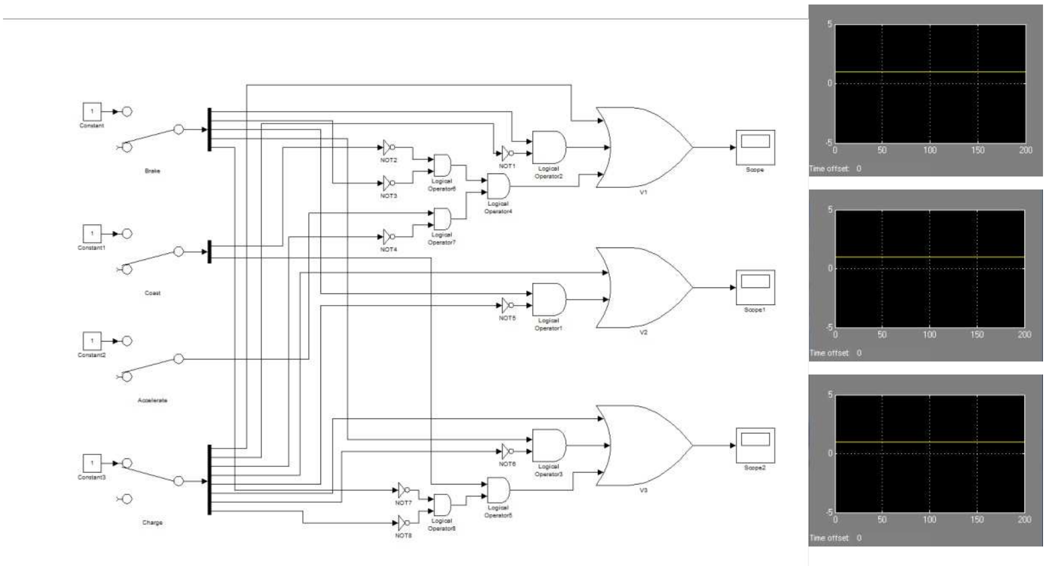
APPENDIX E: SIMULINK MODEL OF LOGIC CIRCUIT

This appendix will demonstrate the Simulink model of our logic circuit. On the left side of the model, one can see which of the switches are closed. On the right side, the outputs of each of the scopes are shown. When the output equals one, this means that the system will apply voltage to that valve. The switches on the left side are “brake”, “coast”, “accelerate” and “charge” from top to bottom. The scopes on the right side represent “Valve 1”, “Valve 2” and “Valve 3” from top to bottom as well. Notice that the logic system successfully follows the mode priority explained in the “Electrical Subsystem” section.

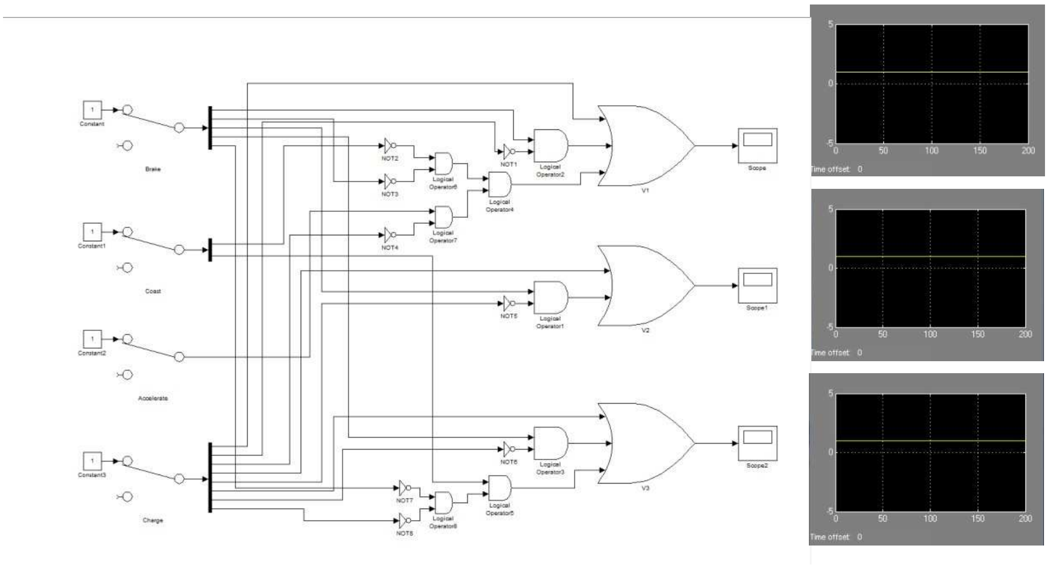
Zero switches closed; “pedal” mode; zero valves powered



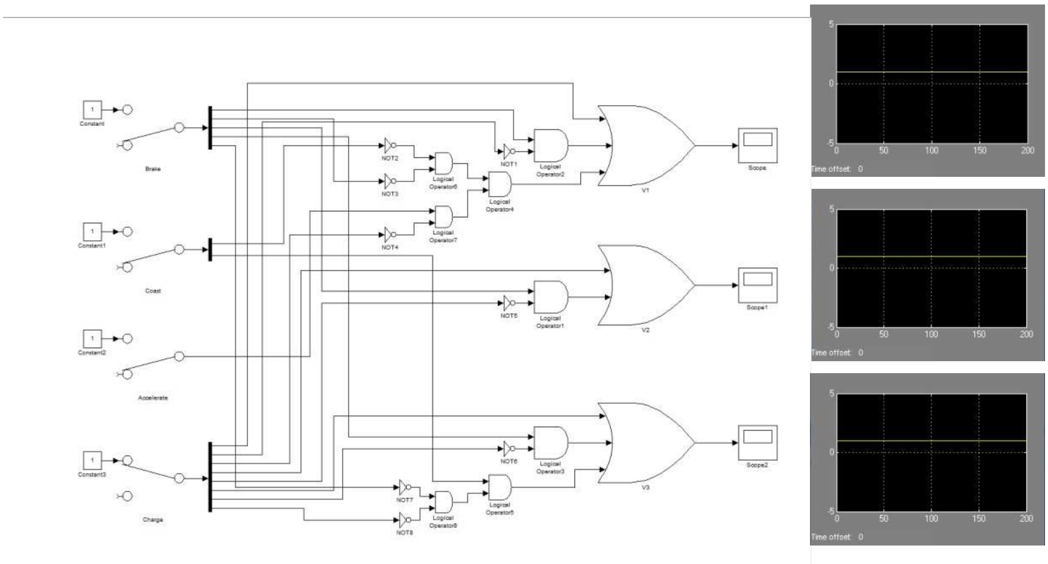
Charge switch closed; “charge” mode; all valves powered



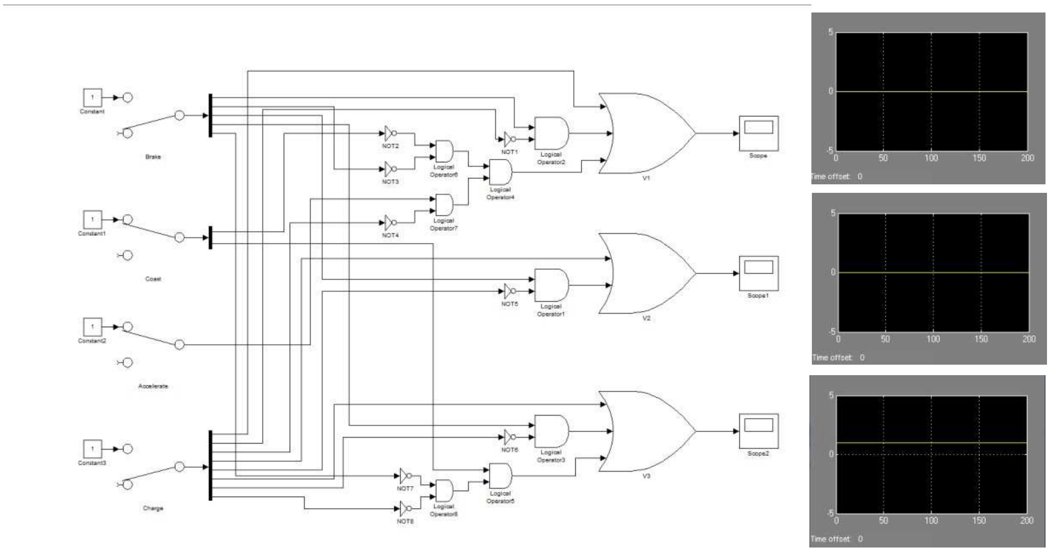
All switches closed; “charge” mode; all valves powered



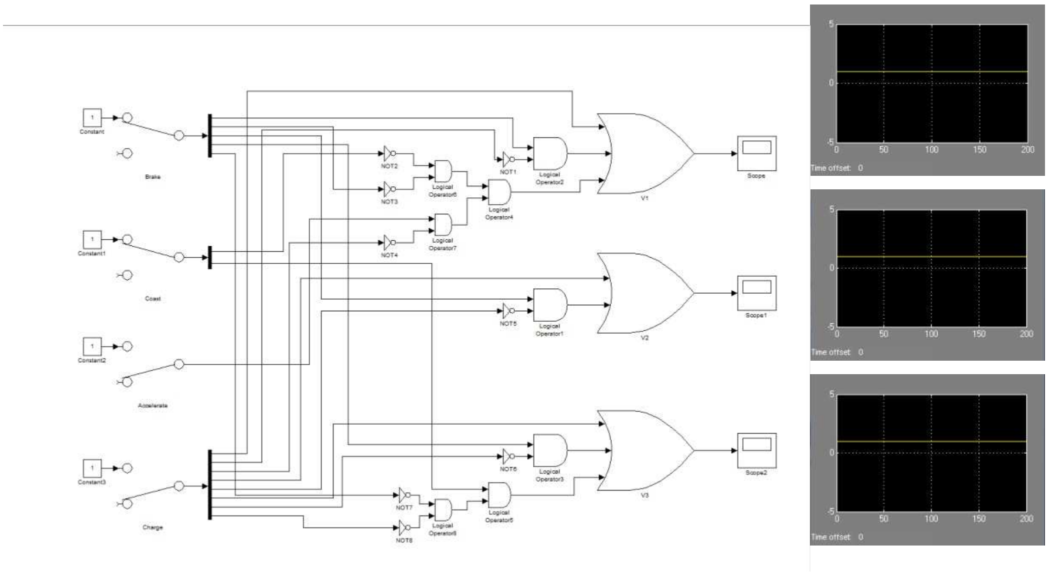
Accelerate switch closed; “accelerate” mode; valve 1 powered



Accelerate and coast switches closed; “coast” mode; valve 3 powered



Coast and brake switches closed; “brake” mode; all valves powered



APPENDIX F: BILL OF MATERIALS

Item	Manufacturer	Model number	Supplier	Quantity	Unit cost	Total
Bike and parts						
Bike	Raleigh		Steve Hannon	1	$ -	$ -
Internal hub	Shimano	SG-8R36	Shimano	1	$ -	$ -
Rack			Andrew Berwald	1	$ -	$ -
Basket	Pyramid		Niagara Cycle	1	$ 8.50	$ 8.50
Shipping	USPS	Priority Mail	Niagara Cycle	1	$ 6.20	$ 6.20
Wheel			Two Wheel Tango	1	$ 42.00	$ 42.00
Spokes			Two Wheel Tango	36	$ 1.00	$ 36.00
Spoke nipples			Two Wheel Tango	36	$ 0.10	$ 3.60
Tubes			Two Wheel Tango	3	$ 6.99	$ 20.97
Tire			Two Wheel Tango	2	$ 17.99	$ 35.98
Hydraulics						
pump motors	Parker	09S-E-CK-P	Parker	2	$ 670.00	$ 1,340.00
302 series #6 hydraulic hose (inches)	Parker	302-6	Parker	120	$ -	$ -
Female JIC 37° - Swivel - 90° Elbow - Short Drop	Parker	23930-6-6	Parker	6	$ -	$ -
Female JIC 37° - Swivel	Parker	20630-6-6	Parker	2	$ -	$ -
Female JIC 37° - Swivel - 45° Elbow - Short Drop	Parker	23730-6-6	Parker	4	$ -	$ -
Straight Thread Connector - 37° Flare / SAE-ORB	Parker	6 F5OX	Parker	16	$ -	$ -
Swivel Elbow Connector - 37° Swivel / NPTF	Parker	6-6 X6EF	Parker	1	$ -	$ -
Pipe Coupling - NPTF / NPTF	Parker	3/8 GG	Parker	1	$ -	$ -
MCB - Male Connector - Adapter	Parker	P6MCB6	Parker	2	$ -	$ -

MEB - Male Elbow Connector	Parker	P6MEB6	Parker	1	$ -	$ -
Female Pipe Adapter - SAE-ORB / NPTF	Parker	6-3/8 F5OG	Parker	2	$ -	$ -
MCB - Male Connector - Adapter	Parker	P3MCB2	Parker	2	$ -	$ -
TUB - Tee Union	Parker	P3TUB3	Parker	2	$ -	$ -
Swivel Nut Union Tee - 37° Swivel (all three ends)	Parker	6 JX6	Parker	2	$ -	$ -
Swivel Nut Branch Tee - 37° Flare / 37° Flare / - 37° Swivel	Parker	6 S6X	Parker	1	$ -	$ -
Swivel Nut Run Tee - 37° Flare / 37° Swivel / - 37° Flare	Parker	6 R6X	Parker	3	$ -	$ -
Swivel Straight Thread Connector - 37° Swivel / SAE-ORB	Parker	6-8 F65OX	Parker	1	$ -	$ -
Extender and Expander - 37° Flare / 37° Flare Swivel	Parker	6 XHX6	Parker	4	$ -	$ -
Femle Elbow - 37° Flare / NPTF	Parker	6-6 DTX	Parker	1	$ -	$ -
Swivel Nut Elbow - 37° Flare / 37° Swivel	Parker	6 C6X	Parker	3	$ -	$ -
Swivel Straight Thread Connector - 37° Swivel / SAE-ORB	Parker	6 F65OX	Parker	3	$ -	$ -
Worm Drive Clamp	Parker	97HC-3	Parker	4	$ -	$ -
Worm Drive Clamp	Parker	97HC-12	Parker	2	$ -	$ -
Accumulator	Parker	SKC402921	Parker	1	$ -	$ -
Extender and Expander - 37° Flare / 37° Flare Swivel	Parker	6 XHX6-S	Parker	5	$ -	$ -
Swivel Nut Run Tee - 37° Flare / 37° Swivel / - 37° Flare	Parker	6 R6X-S	Parker	1	$ -	$ -
Crimped hose assembly	Parker	F-431-06-39-04-06-04-24	Parker	1	$ -	$ -
Female connector- 37° Flare / NPTF	Parker	4-4 GTX-S	Parker	1	$ -	$ -
Female JIC 37° - Swivel	Parker	20630-6-6	Parker	2	$ -	$ -
Male JIC 37° - Rigid	Parker	20330-6-6	Parker	2	$ -	$ -
Pressure relief valve	Parker	A02A2PZN-6T	Parker	1	$ 49.00	$ 49.00
Normally closed poppet valve	Eaton Vickers	SBV11-8-C-S6T-12DQP	RHM Fluid Power	1	$ 80.85	$ 80.85

Normally open poppet valve	Eaton Vickers	SBV11-8-O-S6T-12DQP	RHM Fluid Power	2	$ 81.17	$ 162.34
Check valve	Parker	C620S	Connector Specialists	1	$ 27.00	$ 27.00
Check valve	Parker	C620S1	Parker	1	$ 22.00	$ 22.00
Automatic transmission fluid	Pennzoil		Kroger	4	$ 2.79	$ 11.16
Gauge		3846K84	McMaster-Carr	1	$ 7.85	$ 7.85
Caravan coolant reservoir	Dodge		Aachen Auto	1	$ 10.00	$ 10.00
3/8" ID polyethylene tubing			Carpenter Bros.	6	$ 0.89	$ 5.34
1/8" ID polyethylene tubing			Carpenter Bros.	4	$ 0.39	$ 1.56
						$ -
						$ -
Electrical						
Lead acid battery	Enersys	NP7-12	Newark	1	$23.67	$ 23.67
Prototyping board			Radio Shack	3	$ 2.00	$ 6.00
Pushbutton	C&K	KS12R21CQD	Newark	3	$ 2.55	$ 7.65
Rocker switch	Cherry	SRB24A2HBBNN	Newark	2	$ 0.82	$ 1.64
Logic gate	Fairchild Semiconductor	74AC08PC	Newark	2	$ 0.16	$ 0.31
Logic gate	Fairchild Semiconductor	LM78M05CT	Newark	2	$ 0.41	$ 0.81
Relay	Tyco Electronics	PCH-105D2H	Newark	3	$ 1.47	$ 4.41
Shipping	UPS	Ground	Newark	1	$ 11.72	$ 11.72
Relay	Omron	G5LE-1-DC12	Newark	4	$ 0.73	$ 2.94
MOSFET	Vishay	IRL510PBF	Newark	4	$ 0.44	$ 1.78
Shipping	UPS	Ground	Newark	1	$ 5.01	$ 5.01
						$ -
Mechanical Drive						
13 tooth hubless sprocket	SDP/SI	A 6C 7-25013	SDP/SI	1	$ 3.31	$ 3.31
20 tooth hubless sprocket	SDP/SI	A 6C 7-25020	SDP/SI	1	$ 3.75	$ 3.75
85 tooth hubless sprocket	SDP/SI	A 6C 7-25085	SDP/SI	3	$ 28.04	$ 84.12
125 tooth hubless sprocket	SDP/SI	A 6C 7-25125	SDP/SI	1	$ 46.57	$ 46.57
#25 pitch roller chain per foot	SDP/SI	A 6Q 7-25	SDP/SI	9	$ 3.69	$ 33.21
Offset master link	SDP/SI	A 6Q 7-H25OSCLS	SDP/SI	2	$ 5.77	$ 11.54

Spring clip master link	SDP/SI	A 6Q 7-H25SCCL	SDP/SI	2	$ 2.00	$ 4.00
Shipping	UPS	Ground	SDP/SI	1	$ 12.65	$ 12.65
Shipping	UPS	Ground	SDP/SI	1	$ 11.96	$ 11.96
Ball bearing		6384K49	McMaster-Carr	1	$ 7.83	$ 7.83
Raw materials						
Steel tubing, 1"OD, .87" ID		7767T23	McMaster-Carr	1	$ 11.78	$ 11.78
Steel rectangular bar, 1/4" thick		90075K231	McMaster-Carr	1	$ 7.37	$ 7.37
Steel rod, 1" diameter		90075K231	McMaster-Carr	1	$ 7.83	$ 7.83
Shipping	FedEx	Ground	McMaster-Carr	1	$ 10.50	$ 10.50
24"x24"x.032" 6061 aluminum sheet			Alro	1	$ 15.87	$ 15.87
Primer	Do It Best		Carpenter Bros.	2	$ 5.29	$ 10.58
Spray paint	Do It Best	Bright yellow	Carpenter Bros.	1	$ 3.99	$ 3.99
Spray paint	Do It Best	Navy	Carpenter Bros.	1	$ 3.99	$ 3.99
						Total
						$ 2,227.14

APPENDIX G: BEARING CARRIER CALCULATIONS

Table G1: Description of variables used in calculations

Variables	Description	Units
μ	Coefficient of friction	NA
P	Pressure at interface	psi
A	Area of interface	in^2
$r_{interface}$	Radius of interface	in
S.F.	Safety factor	NA
T	Torque	lb*in
τ	Shear stress	psi
V	Shear load	lbs
Q	Statical moment of area	in^3
A’	Cross-sectional area above y’	in^2
y’	Distance from neutral axis where shear stress is calculated	in
$\bar{y}$’	Distance from neutral axis to centriod of A’	in
I	Second moment of area	in^4
t	Thickness perpendicular to shear	in
E	Young’s modulus	psi
M	Bending moment	lb*in
δ	Deflection	in
r_2	Outer radius	in
r_1	Inner radius	in
c	Max distance from centroid	in
L	Length of beam	in
ν	Poison’s Ratio	NA
α	Coefficient of thermal expansion	$1/^oF$

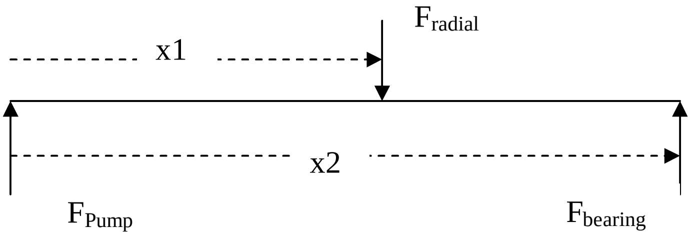
Forces on bearing shaft extension

The peak torque acting on the pump is 45 lb*in. We are able to therefore find the tension in the chain by use of the following formula.

$$T = F * r \qquad \text{Eqn. G1}$$

With a pitch radius of 0.5225in, the tension in the chain is 85 lbs. However, in the following calculations 90 lbs was used because it gives answers with rounded values. Increasing the force by 5 lbs in the calculation doesn’t underestimate any of the forces, stresses, or deflections found, but in fact installs a safety factor, albeit small.

Figure G1: Force Balance on Shaft Extension



The pump is limited to a radial load of 45lbs, and we have designed this bearing carrier with a safety factor of 2.25, which results in F_{pump}= 20lbs. This was done because when manufacturing it is impossible for there to be zero misalignment, especially when welding components together. A simple force balance was used, giving

$$F_{radial} = F_{pump} + F_{bearing} \qquad \text{Eqn. G2}$$

With values of F_{radial}=90lbs and F_{pump}=20lbs, we find that $F_{bearing}$=70lbs.

We aimed at making the shaft as short as possible, so we looked at possible ratios of x1/x2. This was done by summing moments around F_{pump}, giving,

$$F_{radial} * x1 = F_{bearing} * x2 \qquad \text{Eqn. G3}$$

Due to the packaging constaints, we determined x1 had to equal 1.25 inches. This results in x2=1.607inches.

Stress in shaft extension

A conservative estimate of the stresses in the shaft extension can be found by modeling the problem as a cantilevered beam. By use of Equation 8, with M=112.5 in*lb, c=0.25 in, and I=0.0031 in^4, we get a max stress of 9,167 psi, resulting in a safety factor of 4 against yield.

Stress and deflection of bearing support

The bearing support will be welded to the mount and will behave as cantilevered beam, so it is necessary to analyze the bending stress at the weld and the deflection at the bearing. Due to the geometry, we are able to use beam theory to determine these values. The stress is found by using the following equation

$$\sigma = \frac{M * c}{I} \qquad \text{Eqn. G4}$$

Where σ

$$M = F_{bearing} * x2, \quad I = \frac{\pi}{8}(r_2^4 - r_1^4) \qquad \text{Eqn. G5, G6}$$

The geometry of the bearing support at the weld is r_2=1.25in and r_1=1.125in, which gives I=0.32971in^4. With this, we can calculate the max stress giving σ=230 psi, which is well within the yield strength of 36,000 psi.

The deflection of the bearing support can be found by using

$$\delta = \frac{-F_{bearing} * L^3}{3 * E * I} \qquad \text{Eqn. G7}$$

With a length of 1.8in, the deflection was found to be 1.77*10^{-5} in.

Shrink Fit

The framework used to solve this problem was to calculate:

1. Interface pressure to resist sprocket slipping on shaft
2. Interference to create that interface pressure
3. Temperature difference so sprocket can slide over the shaft and shrink down onto shaft at the correct interference
4. Stress in sprocket/shaft to ensure there is no plastic deformation in either pieces

To calculate the interface pressure from step 1, the following equation was used

$$\mu * P * A * r = S.F. * T \qquad \text{Eqn. G8}$$

The coefficient of friction is 0.8, the radius is 0.25 in, the thickness of the interface is 0.11 in, the torque is 45 lb*in, the safety factor is 10. This gives an interface pressure of 13,000 lbs.

To calculate the interference we had to look at the stresses of the shaft and sprocket. Due to the relatively low RPM and the small size of the sprocket, the expansion of the sprocket caused by centripetal forces was negligible and was excluded from the following calculations. For the shaft,

$$\sigma_{rr,shaft} = A_{shaft} + \frac{B_{shaft}}{r^2} \qquad \text{Eqn. G9}$$

with B.C. $\sigma_{rr,shaft}<\infty$ at r=0, and $\sigma_{rr,shaft}$=-13,000 at r=0.25in, giving $A_{shaft} = -13{,}000$ and $B_{shaft} = 0$. For the sprocket,

$$\sigma_{rr,sprocket} = A_{sprocket} + \frac{B_{sprocket}}{r^2} \qquad \text{Eqn. G10}$$

With B.C. $\sigma_{rr,sprocket}$=-13,000 at r=0.25in, and $\sigma_{rr,sprocket}$=0 at r=.5225in, giving $A_{sprocket} = 1053$ and
$B_{sprocket} = 3860$.

The deflection of each the shaft and sprocket is

$$u_{r,shaft} = \frac{A_{shaft}(1-\nu)*r}{E}, \qquad u_{r,sprocket} = \frac{A_{sprocket}(1-\nu)*r}{E} - \frac{(1-\nu)*B_{sprocket}}{E*r}$$ Eqn. G11, G12

With a Poisons ratio of 0.3 and a Young's Modulus of $30*10^6$ psi, $\mathrm{u}_{\mathrm{r,shaft}} = 7.6 * 10^{-5}\mathrm{in}$ and $\mathrm{u}_{\mathrm{r,sprocket}} = 3.7 * 10^{-4}\mathrm{in}$. The interference is then calculated from

$$\delta = u_{r,sprocket} - u_{r,shaft}$$ Eqn. G13

To find the temperature difference so that the sprocket can slide over the shaft is found by

$$\Delta T = \frac{\delta}{r*\alpha}$$ Eqn. G14

With a radius of 0.25in and coefficient of thermal expansion of $7*10^{-6}$ 1/^{o}F, we determined we needed to heat the sprocket to a temperature of 250 ^{o}F. This low heating temperature will have no heat treating effect to the sprocket.

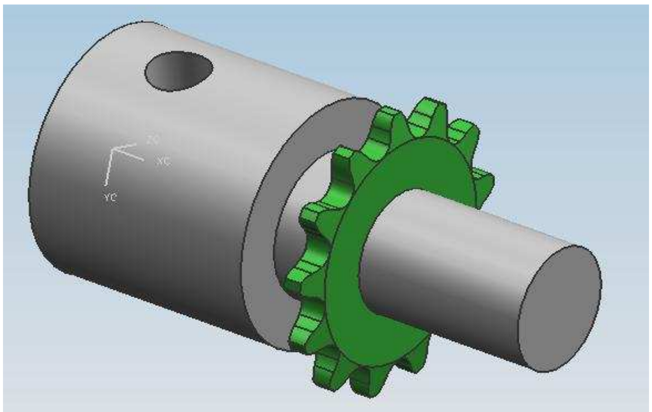
It was also necessary to check that the ultimate stress was not exceeded. The largest stress is found at the interface, with a value of 48,000 psi which is within the max strength of 58,000 psi.

APPENDIX H: DESIGN ANALYSIS ASSIGNMENT

Materials Selection Assignment (Functional Performance)

Component: shaft extension

Figure H1: Shaft Extension with Sprocket

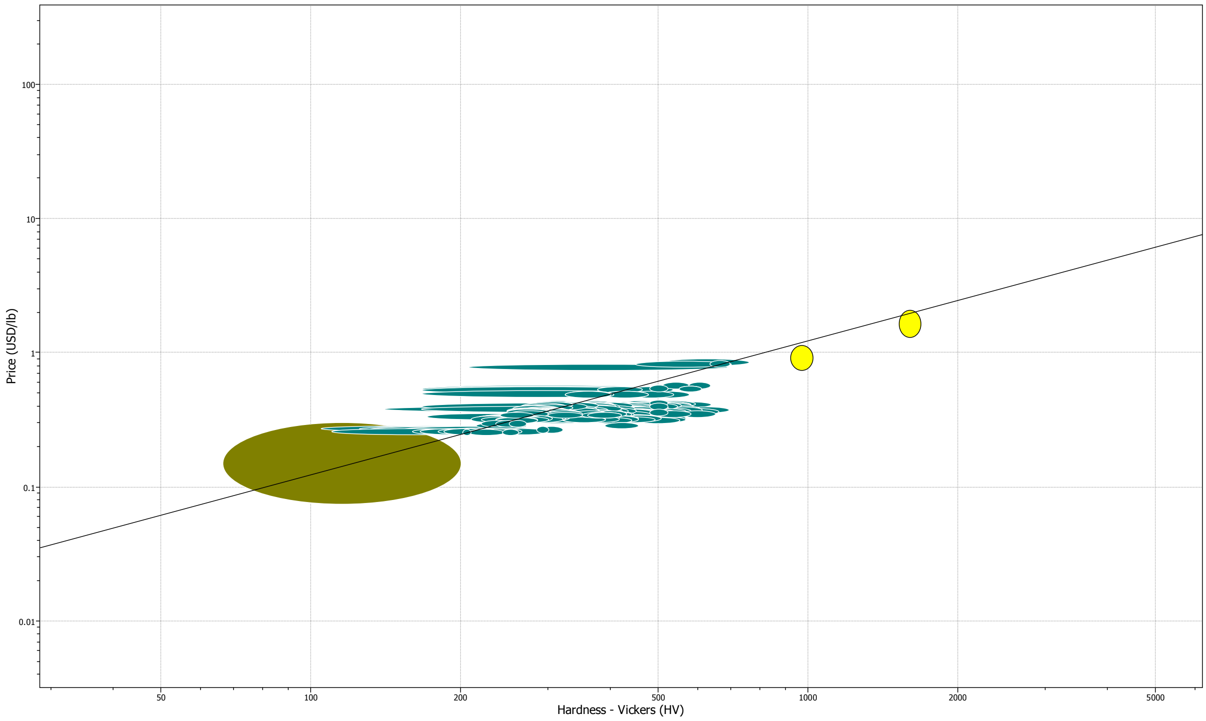


The shaft extensions connect the shafts of the pump motors to their sprockets. They must be machinable, low cost, support a load of about 400 N, and connect to the sprocket without slipping.

To ensure that the sprocket does not slip, we must prevent the shaft extensions from becoming indented by choosing a material with a high hardness. In order to support a load of 400 N, the shaft extension must have a yield strength of 126 MPa (safety factor of 2).

To select the best materials, we plotted price vs. hardness (Figure H2) using CES EduPack and drew a line to expose the materials with the highest hardness and lowest price. We also added a limit selection to remove any materials with yield strengths below 126 MPa. The software exposed five possible materials: alumina, carbon steel, cast iron, low alloy steel, and reactive powder concrete.

Figure H2: Density vs. Price for Shaft Extension



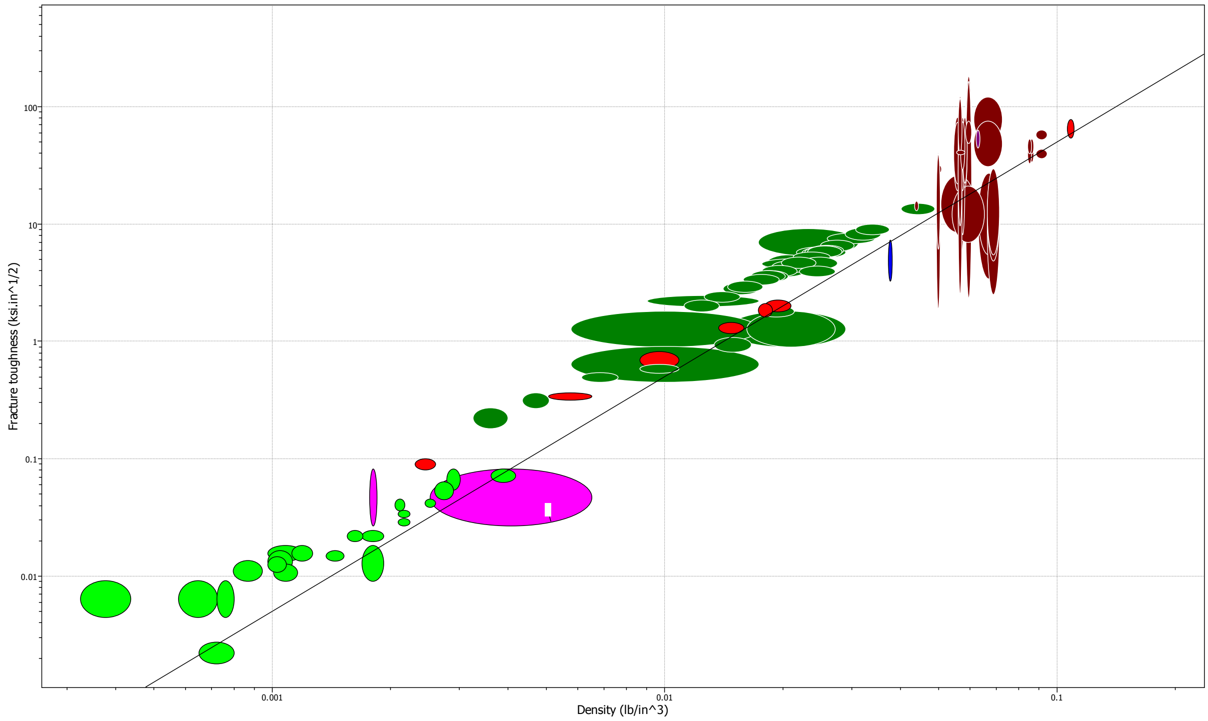
Alumina is not easily available in the size and shape we wanted, and we cannot easily form reactive powder concrete with our equipment. Although we initially planned to shrink fit the sprocket to the shaft extension, we limited our search to steel alloys because we wanted to leave open the possibility of welding it to the sprocket. Ultimately, we selected 12L14 carbon steel because it was the cheapest alloy from McMaster-Carr that was available in the size and shape we needed. Further, it is machinable and its material properties meet our needs.

Safety shield

The safety shield protects the rider from leaking or bursting hose or fittings. It should be lightweight, bendable, and able to absorb the impact of a bursting fitting.

To prevent the shock of a bursting fitting from penetrating the shield, we want to maximize fracture toughness. To keep the weight low, we want to minimize density. To select the best materials, we plotted fracture toughness vs. density (Figure H3) using CES EduPack and drew a line to expose the materials with the highest fracture toughness and lowest density. The software exposed five possible materials: aluminum, aluminum-SiC foam, woods, carbon fiber, and polyethylene foam.

Figure H3: Density vs. Hardness for Safety Shield



Aluminum-Si foam would have been a good choice and is typically used for energy absorption and crash protection. However, its cost of nearly $100 for a 24” by 24” sheet is high. Woods are lightweight but thick and not easily bendable. Carbon fiber is too expensive; the cost would exceed $100 for the amount we need. Although polyethylene foam is lightweight, flexible, and resistant to cracking, we worried that a whipping hose would break through it. Ultimately, we chose a sheet of 6061 aluminum because it is lightweight, able to absorb impact, easily formed into our desired shape, weldable, and inexpensive.

Material Selection Assignment (Environmental Performance)

In this assignment, we compared the environmental impacts of two material candidates for each of two different parts: the shaft extensions and the safety shield. We used SimaPro 7 software with the Eco-indicator 99 method. This method calculates emissions associated with various materials and can assign an overall amount of environmental damage each material causes through a point system. The Eco-indicator 99 method seems to consider the damage meta-category of “resources” to be the most important.

Shaft extension

We considered using cast iron (GG35 I) and steel (GS-70 I) for the shaft extensions. These are similar materials, but steel has slightly larger negative environmental impact, as shown by the total number of points in Figure H7. The impact of each material relative to the other is probably the same when considering their entire lifecycles because they employ the same processes for shipping, machining, and disposal.

Based on this environmental analysis, we would not change materials from steel. Although steel has a slightly greater negative environmental impact, it offers strength and cost advantages.

Figure H4: Emissions associated with cast iron and steel shaft extensions

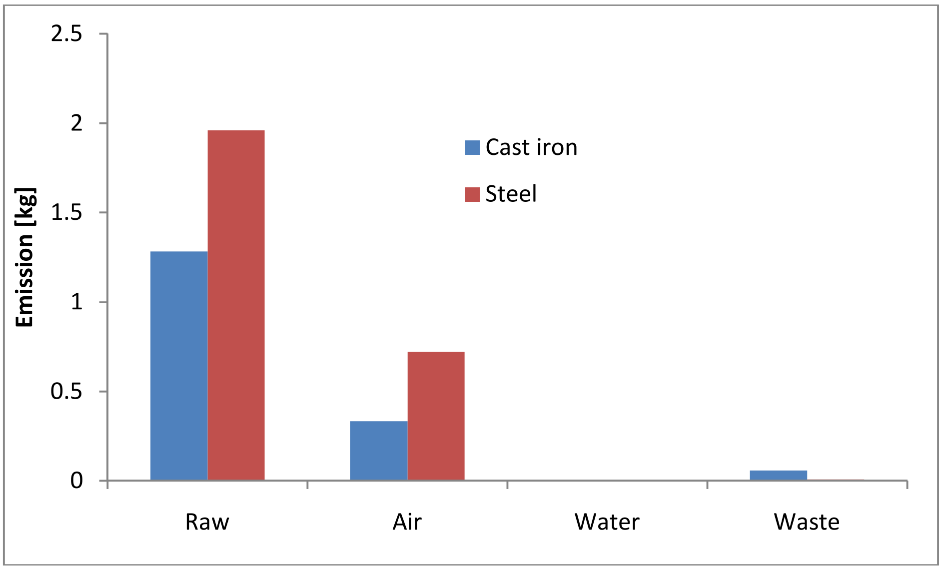
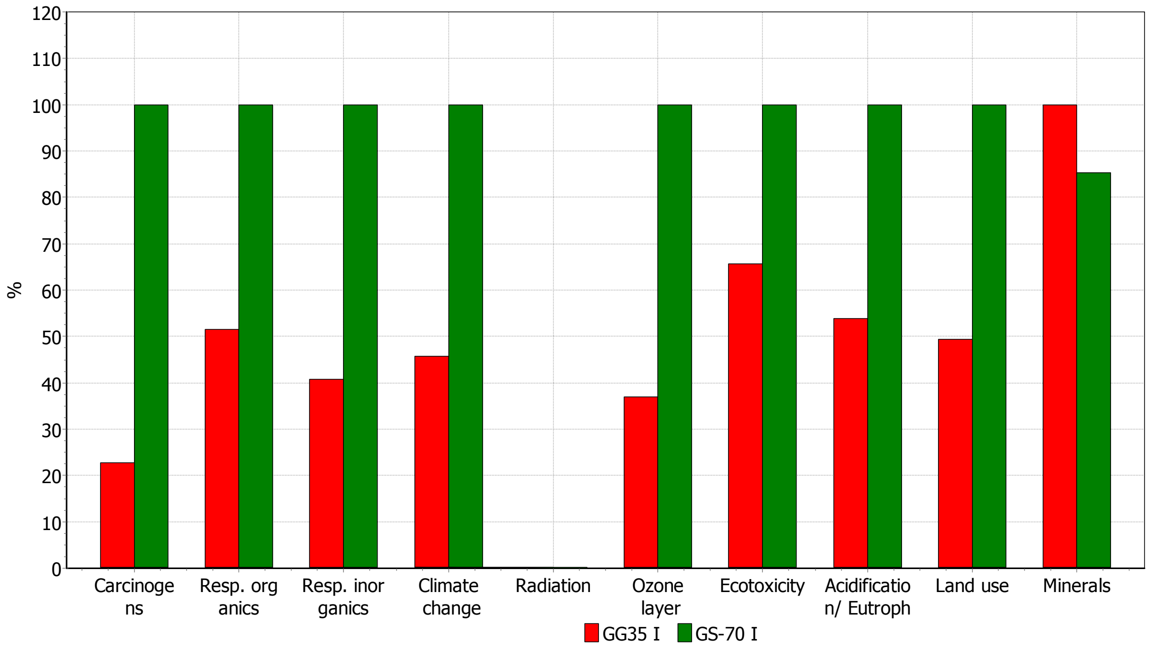
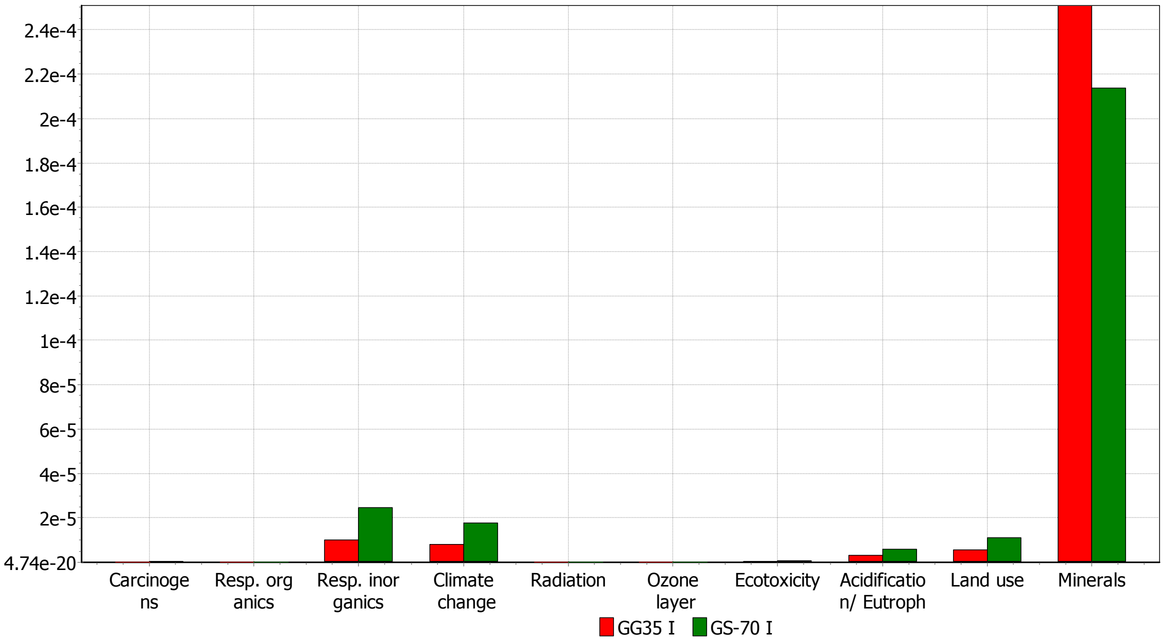


Figure H5: Relative impacts of cast iron and steel shaft extensions



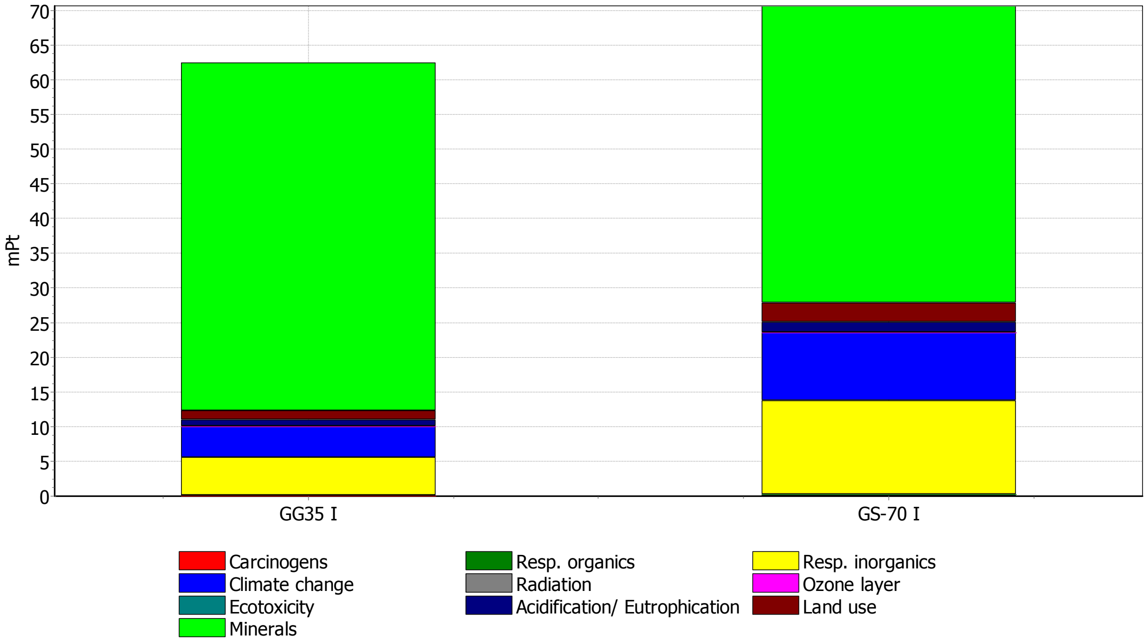
Comparing 0.7 kg 'GG35 I' with 0.7 kg 'GS-70 I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / characterization

Figure H6: Normalized score of cast iron and steel shaft extensions



Comparing 0.7 kg 'GG35 I' with 0.7 kg 'GS-70 I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / normalization

Figure H7: Single score comparison of cast iron and steel shaft extensions



Comparing 0.7 kg 'GG35 I' with 0.7 kg 'GS-70 I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / single score

Safety shield

We considered using sheets of aluminum and carbon fiber for the safety shield. We discovered that the environmental impact of aluminum is substantially greater than that of carbon fiber. Although it produces more raw emissions, carbon fiber's air emissions and energy use are much lower than aluminum's. Further, we would need less mass of carbon fiber.

When working with small quantities as we did for our project, it is possible that carbon fiber would have more impact over its lifecycle than aluminum. Carbon fiber requires a mold and would generate more packaging material. Aluminum uses fewer resources to form; it was bent and cut using a manual punch, shear, and bender.

If we had the budget or wanted to make larger quantities, we would consider changing our safety shield from aluminum to carbon fiber. In addition to having less environmental impact, carbon fiber is lighter, an advantage for a race bicycle. However, carbon fiber is much more expensive than aluminum.

Figure H8: Emissions associated with carbon fiber and aluminum safety shields

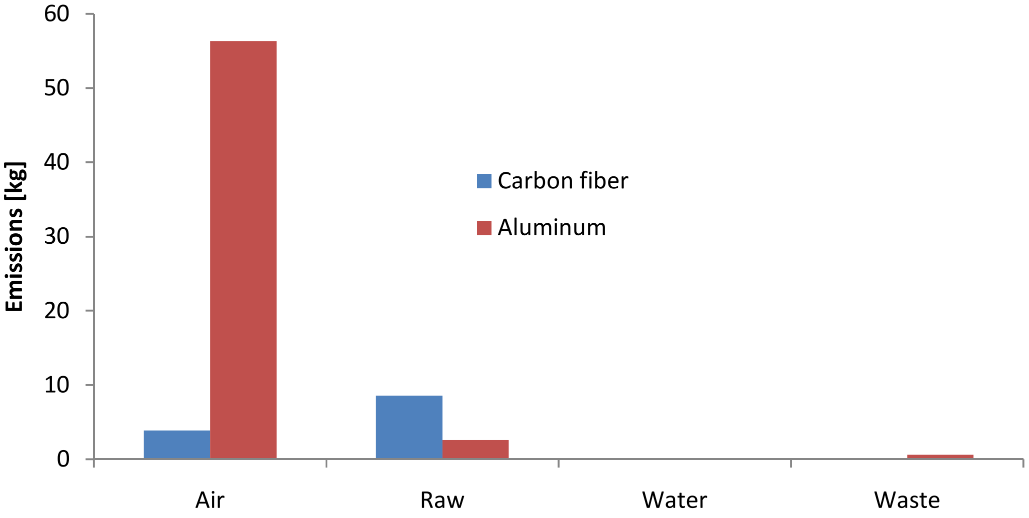
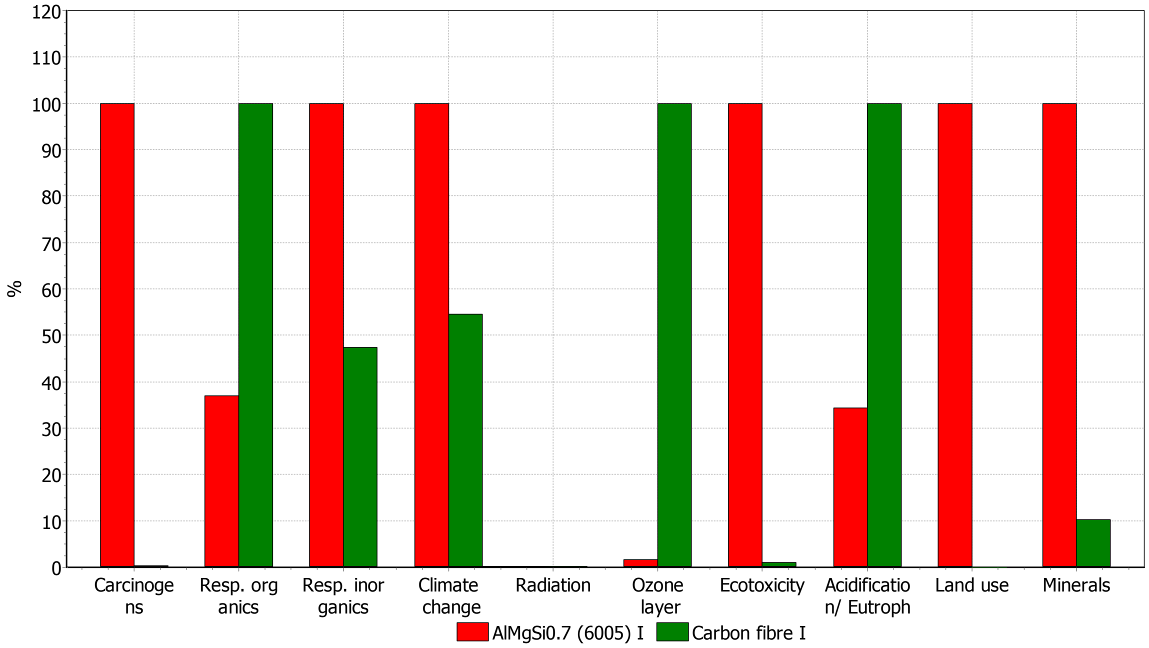
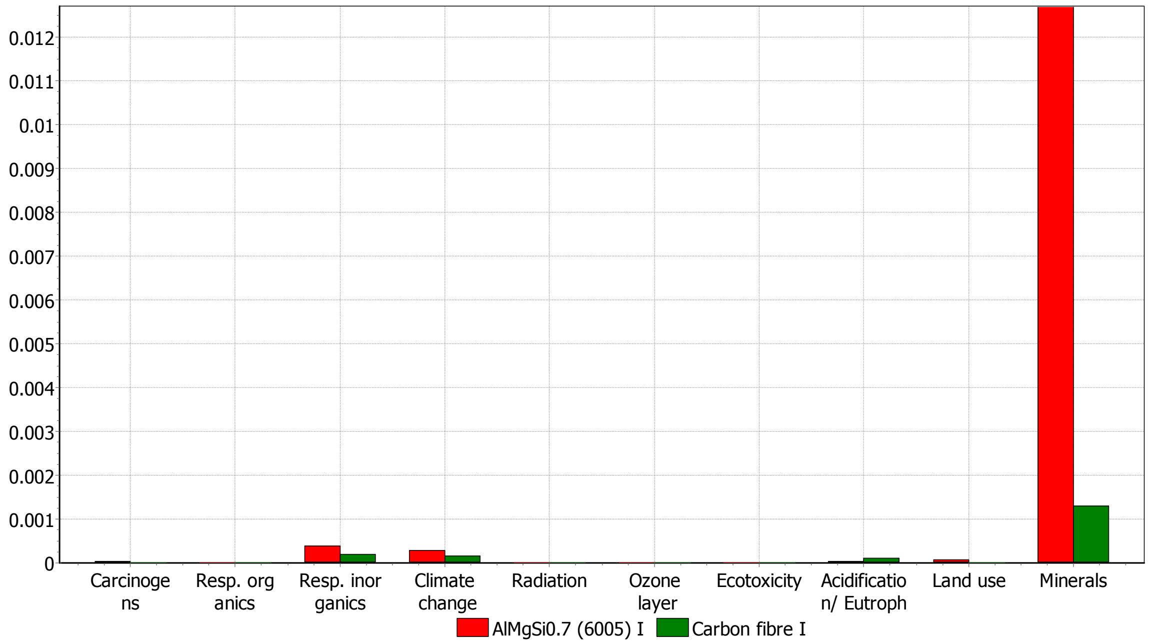


Figure H9: Relative impacts of carbon fiber and aluminum safety shields



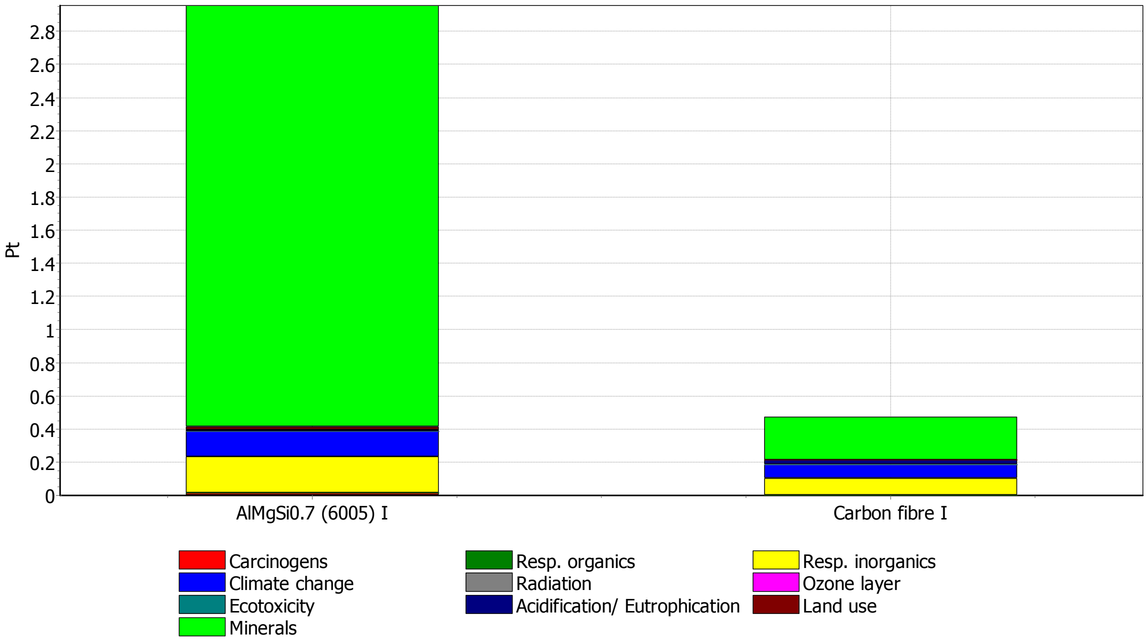
Comparing 1 kg 'AlMgSi0.7 (6005) I' with 0.5 kg 'Carbon fibre I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / damage assessmen

Figure H10: Normalized score of carbon fiber and aluminum safety shields



Comparing 1 kg 'AlMgSi0.7 (6005) I' with 0.5 kg 'Carbon fibre I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / normalization

Figure H11: Single score comparison of carbon fiber and aluminum safety shields



Comparing 1 kg 'AlMgSi0.7 (6005) I' with 0.5 kg 'Carbon fibre I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / single score

Manufacturing Process Selection Assignment

We designed our bicycle with the intention of building one to compete in the Chainless Challenge competition. We do not envision selling millions of them to consumers, but it is possible that there is demand for about 20 more for use as an educational tool. Other Chainless Challenge teams may want to buy these bicycles and modify them to suit their own riders. Additionally, trade schools and colleges could use them as an aide in teaching hydraulics. A quantity of 20 bicycles would still be hand built, but their components could be manufactured more efficiently.

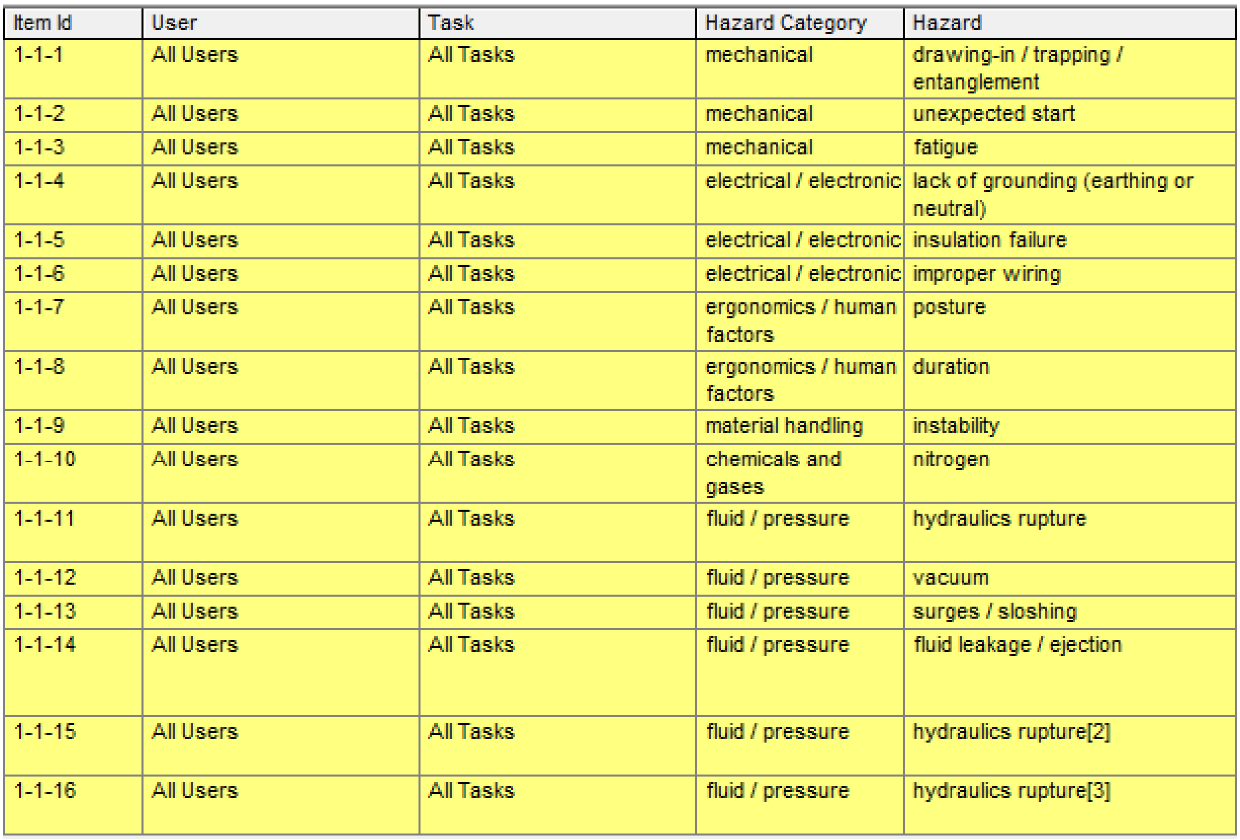
Bearing carrier manufacturing

The bearing carrier has tight tolerances for its diameter of about ± 0.001 to allow the sprocket to shrink fit on to it. Turning the bearing carrier from stock can meet these tolerances and is economical for producing a quantity of 40. Most lathes are easily able to produce a part of this size. Casting would be a possibility for a larger quantity. However, a cast part would likely require additional machining operations to reach the required tolerances. CES EduPack also suggests electro-discharge machining and electroforming, but these processes require equipment that is more difficult to find.

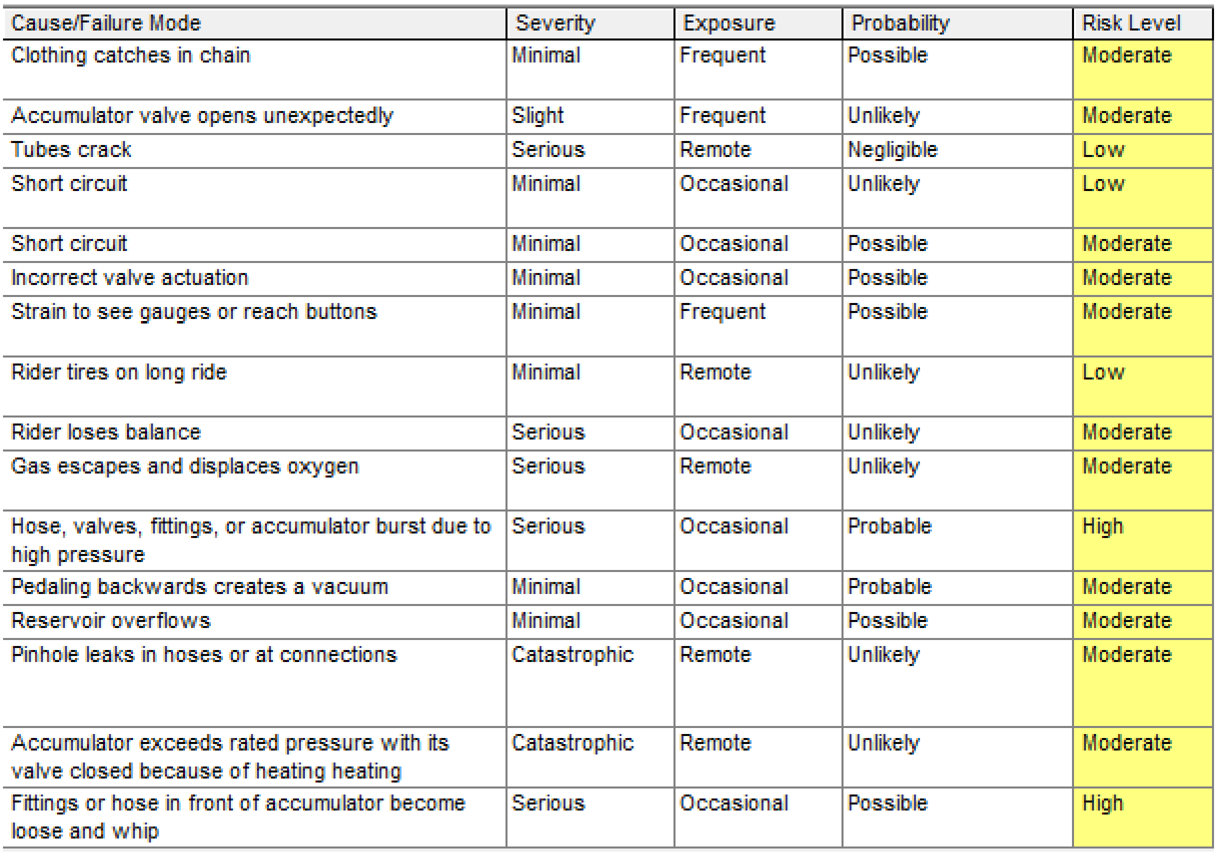
Safety shield manufacturing

The safety shield requires pieces to be cut from a sheet of aluminum and holes to be punched. Tolerances are loose on both the location of holes and size of pieces. Although cutting the aluminum with a shear and punch produces the required tolerances, laser cutting is faster. Laser cutting eliminates the separate steps of cutting the profile of the sheet, rounding edges on a sander, and punching holes. Additionally, laser cutting produces less scrap because the operator can plan the layout of parts on the sheet in advance to minimize waste. One drawback of laser cutting, however, is that the equipment may not be readily available, and not all laser cutters can cut metals.

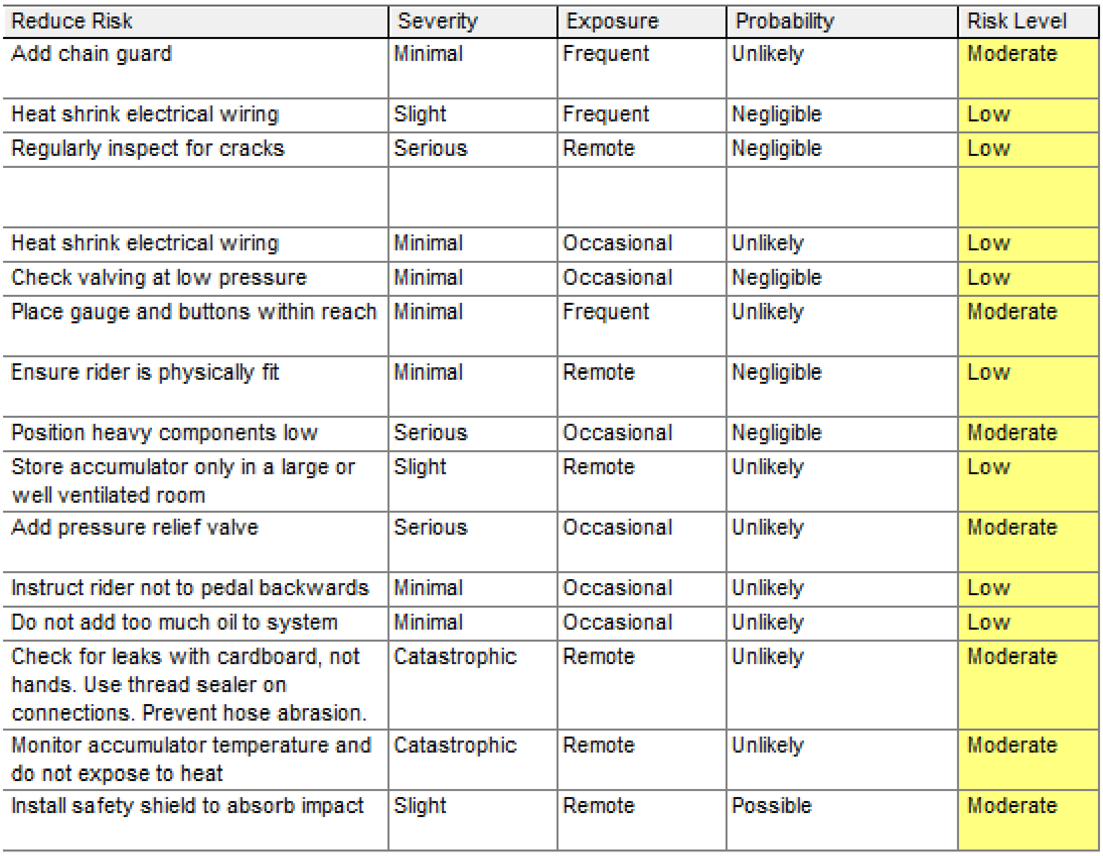
APPENDIX I: DESIGNSAFE SOFTWARE RESULTS



Item Id	User	Task	Hazard Category	Hazard
1-1-1	All Users	All Tasks	mechanical	drawing-in / trapping / entanglement
1-1-2	All Users	All Tasks	mechanical	unexpected start
1-1-3	All Users	All Tasks	mechanical	fatigue
1-1-4	All Users	All Tasks	electrical / electronic	lack of grounding (earthing or neutral)
1-1-5	All Users	All Tasks	electrical / electronic	insulation failure
1-1-6	All Users	All Tasks	electrical / electronic	improper wiring
1-1-7	All Users	All Tasks	ergonomics / human factors	posture
1-1-8	All Users	All Tasks	ergonomics / human factors	duration
1-1-9	All Users	All Tasks	material handling	instability
1-1-10	All Users	All Tasks	chemicals and gases	nitrogen
1-1-11	All Users	All Tasks	fluid / pressure	hydraulics rupture
1-1-12	All Users	All Tasks	fluid / pressure	vacuum
1-1-13	All Users	All Tasks	fluid / pressure	surges / sloshing
1-1-14	All Users	All Tasks	fluid / pressure	fluid leakage / ejection
1-1-15	All Users	All Tasks	fluid / pressure	hydraulics rupture[2]
1-1-16	All Users	All Tasks	fluid / pressure	hydraulics rupture[3]



Cause/Failure Mode	Severity	Exposure	Probability	Risk Level
Clothing catches in chain	Minimal	Frequent	Possible	Moderate
Accumulator valve opens unexpectedly	Slight	Frequent	Unlikely	Moderate
Tubes crack	Serious	Remote	Negligible	Low
Short circuit	Minimal	Occasional	Unlikely	Low
Short circuit	Minimal	Occasional	Possible	Moderate
Incorrect valve actuation	Minimal	Occasional	Possible	Moderate
Strain to see gauges or reach buttons	Minimal	Frequent	Possible	Moderate
Rider tires on long ride	Minimal	Remote	Unlikely	Low
Rider loses balance	Serious	Occasional	Unlikely	Moderate
Gas escapes and displaces oxygen	Serious	Remote	Unlikely	Moderate
Hose, valves, fittings, or accumulator burst due to high pressure	Serious	Occasional	Probable	High
Pedaling backwards creates a vacuum	Minimal	Occasional	Probable	Moderate
Reservoir overflows	Minimal	Occasional	Possible	Moderate
Pinhole leaks in hoses or at connections	Catastrophic	Remote	Unlikely	Moderate
Accumulator exceeds rated pressure with its valve closed because of heating heating	Catastrophic	Remote	Unlikely	Moderate
Fittings or hose in front of accumulator become loose and whip	Serious	Occasional	Possible	High



Reduce Risk	Severity	Exposure	Probability	Risk Level
Add chain guard	Minimal	Frequent	Unlikely	Moderate
Heat shrink electrical wiring	Slight	Frequent	Negligible	Low
Regularly inspect for cracks	Serious	Remote	Negligible	Low
Heat shrink electrical wiring	Minimal	Occasional	Unlikely	Low
Check valving at low pressure	Minimal	Occasional	Negligible	Low
Place gauge and buttons within reach	Minimal	Frequent	Unlikely	Moderate
Ensure rider is physically fit	Minimal	Remote	Negligible	Low
Position heavy components low	Serious	Occasional	Negligible	Moderate
Store accumulator only in a large or well ventilated room	Slight	Remote	Unlikely	Low
Add pressure relief valve	Serious	Occasional	Unlikely	Moderate
Instruct rider not to pedal backwards	Minimal	Occasional	Unlikely	Low
Do not add too much oil to system	Minimal	Occasional	Unlikely	Low
Check for leaks with cardboard, not hands. Use thread sealer on connections. Prevent hose abrasion.	Catastrophic	Remote	Unlikely	Moderate
Monitor accumulator temperature and do not expose to heat	Catastrophic	Remote	Unlikely	Moderate
Install safety shield to absorb impact	Slight	Remote	Possible	Moderate

APPENDIX J: CHANGES SINCE DR3

Gear Hub

Originally, we had intended on having a gear hub that was both able to apply torque in both angular directions and change gears as well. Unfortunately, the disabling of the gear hub's free-wheeling feature has proven to be more difficult than we had thought, and our design did not successfully create a hub that could apply torque in both directions. The part of the gear hub that we had isolated as the piece that allowed it to free-wheel was not the only thing responsible for this. There was another ratcheting mechanism behind the one in question that we found after our attempt to disable the first. This has caused us to create a fixed gear hub on the bicycle's original rear wheel, so that the rear wheel can transmit torque in both directions, as is necessary for the regenerative braking.

Figure J1: Picture of Fixed-Gear Rear Wheel

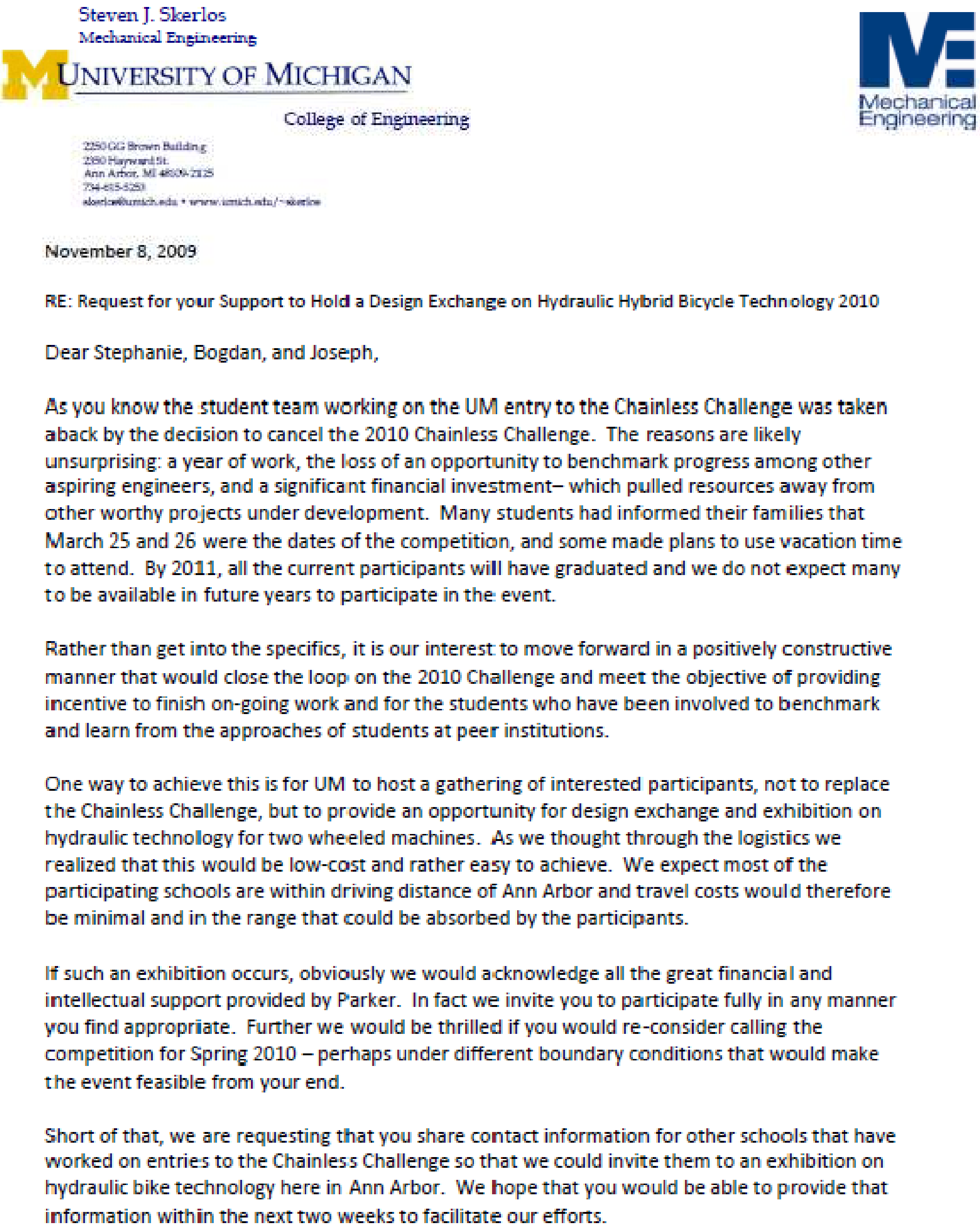
From Shrink Fits to Welds

The shrink fits that we had originally intended to use on the shaft extensions on the pump motors did not hold as well as we had hoped, and the interface slipped before we could apply the necessary torque. This is most likely due to errors in manufacturing tolerances. The sprockets have now been welded to the shaft extensions and are successfully supplying the necessary torque.

Parker Valves instead of Eaton Valves

Due to the late arrival of our normally open Eaton poppet valves, we have borrowed 2 normally open Parker spool valves from the EPA. The Parker solenoids are 12V just as the Eaton valves are, but because they are spool valves, they will leak more than the Eaton valves will. The Parker valves are 3-way valves, while we only needed 2-way. This has resulted in the need to plug one of the ports, and due to the different port location, a slightly different layout of our hydraulic system. The Parker valves are also heavier than the Eaton valves. The Parker valves will be used for preliminary testing procedures, but will be replaced by the Eaton valves as soon as they arrive.

APPENDIX K: Letter to Parker



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Mechanical Engineering

November 8, 2009

RE: Request for your Support to Hold a Design Exchange on Hydraulic Hylbrid Bicycle Technology 2010

Dear Stephanie, Bogdan, and Joseph,

As you know the student team working on the UM entry to the Chainless Challenge was taken aback by the decision to cancel the 2010 Chainless Challenge. The reasons are likely unsurprising: a year of work, the loss of an opportunity to benchmark progress among other aspiring engineers, and a significant financial investment– which pulled resources away from other worthy projects under development. Many students had informed their families that March 25 and 26 were the dates of the competition, and some made plans to use vacation time to attend. By 2011, all the current participants will have graduated and we do not expect many to be available in future years to participate in the event.

Rather than get into the specifics, it is our interest to move forward in a positively constructive manner that would close the loop on the 2010 Challenge and meet the objective of providing incentive to finish on-going work and for the students who have been involved to benchmark and learn from the approaches of students at peer institutions.

One way to achieve this is for UM to host a gathering of interested participants, not to replace the Chainless Challenge, but to provide an opportunity for design exchange and exhibition on hydraulic technology for two wheeled machines. As we thought through the logistics we realized that this would be low-cost and rather easy to achieve. We expect most of the participating schools are within driving distance of Ann Arbor and travel costs would therefore be minimal and in the range that could be absorbed by the participants.

If such an exhibition occurs, obviously we would acknowledge all the great financial and intellectual support provided by Parker. In fact we invite you to participate fully in any manner you find appropriate. Further we would be thrilled if you would re-consider calling the competition for Spring 2010 – perhaps under different boundary conditions that would make the event feasible from your end.

Short of that, we are requesting that you share contact information for other schools that have worked on entries to the Chainless Challenge so that we could invite them to an exhibition on hydraulic bike technology here in Ann Arbor. We hope that you would be able to provide that information within the next two weeks to facilitate our efforts.

We acknowledge your profound contributions to student education here at UM and the difficult state of the manufacturing industry. We are grateful for your continuing material support as we ready our entry for its public viewing in one form or another.

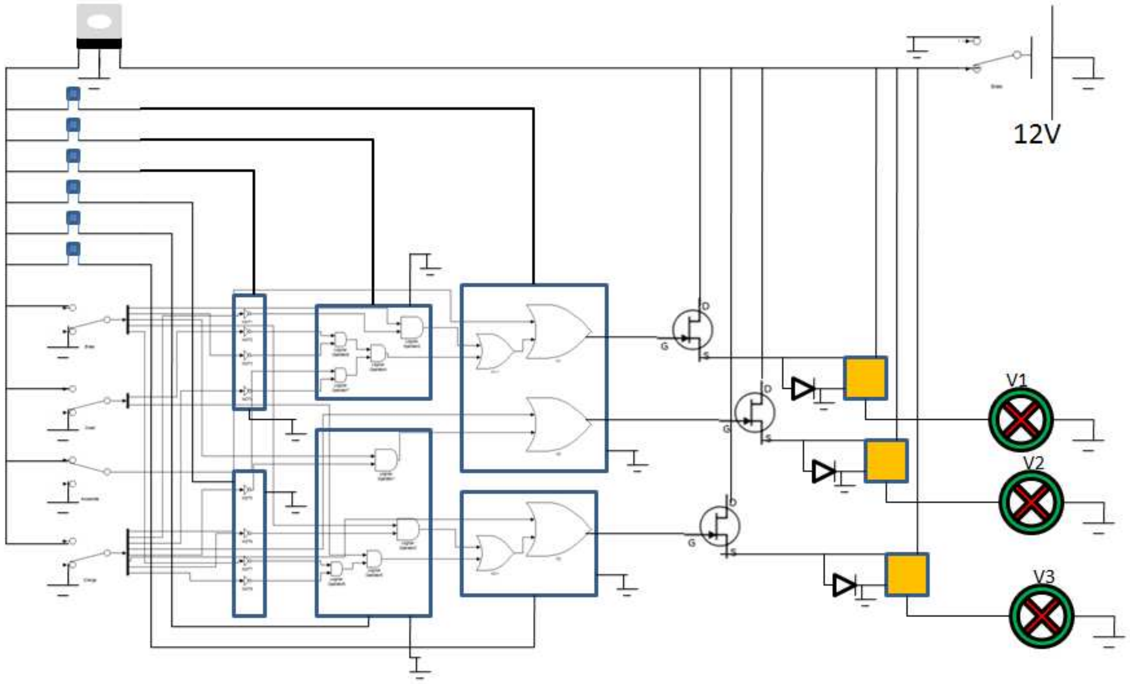
We also look forward to continuing interactions and hope you understand our strong motivation to move forward with some event in 2010.

Sincerely,

Steven J. Skerlos
Associate Professor and Chair of Graduate Education
Mechanical Engineering

On behalf of:
Henry Kohring, senior design team member and BLUElab member
Andrew Berwald, senior design team member
Phillip Bonkoski, senior design team member
Christopher Levay, senior design team member
Aidan Feldman, BLUElab member
Stephen Hannon, BLUElab member
Joshua Langsfeld, BLUElab member

APPENDIX L: Wiring Diagram



Legend

Decoupling Capacitor

5V Linear Regulator

▭ Logic IC

MOSFET

Protection Diode

AND Gate

🟨 Relay

⊗ Solenoid Valve

Battery

⏚ Ground

OR Gate

Inverter

Logic Gates Contained Within ICs