Final Report

Hydraulic Regenerative Braking for a 20" Bicycle Wheel

ME 450: Design and Manufacturing III

Winter 2008

Team

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April 15, 2008

Executive summary

Group 14: 20" Hydraulic Regenerative Braking Bicycle Wheel

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Design Problem: Group 14, in conjunction with David Swain of the Environmental Protection Agency, is charged with creating a hydraulic powered bicycle system complete with a regenerative braking designed to be fully contained in a child's 20 inch bicycle wheel. This bicycle will provide a mode of transportation that is easier to use than a standard bicycle while at the same time generating zero harmful emissions.

Customer Requirements and Engineering Specifications: Working with our group sponsor, David Swain, we have generated several customer requirements for our hydraulic bicycle wheel. These include the bicycle being attractive, safe, easy to use, lightweight, and universally applicable to a standard child's bike. Based on these guidelines, our system must fit into a 20 inch bike wheel diameter, be less than four inches wide, less than 16 pounds in weight, and provide acceleration and deceleration appropriate for a young bike rider.

Concept Generation, Evaluation, and Selection of Alpha Design: A brainstorming session generated ideas for each of the four main components of the system: hydraulic circuit, drive train, support hub, and support bracket. Using Pugh charts, we objectively weighed the merits and disadvantages of each design. Finally, we selected the highest scoring designs and merged them into one alpha prototype model. The chosen design is a simplified hydraulic circuit that utilizes an electromechanical clutch system. Power is transferred using a graduated gear train. The wheel is supported with a beveled hub shell bolted to each side of the bike rim. The system components are supported by a thin bracket rigidly attached to the bike axle and parallel to the bike tire.

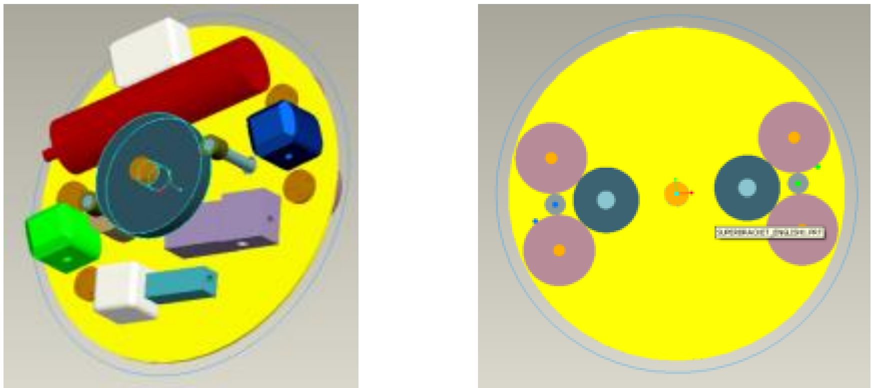
Engineering Challenges: We must condense standard hydraulic components into a small space. The gearing system must be precisely designed for appropriate loads, the bike hub needs to be light weight strong, and manufactured for max volume. The support bracket must withstand the torque applied by the hydraulic system, yet be as lightweight as possible.

Final Concept: After careful engineering analysis of our alpha prototype, our final design is presented on the following page. This design will be presented at the Design Exposition on April 10, 2008. Our prototype will include all of the design components except for the hydraulic pump and motor. These components were to be provided to us but have since been held up in production.

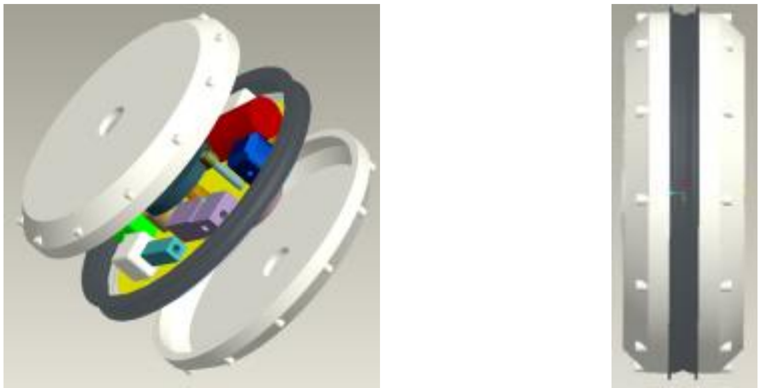
Fabrication Plan/Cost Analysis: All of the fabrication has taken place in a machine shop using mills, lathes, drill press, and hand tools. The main components to be fabricated are: super bracket – circular sheet of steel with milled holes and tube welded through the middle, hub – mill cavity in red board and lay fiberglass, forks – cut and bend 1" steel tube, standoff brackets – machined from aluminum to support clutch and shaft, spider brackets – machined on lathe and mill to house bearing, and main gear – machine through holes. Assembly requires only basic hand tools. The cost of raw materials is minimal totaling in under $100. Assembly is done by our team and only costs time.

Test Results/Critique: We did not achieve the weight or width requirements. We exceeded the target weight by 27lbs and width by 1". We were able to fit the entire hydraulic circuit and gears inside a 20" wheel hub and have a 'to scale' functional prototype with electronics that is only missing the pump and motors. We also were able to make the hub attractive, the sponsor's most important requirement. Overall this was a successful prototype that will be a great starting point for next semester's team to take over. A picture of the prototype can be seen on the following page.

Final Concept – Engineering Drawings



Final concept: front view and rear view, showing the hydraulic circuit mounted on the support bracket, as well as the gear train system. The bike axle runs through the center of the bracket and the driving gear.



Final concept: exploded view and side view of the assembled system. The two halves of the bike hub will attach directly to the bike rim where the tire will ride. The entire system will fit between the bike forks of a child's bike.

Final prototype: Inside and outside view of final prototype shown in expo.

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1. Abstract

With today's need for better fuel economy and emissions reduction, hybrid technology has become increasingly popular. The Environmental Protection Agency (EPA) is currently pursuing research in regenerative braking hydraulic hybrids which pressurizes fluid upon braking to partially power the vehicle. As a zero-emissions solution, the EPA has collaborated with ME450 students to apply this technology to a bicycle, attempting to fit the system in an average 26" size wheel. This semester, our goal is to fit the system into a 20" wheel while also reducing the weight by half. We will be adjusting internal components for weight, changing any part of the system to improve functionality, and improve the efficiency and manufacturability of the system.

2. Introduction

2.1 Background and Motivation

The search for alternative energy is becoming increasingly urgent due to the innumerable threats imposed by climate change and dependence on foreign oil. In the United States, transportation is a primary source of pollution and oil consumption, producing 30% of CO_2 emissions and using 69% of the total oil consumed [1]. The Environmental Protection Agency (EPA), created in 1970 under President Richard Nixon, is a federal government agency in charge of regulations involving public health and protection of the environment, including air pollution and transportation impacts [2]. The EPA was also recently granted the authority to regulate greenhouse gas emissions from automobiles [2]. In efforts to help the automotive industry find sustainable transportation solutions, the EPA has conducted mass research in alternative fuels.

2.2 Project Summary

As a fuel- and emission-free option to traditional modes of travel, bicycling remains an important means of transportation in cities and high-traffic areas. They are reliable, convenient, and sometimes faster than driving. However, because they require more work to operate, they are frequently dismissed for a car. In order to increase attraction to bicycles, students from ME450 have collaborated with the EPA for four years to implement a hydraulic launch assist (HLA) system into a bicycle wheel which may be retrofit onto any standard front bicycle fork. This technology, being pursued in various vehicle types, uses a regenerative braking system (RBS) to store wasted energy which is then used to propel the rider to near their original speed. Previous semesters have worked, in collaboration with our EPA sponsor and customer, David Swain, to produce a working prototype and reduce the weight and size to fit standard bicycle forks. This semester, our task is to further reduce the size to be half the weight and fit a 20" wheel on a child's bike or a BMX bike.

The RBS works by activating gears connecting the wheel to the pump when braking to pressurize an incompressible fluid in a high pressure piston accumulator from a low pressure accumulator. The increasing pressure in the high pressure accumulator decelerates and stops the bicycle. A launch button, pushed by the rider, activates the electric valves, reversing the fluid flow and allowing the high pressure fluid to power the hydraulic motor. The motor powers the gears which connect to the wheel that accelerates the bicycle back to approximately 70% of the original speed.

This semester, we have essentially met the goal of reducing the size of the system to fit within the standard rim and fork dimensions. Our prototype weight was approximately twice that of our target value, but allows room for significant weight reduction without changing the design concept. We have also greatly reduced the amount of frictional resistance through simplification of the hydraulic circuit and incorporation of clutches to allow the wheel to spin freely from the pump and motor when not braking or launching. Due to time restrictions conflicting with the delivery of our custom ordered pump and motor, our final prototype could not reach the operational and testing stages. However, we have built the prototype such that the system will be ready for that stage when our model pump and motor are replaced with the correct ones.

3. Engineering Specification Development

We now discuss the goals and wishes of our customer and sponsor from the final product. These goals lead to specific engineering parameters that we seek to achieve and incorporate in our design. Finally, we will discuss the current technology and benchmarks that our final design product would be compared with.

3.1 Customer Requirements

Due to the great similarity of this semester's project outlook to previous semesters, the customer requirements and engineering specifications are largely based on those formulated by previous groups. Our sponsor and customer, David Swain has helped us put together the most important customer requirements which are listed in our Quality Function Deployment Diagram (QFD) in Appendix A. Below is a table of customer requirements used by previous groups and new requirements we have added. They are listed in order of decreasing importance. Our new requirements emerge from the new wheel size goal for this semester's project.

Importance	**Old Requirements**	**New Requirements**
High	Universal Application Safe Lightweight Aesthetically Pleasing Maintains Bicycle Function	Design for Child Use
Medium	Efficient Natural Rate of Braking Easy to Use Reliable Easy to Service	
Low	Sufficient Top Speed	Acceptable for BMX Use

Table 1: Customer Requirements

The most important customer requirements for the wheel are those that are important for producing a widely applicable product that is useful, desirable, and safe. First, it must be appropriate for use by children, which implies the size, weight, and extra safety precautions that may be necessary. It also must be retrofit to any bicycle with 20" wheels. Because of the large amount of stored energy potential and the high operating pressures, safety is a huge concern. We must assure that the power is properly controlled and has failsafe options to prevent catastrophe in the event of a malfunction. The high pressure hydraulics must be contained with shielding in the event that the plumbing is damaged. The wheel must maintain a low weight comparable to an average wheel for functionality. Our customer also requires that the wheel have a desirable appearance. Finally, it must function essentially the same way as normal bicycles while it is not launching.

Ranking in medium importance are aspects of the functionality of the bicycle. These are areas that may be improved after a working prototype is produced. Efficiency is necessary to maintain a low effort for riding and a high level of improvement (i.e. a good launch) compared with a standard bicycle. The ease of use is important to minimize the time required to learn and feel comfortable with riding. Reliability on a functional system for an extended time is also necessary. A natural rate of braking is important for comfortable and safe riding. Finally, minimizing effort and complexity for repairs is an additional desire if the bicycle does malfunction, especially in our current prototype stage.

Last, because we are focused on developing a working prototype, sufficient top speed is currently a low priority. We also consider the potential use of the wheel for BMX (bicycle motor cross) use, which may imply greater levels of shock than typical use by children.

3.2 Engineering Specifications

The engineering specifications are technical constraints that are derived from the desires signified by the customer requirements. Because most of our customer requirements were the same as those in previous semesters, many of our engineering requirements remained the same also. However, our target values are modified to accommodate a smaller wheel and assuming a smaller weight of the child and bike. These specifications are listed in decreasing order of importance in Table 2. We have determined the order of importance of our engineering specifications based on our QFD, which ranks the specifications by the sum of the weighted correlation coefficients of technical requirements to customer requirements.

According to our QFD, the engineering specification with the greatest importance is **having a maximum weight of 16 lbs**; approximately half of last semester's prototype. This is a limit requested by our customer, David Swain, which essentially requires minimizing the weight as much as possible. As our QFD shows, nearly all of the customer requirements will be closer met with a lightweight system.

	Description	**Targets**
Increasing Priority ↑	Maximum Weight	<< 16lb
	Hub Width	≤ 4”
	Hub Diameter	< 15”
	Prototype Functionality	Able to ride the bicycle
	Maximum Launching Acceleration	2.0- 2.5 m/s^2
	Maximum Braking Deceleration	2.20- 3.63 m/s^2
	Gear Ratio	17.5-18.5 : 1
	Working Pressure	2700- 4000 psi
	Maximum Volume of hydraulic fluid	0.30 - 0.32 L
	Hydraulic Fluid Filtration	
	Motor/Pump Displacement	0.51cc - 0.64cc

Table 2: Engineering Specifications

Next in importance are the **hub width and hub diameter**, which are set at standard fork and rim sizes for 20” bicycle wheels. These relate to the high priority customer requirements of universal application and design for child’s bicycle. The width target is the same as the previous projects, but the wheel diameter is now 20” instead of 26”.

The prototype functionality is our next highest priority. Because this project has had several semesters of research and development already, our sponsor would like us to have a working prototype which meets our top three priority requirements discussed above and incorporates many of the design components that have already been developed by previous work.

Our next important requirements are the **braking and launching deceleration and acceleration**, respectively. These are important parameters which determine the safety, functionality, and ease of use. The deceleration, as explicitly requested by the customer, must be at a natural rate that is comfortable for the rider and will not throw them off the bicycle. This has been determined by previous semesters to be 3.63 m/s^2 maximum. Likewise, previous semesters have determined the maximum acceleration that is safe and does not allow the tire to skid is 2.5 m/s^2. These values have been the targets for all previous semesters.

The next priority is having the correct **gear ratio**. This gear ratio is based on the ratio of the minimum torque on the pump to the minimum torque on the wheel required for the minimum comfortable deceleration, based on testing. The minimum deceleration is, calculated in Appendix B, 2.3 m/s^2, based on previous testing at various minimum pressures, or “precharges” of the high pressure accumulator. Our final gear ratio is calculated to be 18:1.

The **working pressure** of the system is next in importance. This range of working pressures has been chosen by our sponsor based on the amount of energy stored in the high pressure accumulator that would launch a lower limit weight of approximately 50 kg (child plus bicycle weight) to a safe maximum speed of approximately 20 mph as established by previous semesters. Based on our calculations, shown in the Appendix, and the graph shown in Figure 1, the 0.32 L accumulator is the smallest 4000 psi accumulator that will provide this amount of energy. Our precharge, based on this energy requirement, is then 2700 psi.

The maximum **volume of hydraulic fluid** is the next highest in importance. We have set this volume of fluid equal to approximately 3 times the change in volume of the high pressure accumulator when going from low to high pressure to ensure there is enough fluid in the hydraulic circuit to prevent air bubbles from circulating and reducing efficiency while minimizing the spatial requirements of the low pressure accumulator. Our calculations are shown in Appendix B.

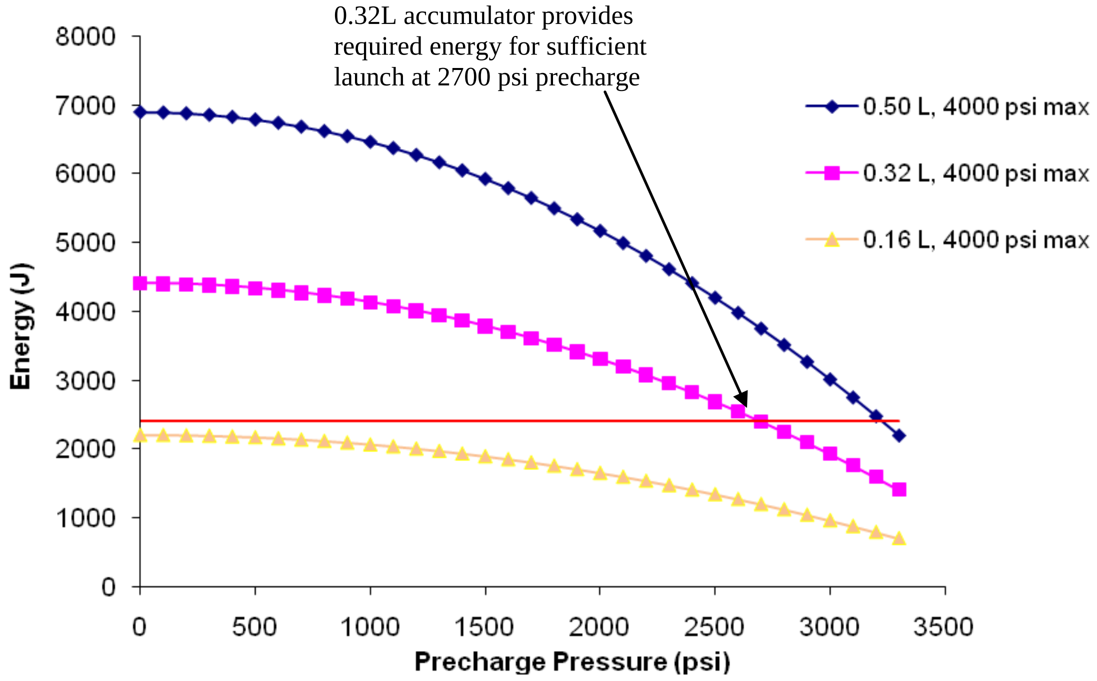


Figure 1: We chose the 0.32 L 4000 psi high pressure accumulator based on energy storage requirements and size

Having **hydraulic fluid filtration** is the second lowest priority for engineering specifications. This is a feature of the hydraulic circuit recommended by our EPA sponsor, David Swain. The filtration of the fluid would ideally prevent the malfunction of valves (and consequently the whole system) due to metal shards or other debris which may find its way into the hydraulic circuit. The filtration must be rated for the maximum system pressure of 4000 psi.

Finally, the **motor and pump displacements** per revolution are the least important engineering specifications. These were, again, chosen by our sponsor, David Swain, based on a balance between power capabilities and size. The braking deceleration depends on the pump displacement and the precharge pressure. Thus, because the precharge can be changed, the displacements are of lower importance. The motor is scaled down by about 20% from the pump for safety reasons, to assure that the pump (braking) would overpower the motor (accelerating) in the event of a valve malfunction.

Our overall equation relating the torque (and hence accumulator pressure) to the acceleration or deceleration of the bicycle is:

$$T_{P/M} * \eta * GR = M * a * r \qquad \text{Eq. 1}$$

where $T_{P/M}$ is the torque at the pump or motor from the fluid, η is the overall efficiency assumed to be 82.5% based on previous prototypes, GR is the gear ratio equal to 18/1, M is the mass of the bike plus rider assumed to be 50 kg, a is the acceleration or deceleration rate, and r is the wheel radius equal to 10". The torque at the pump or motor relates to the pressure in the accumulator and the displacement per revolution of the pump or motor. Equation 1 may be written as:

$$disp * P \big/ 2\pi * \eta * GR = M * a * r \qquad \text{Eq. 2}$$

where *disp* is the displacement per revolution equal to 6.4 x 10^{-4} L/rev for the pump and 5.1 x 10^{-4} L/rev for the motor, and P is the pressure in kPa.

These equations show us that if our efficiency were lower than assumed or the rider were heavier than assumed, the precharge can be increased to provide the same minimum acceleration and deceleration, and the maximum acceleration and deceleration would be lower for a maximum pressure of 4000 psi.

3.3 Literature Search and Technical Benchmarks

Much of the information was provided for us by our EPA sponsor, Dr. David Swain. This includes all of the work done by previous teams as well as patents and technical benchmarks found during their research. Jason Moore and Alex Lagina, students who have been participating in this project for several semesters, have also provided much of their work and technical knowledge for this research.

The original bike hub hydraulic system's patent was applied for (application # 20070126284) by our own Jason Moore in December 2006. He and other previous ME450 groups have provided much of the calculations regarding appropriate acceleration and deceleration of the bicycle, the pressure levels in the high and low pressure accumulator, calculations of forces and torques, and the volume of the pump, motor, and accumulator. The previous prototypes and designs are still yet to fit within standard fork dimensions, and have only attempted to fit within a 26" wheel diameter. Also, the previous prototype weights are still over 30 pounds. In addition to excess weight, the overall system requires several times the effort by the rider to petal when not launching or braking due to excessive friction and resistance from continual movement of the internal components when the wheel is rotating.

In addition to research on this particular project, we have found a number of developments that compare to or utilize this rapidly emerging hybrid technology.

The RevoPower retrofit wheel is a similar concept to our own. It is a fully contained gasoline engine powered front wheel that can be attached to almost any standard size bicycle. The gas engine is designed to help power the bike. It only runs when the bike is being pedaled, and it has a shutoff option as well. The system is advertised to help obtain 200 plus miles to each gallon of gas consumed [3]. In order to further investigate the merits of the RevoPower bicycle, we contacted the inventor, Steve Katsaros.

The Parker Hannifin Corp.'s Chainless Challenge is a similar hydraulic bicycle challenge which can greatly be related to our own project. This competition has initiated a number of new ideas in the field of human powered hydraulic hybrid vehicles.

4. Concept Generation

In order to generate possible concepts for our project, we chose to use the functional decomposition and brainstorming method. Functional decomposition allowed us to develop more ideas by focusing on each subsystem separately. By brainstorming separately, and then uniting and discussing our ideas together, we felt that we could achieve the best combination of utilizing the entire group's creative force and objective analysis of individual designs. In the process, we attempted to place as few restrictions and "hard and fast" rules to follow as we could, so that we would consider the design problem from all possible angles.

4.1 Functional Decomposition

Before we began brainstorming separately, we used a functional decomposition diagram to break the overall design into its simplest components (See Figure 2). This allowed us to split the design problem into four operational subgroups: the hydraulic circuit, the power transfer system, the "superbracket" axle and circuit support system, and the bike wheel hub system. Each subsystem also has one or more components.

Hydraulic Circuit: Within the hydraulic circuit are many components and much room for design improvement. The pump and motor are used for energy conversion from potential to mechanical and back. The high and low pressure accumulators are used for storing the hydraulic fluid and, thus, storing the energy (in the high pressure accumulator). The plumbing includes hoses, fittings, and valves. These direct the hydraulic fluid to and from the energy storage components (accumulator) to the energy conversion components (pump and motor), and make sure that the fluid does not flow in the wrong direction.

Power Transfer System: The power transfer system includes the gears and clutches. The gears transfer rotational motion and torque from the motor to the wheel or from the wheel to the pump. The clutches, a new component since previous semesters, prevent the pump from spinning when the bicycle is not stopping, and prevent the motor from spinning when the bicycle is not launching.

"Superbracket" Support: The "superbracket" and axle system support the hydraulic circuit and most of the power transfer system, and hold them all stationary relative to the axle.

Wheel Hub System: The wheel hub includes the wheel rim, the shell that rotates about the axle, and the axle itself. The shell provides the strength to hold up the bicycle, acts as a safety shield for the high pressure system, and is also connected to the main gear which transfers the torque to rotate the wheel. The axle support is another component holding the bicycle up and it also provides resistance to axle rotation relative to the bicycle fork.

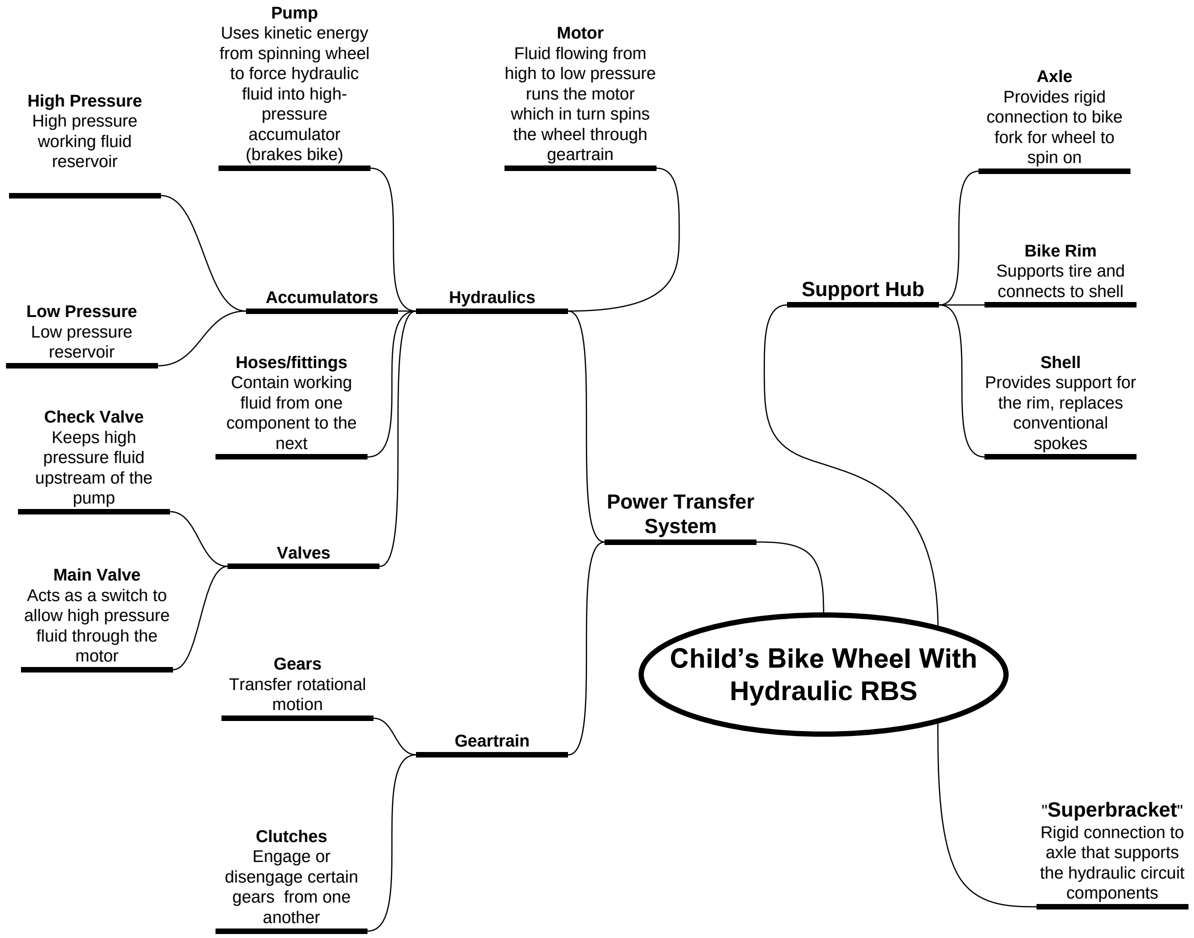


Figure 2: Functional decomposition of the child's bike wheel with hydraulic RBS

4.2 Brainstorming

Next, we agreed to individually set aside time to brainstorm concepts for each subsystem and sketch each idea. From there, we met as a group where we had access to a large dry erase board. There, at the same time each member of the group went to work sketching their ideas on the board for the rest of group. Emphasis was on creativity and quantity of designs presented.

Once all of the design concepts were drawn on the boards, we went through each drawing individually. The author was given the chance to present their idea and explain it thoroughly to the rest of the group. The only rules at this point were that other group members could only ask for clarification on each design. After all the design concepts were presented, the group was given a chance to debate. Group members could offer suggestions, variations, combinations of different ideas, etc.

It must be stressed that throughout the concept generation and selection process, the emphasis was on creativity rather than a rigid process. Therefore, the method described above was not followed to the letter in every instance. It was quite common for the process to be tweaked as we went along. Debate bordering on good-natured argument was encouraged. The final design is a mesh of several good ideas that were modified and changed over the course of the selection.

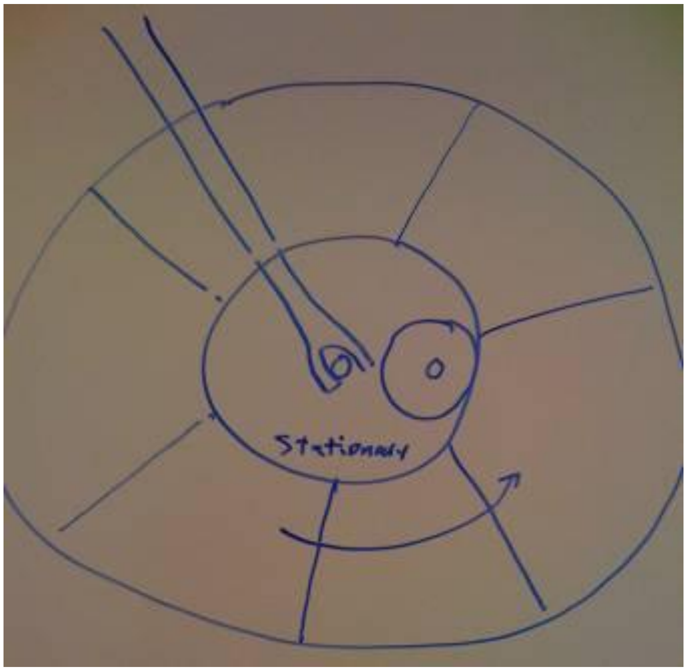


Figure 3: Example of concept drawing using dry erase board during brainstorming

5. Concept Selection Process

After our brainstorming phase, we used several methods to narrow down our options and eventually lead to the best design based on our customer requirements and their relative importance.

First, the concepts were initially reduced by eliminating the ideas that were not physically possible or were infeasible. Next, we eliminated several ideas that were inferior to the benchmark designs established by previous semesters.

5.1 Selected Design Components from Previous Semesters

Several of the previous design components that have been established by previous semesters were found to be our best options, and we chose to keep them over redesigning.

Hydraulic Circuit: In the hydraulic circuit, the main components remain the same; a pump, motor, low pressure and high pressure accumulators, and directional valves. Also, previous semesters have determined that PETE plastic is compatible with our hydraulic fluid, and any bottle made of this material is acceptable for use; previous teams used a honey bottle. We plan to mimic this design. Also, to prevent air from getting into the hydraulic circuit, the best location and orientation for this bottle is at the top of the superbracket with the opening angled forward on the bicycle and toward the ground. The pump will ideally be just below that. For high efficiency, it is less desirable to have pressure losses going from the pump to the high pressure accumulator than from the high pressure accumulator to the motor. Thus, it is preferable to maintain a straight fitting from the pump to the accumulator if a bend must be placed between the accumulator and either the pump or the motor. Figure 12 shows an example of this. They have found flexible plastic reinforced tubes to be preferred over metal piping. Previous groups have used ½” inner diameter hose over $^{3}/_{8}$” due to the approximate doubling of pressure losses with the smaller hose. They have also found solenoid valves to be preferred over pressure sensing valves and manually operated valves. We incorporate all of these things into our design.

Power Transfer System: Previous groups have found gearing to be the most efficient and effective way to transfer the rotation of the pump and motor to the wheel. Other options that were ruled out in their analysis were a linkage system, cams, chain and sprockets, and a belt and pulley.

"Superbracket" Support: The idea of the superbracket remains essentially the same. The shape of the superbracket may evolve, but this is preferred over mounting everything directly to the axle or allowing the entire system to rotate with the hub wheel.

Wheel Hub System: Again, the basic concept of a strong hub with the main gear attached to it will also be used in our design.

5.2 New Concept Selection

Finally, the primary selection tool was introduced. In order to help make an objective comparison of the designs, Pugh charts were set up. Each subsystem was analyzed within its own Pugh chart. Several components of subsystems were analyzed separately with Pugh charts. Each concept was compared to a baseline design (designs taken from previous semester's project design) as well as the other concepts generated for that subsystem. The customer requirements were listed as separate grading categories with the weightings taken from our QFD. The baseline design was rated as a zero for each of the categories. Then, each design was rated either positive (better than the baseline), negative (worse), or zero (comparable). The results were tabulated at the end of the table, and the design with the best score was selected.

Subsystem 1 – Hydraulic Circuit

Criteria	**Weight**	**Baseline** Clutch bearing motor, two 3- way valves	**Concept 1** Clutch pump & clutch bearing motor, one 2-way valve	**Concept 2** Pump/Motor as one, one 4-way valve
Universal Application	9	0	0	0
Natural Rate of Braking	3	0	0	-1(no option for “partial brake” using pump and motor together)
Sufficient Top Speed	1	0	0	0
Efficient	3	0	+1(less plumbing & pump can disengage)	+1 (less plumbing)
Lightweight	9	0	+1 (less plumbing, one less valve)	+1 (less plumbing, one less valve)
Reliable	3	0	0	0
Aesthetics	9	0	0	0
Safety	9	0	0	-1 (huge safety concern if pump/motor gets stuck going one direction)
Easy to Use	3	0	0	0
Easy to Service	3	0	0	0
Maintains Bicycle Function	3	0	0	0
Fits Child’s Bike	9	0	+1	+1
Totals	**64 (max)**	**0**	**21**	**9**

Figure 4: For the hydraulic circuit subsystem, our best choice was to add clutches to both the pump and motor and use only a 2-way valve.

For the hydraulic circuit, previous prototypes lacked a clutch at the pump and required continuous circulation of the fluid. They used two 3-way gears to direct the fluid in circles when not launching or braking. Our other option was to use a motor that also acts as a pump, and use a 4- way gear to connect the two sides of the pump/motor and the high and low pressure accumulators. However, if this valve fails, the pump/motor will only go in one direction which poses a huge safety concern. Our system incorporates a single loop using a 2-way valve to prevent or allow the fluid to flow through the motor.

Subsystem 2 - Power Transfer System

Criteria	**Weight**	**Baseline** Bevel gears	**Concept 1** Double gear system – pump/motor	**Concept 2** Single gear plus support bracket	**Concept 3** Pump/motor sandwiched by ring gear and spur gear
Universal Application	9	0	0	0	0
Natural Rate of Braking	3	0	0	0	0
Sufficient Top Speed	1	0	0	0	0
Efficient	3	0	0	+1 (least amount of additional gearing)	-1 (No opportunity for electromechanical clutch)
Lightweight	9	0	+1 (lighter pump/motor)	+1 (lighter pump/motor)	+1 (lighter pump/motor)
Reliable	3	0	+1 (provides necessary radial support to pump/motor)	-1 (unreliable support for pump/motor)	0
Aesthetics	9	0	0	0	0
Safety	9	0	0	0	0
Easy to Use	3	0	0	0	0
Easy to Service	3	0	0	0	0
Maintains Bicycle Function	3	0	0	0	0
Fits Child's Bike	9	0	+1	+1	+1
Totals	**64 (max)**	**0**	**21**	**15**	**15**

Figure 5: For our second subsystem, the power transfer unit, a double gear system coming off of the pump and the motor scored the highest.

Unlike previous semesters, we must avoid any thrust loads on the pump and motor axle. A bracket would not be enough to support the axle. Thus, our best choice for the power transfer system was to balance the torques and forces by putting a gear that each lead to the main gear on both sides of the pump/motor axle.

Subsystem 3 – "Superbracket" Support

Criteria	**Weight**	**Baseline** Circular bracket aligned with rim	**Concept 1** Thin bracket aligned with rim – designed to fit components	**Concept 2** Double bracket sandwiching components	**Concept 3** Stationary inner cylinder with transverse accumulator
Universal Application	9	0	0	0	0
Natural Rate of Braking	3	0	0	0	0
Sufficient Top Speed	1	0	0	0	0
Efficient	3	0	0	0	0
Lightweight	9	0	+1 (uses only necessary material)	-1	-1
Reliable	3	0	0	+1 (provides additional protection)	-1 (involves using a large bearing system)
Aesthetics	9	0	0	0	0
Safety	9	0	+1 (hydraulics are contained within hub)	+1 (hydraulics are contained within hub)	-1 (accumulator is exposed)
Easy to Use	3	0	0	0	0
Easy to Service	3	0	+1 (hydraulic circuit is exposed when hub is removed)	-1 (hydraulic circuit is sandwiched)	-1 (hydraulic circuit mounted in small space)
Maintains Bicycle Function	3	0	0	0	0
Fits Child's Bike	9	0	0	-1	0
Totals	**64 (max)**	**0**	**12**	**-6**	**-24**

Figure 6: The best score for our third subsystem, the superbracket, was for a thin bracket attached rigidly to the hub that only has material where it is needed, instead of a solid circular bracket.

Our superbracket design remained much the same as previous semesters. We plan on making ours much smaller thanks to our much simpler hydraulic circuit. Thus, most of the components may be mounted very close to the axle.

Subsystem 4 – Wheel Hub System

Criteria	**Weight**	**Baseline** Enclosed shells with 45 degree bevel	**Concept 1** Curved, spoked shells with viewing windows	**Concept 2** Cylindrical shells	**Concept 3** Stationary inner cylinder with transverse accumulator
Universal Application	9	0	0	0	0
Natural Rate of Braking	3	0	0	0	0
Sufficient Top Speed	1	0	0	0	0
Efficient	3	0	0	+1 (provides more space for hydraulics)	0
Lightweight	9	0	+1 (viewing windows remove mass)	-1 (additional mass at stress concentrations)	0
Reliable	3	0	0	0	-1 (involves using a large bearing system)
Aesthetics	9	0	+1 (system is viewable from the outside)	0	0
Safety	9	0	+1 (hydraulics are contained)	+1 (hydraulics are contained)	-1 (accumulator is exposed)
Easy to Use	3	0	0	0	0
Easy to Service	3	0	+1 (remove one side of the hub for service)	+1 (remove one side of the hub for service)	-1 (hydraulic circuit is mounted in small space)
Maintains Bicycle Function	3	0	0	0	0
Fits Child's Bike	9	0	0	-1 (will not fit inside four inch fork)	0
Totals	**64 (max)**	**0**	**21**	**-3**	**-15**

Figure 7: For the fourth subsystem, the support hub, the best score was for a curved shell bolted onto a pre-fabricated bike rim.

Based on aesthetics and strength, we plan to make our hub having a curved surface with fillets and have windows with plexiglass shielding the holes to contain the hydraulics.

Subcomponent of Wheel Hub System: Axle Rotation Prevention

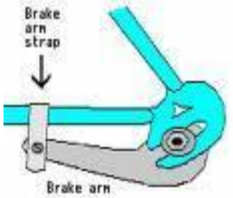
Criteria	**Weight**	**Baseline** Sleeve for fork	**Concept 1** Coaster Brake Design  www.bikewebsite.com
Universal Application	9	0	+1 (more likely to be universal)
Natural Rate of Braking	3	0	0
Sufficient Top Speed	1	0	0
Efficient	3	0	0
Lightweight	9	0	+1 (less material)
Reliable	3	0	0
Aesthetics	9	0	+1 (less noticeable)
Safety	9	0	0
Easy to Use	3	0	0
Easy to Service	3	0	0
Maintains Bicycle Function	3	0	0
Fits Child's Bike	9	0	0
Totals	**64 (max)**	**0**	**27**

Figure 8: A simple coaster brake arm is chosen over a sleeve for the bike fork.

Finally, we have selected an arm that connects rigidly to the axle and has a strap that will retrofit and connect to any bike fork. There will be one on each side of the axle to prevent motion in each direction. This is more likely to fit all bikes than a sleeve, and is less visually obtrusive.

6. Selected Concept (Alpha Design)

Our final selected concept (alpha design) is a fusion of several of the concepts generated by our brainstorming session.

6.1 Alpha Design Layout

Hydraulic Circuit: The basic components of the hydraulic circuit are shown in Figure 8. The low pressure accumulator is a simple bottle made of PETE plastic to hold the fluid when not being used. There is a tube from the outside air to the inside of the bottle to prevent any vacuum as the fluid is pumped from the low pressure accumulator. The high pressure accumulator is a piston style accumulator with nitrogen gas stored in it at an adjustable “precharge” pressure, as discussed before. The pump and motor axles spin as fluid moves through them. The check valve ensures one directional flow through the pump, and the two-way valve is normally closed, and opens when electrically engaged, allowing flow through the motor. The hydraulic circuit design is much different from past regenerative bike hub teams. Instead of using two three way valves and continually circulating fluid, we have opted to use a much simpler two way valve since the motor and pump are using clutches and will not be continuously spinning. Figure 9 is a simple illustration of the hydraulic circuit we plan to use. The black ends on the pump and motor resemble the gears attached.

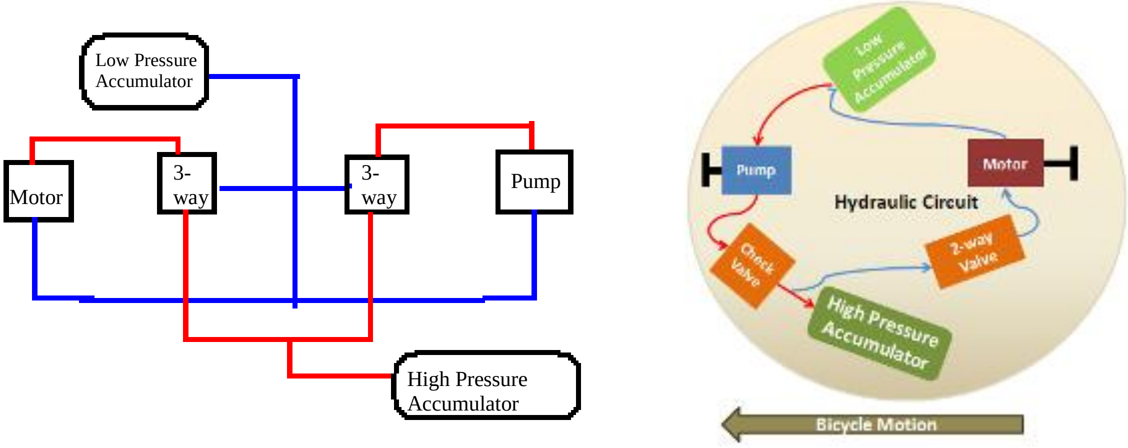
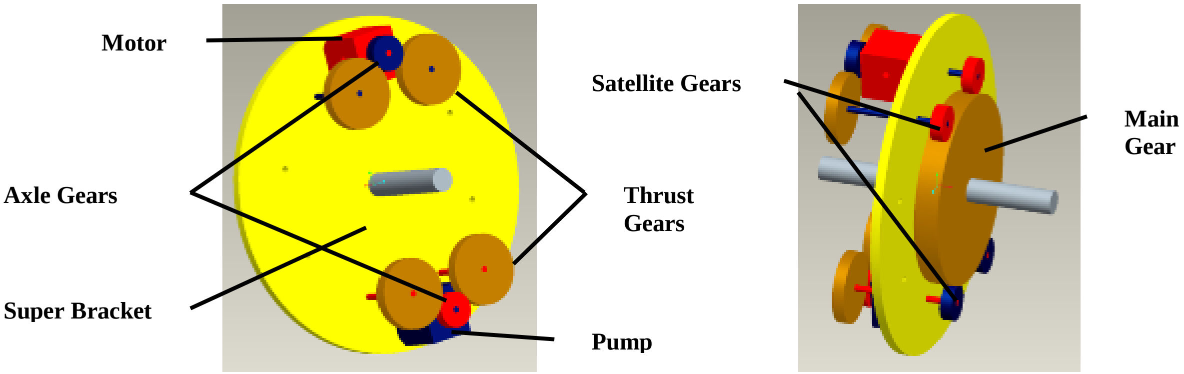


Figure 9: The old hydraulic circuit path (left), and new hydraulic circuit (right) designed to capture braking energy and release it as rotational kinetic energy.

Interior Components: The design includes the hydraulic circuit and power transfer system mounted on a hard plastic “superbracket.” The superbracket will be rigidly attached to the axle and all of these components will remain stationary relative to the bike. It will be circular in shape, with pieces between the mounted components cut out to save on weight. The pump and motor will each have a gear named the “axle gears” on to the driving/driven axle. This gear will be meshed with two supporting gears on opposing sides, named the “thrust gears,” to minimize axial loads, each of which is clutched to two additional gears, called the “satellite gears.” The clutched shafts run next to the pump and motor to align the parts and minimize the width of the wheel. We are using electromechanical clutches for the pump and one way bearing clutches for the motor. The satellite gears will be on the other side of the pump and motor and will be driving a spur gear called the “main gear” that is bolted to one shell of the wheel hub. These shafts will each be supported by a bracket (not pictured) that is countersunk and bolted to the superbracket using flat head bolts and steel standoffs. The target gear ratio for this gear train, as discussed earlier, is 18:1. We plan on a 3:1 gear ratio from the axle gears to the thrust gears, and a 6:1 gear ratio from the satellite gears to the main gear. This layout is shown in Figures 10 and 11.



Figures 10-11: 3-Dimensional depiction of the assembled power transfer unit and superbracket (Fig. 10); side view (Fig. 11)

Exterior Hub: The wheel hub will be in the shape of a bowl. It will overhang the bicycle rim on the sides so that it can be bolted to the rim. An additional lip was created to more evenly disperse weight and not cause huge amounts of shear on the bolts. The sides of the hub will flare out so that maximum volume can be accomplished in a very small space allowing more room to place the motor, pump, accumulators and plumbing. At the center of the hub there is a cutout that allows a piece of metal to be bolted on so that a bearing can be pressed in. The hub will rotate about the bearing which is supported by the axial and allow the bike to roll smoothly. The axle will be mounted to the forks of the child bike. The axle stays stationary by connecting both sides of it to the forks of the bike with the same locking mechanism used in the rear wheels for brakes on childrens bikes; discussed earlier in the report. The axle must be hollow so that plumbing for the brake pressure gauge and switch can be routed out without interfering with the wheel hub rotation.

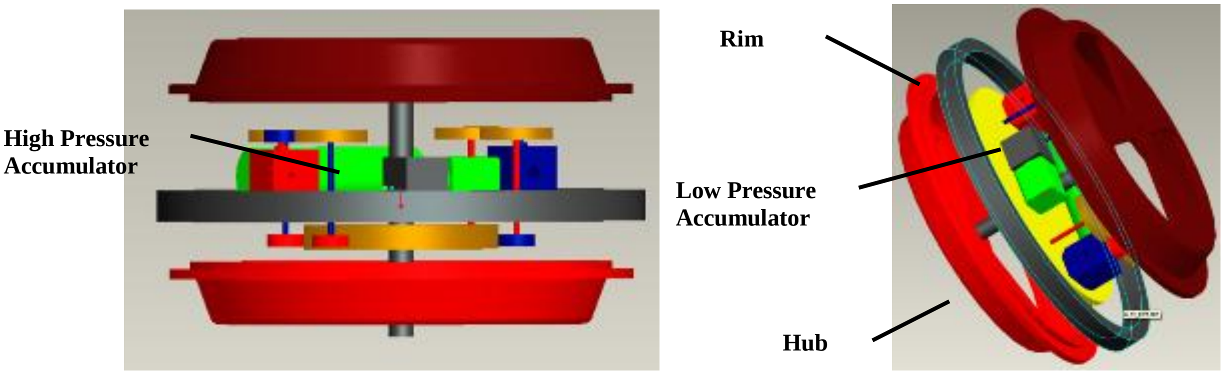


Figure 12- 13: 3-Dimensional depictions of the assembled entire assembly, exploded side view

6.2 Alpha Design Function

Hydraulic Circuit: The overall function of the hydraulic circuit is to store hydraulic fluid in a low pressure container until the pump forces it into the high pressure accumulator. Then, upon launching, the high pressure is released by forcing the fluid through the motor and circulating back to the low pressure container. Our high pressure accumulator is a 4000 psi series accumulator with a precharge of 2700 psi, as discussed before. The change in volume of the accumulator is 0.104 L, based on our calculations shown in the Appendix. Our calculations also show that a full charge of the accumulator stores approximately 2000 J of usable energy. As the bike is decelerating by using the regenerative braking, the two way valve is shut so that no fluid will flow through the motor. A stop from 20 mph or several stops at lower speeds will fully charge the accumulator. When the two way valve is open the fluid cannot pass back into the pump due to the check valve, so it is forced through the motor which propels the bike forward. The maximum flow rate through the pump at 0.64 cc/rev is 1.0 GPM, and the maximum flow rate through the motor is 0.81 GPM. Our calculations are shown in Appendix B. Based on our approximate 80-85% efficiency, the full charge can propel a rider having our minimum weight assumptions (50 kg for bike + rider) back to approximately 17 mph.

Interior Components: We have designed our gear train system based on the pump and motor displacements of 0.64 cc and 0.51 cc, respectively, to have proper decelerations and accelerations. Our calculations in the Appendix show that our maximum deceleration and acceleration are 3.29 m/s^2 and 2.60 m/s^2, respectively. We also designed the gear ratio and precharge pressure such that the minimum deceleration was not too weak, resulting in a final minimum deceleration of 2.3 m/s^2. Again, the addition of clutches allow the shafts in the gears attached to the main gear to spin freely until the launch is activated and the motor gear drives them faster than the wheel is already spinning.

Exterior Hub: The hub must hold the total weight of the bike, regenerative breaking system, passenger, and dynamic loads involved with decelerating, which include weight transfers onto the front forks and torques applied by the motor and pump. The main mechanisms as discussed can be seen on the three dimensional CAD renderings in Figure 12 and 13.

7. Engineering Design Parameter Analysis

We rigorously analyzed our alpha design concept to determine our exact design parameters, component specifications, and materials for our final design. This section describes the decision process leading to our final design parameters.

7.1 Design and Component Selection

Initial Alpha-Design Layout Change: Our initial design includes two shafts with clutches connected to the thrust gears and leading to the satellite gears on the main gear. We realize that these shafts would obstruct the path of the hydraulic plumbing through the pump and motor. Thus, to maintain a balance of forces on the axles while removing the obstruction, we added a third gear, hereby called the “connector gear,” which connects the two thrust gears and moves the shaft leading to the satellite gears to a different side of the pump and motor. This is illustrated in Figure 14. This configuration also reduces the quantity of shafts and clutches by half.

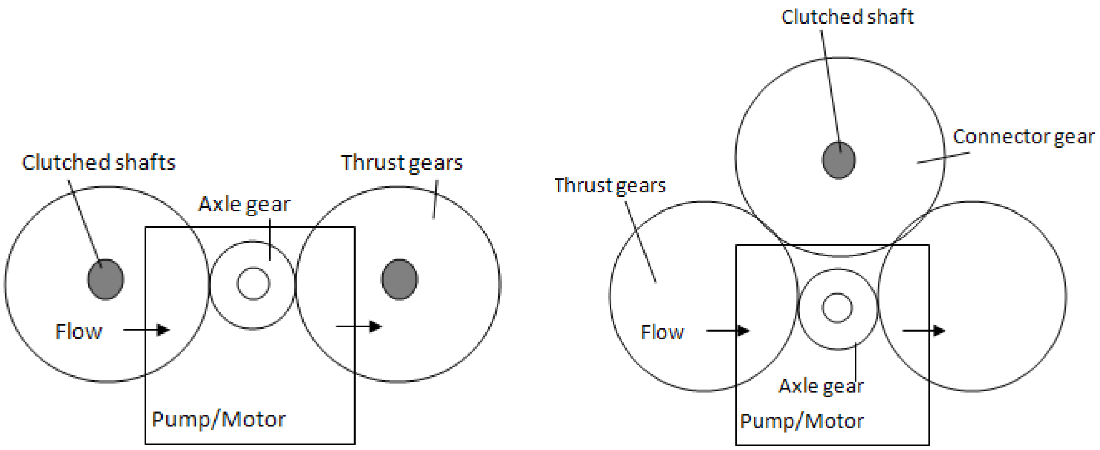


Figure 14: The alpha-prototype design (left) and current modification (right)

Pump and Motor Configuration: Our next consideration in the final layout was the high and low pressure sides of the pump and motor, and the direction of rotation of their axles. Figure 15 shows the configuration of the pump and motor. As shown, the axle is off-centered on one axis. We preferred the shorter distance to be on the side with the clutched shafts to provide more room for clearance, and the shaft to be closer to the center of the wheel to minimize the main gear size. If we put the pump in the front of the wheel so that the fluid in the low pressure accumulator will accelerate toward the pump upon braking, then the pump, motor, and main gear must be on the rider's right side with the axle gears and thrust gears to the rider's left side.

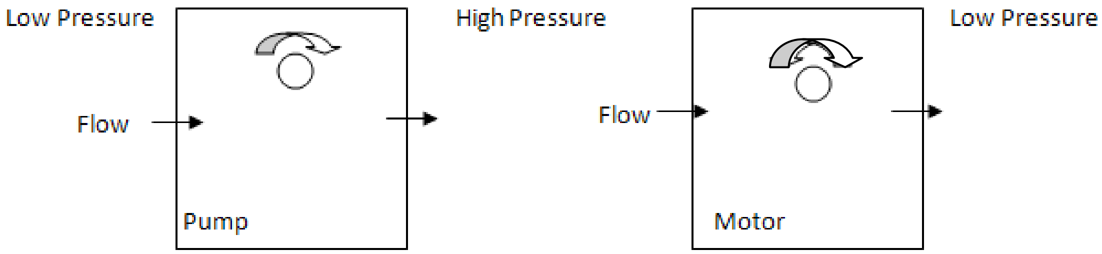


Figure 15: The configuration and rotation direction of the pump and motor

Gear Size Selection: Our gear choices were a critical component with the most constraints. Therefore, we developed the engineering parameters for the gear trains first, allowing the rest of the component specifications and parameters to follow.

We began by assuming a 16 diametral pitch and 14.5 degree pressure angle with a standard ½" face to be strong enough based on the gears used for the 26" wheel having a 12 diametral pitch and 14.5 degree pressure angle, which are slightly stronger for the higher weight and torque requirements on the full size wheel. All of our gears are steel, and the satellite gears must be hardened. First, we chose the smallest axle gear that would meet our horsepower requirements. Following that, we chose the smallest thrust gears and connector gears that would allow clearance for the electromechanical clutch on the pump side and would also be large enough to prevent contact between the axle gear and the connector gear. This is illustrated in Figure 16.

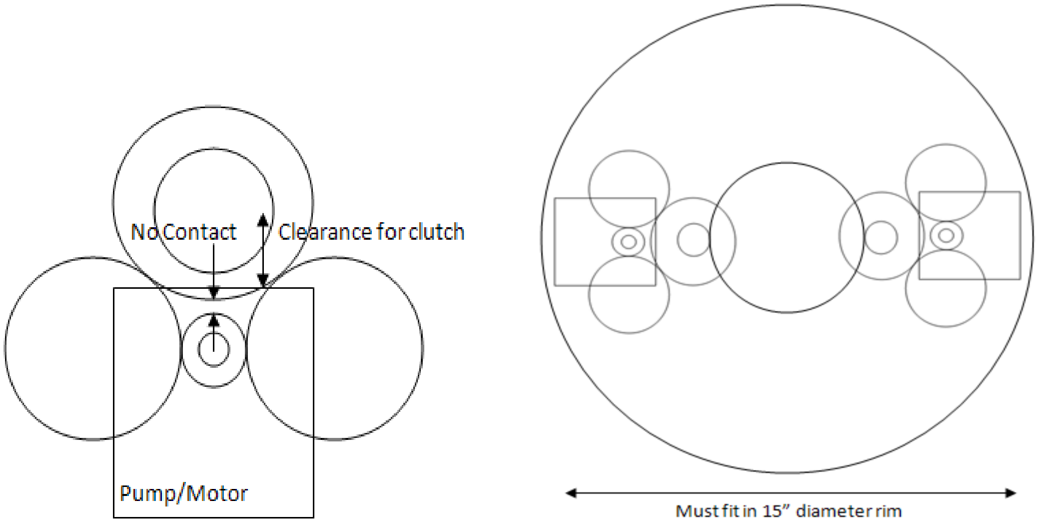


Figure 16: Sizing constraints on gears

The satellite and main gears were sized based on the remaining gear ratio. To obtain an overall 18:1 gear ratio, having already gone through a 44:14 or 3.14:1 gear reduction between the axle gear and connector gear, the remaining gear ratio for main to satellite gears was 18/3.14:1 or 5.73:1. We chose the satellite gears, again, based on minimum size with sufficient strength, and thus determined the main gear size. We then checked that the pump, motor, and thrust gears were all within the wheel rim diameter. This is also shown in Figure 16. Our final gear sizes are summarized in Table 3.

Gear	# Teeth	Pitch Diameter (in.)	Max. RPM	Max. Torque (ft-lbs)	Design Horsepower	Horsepower Rating
Axle	14	0.875	6034	1.7	1.4	1.9
Thrust	48	3.000	1760	5.9	1.4	2.8
Connector	44	2.750	1920	5.4	1.4	2.6
Satellite	14	0.875	1920	5.4	1.4	1.5
Main	80	5.000	336	30.7	1.4	1.7

Table 3: Final gear dimensions and specifications

Gear Strength Specifications: We calculated the maximum horsepower of the system and checked the horsepower ratings for each to assure we were within our limits. Our calculations can be seen in Appendix B. The design horsepower is based on the torque, rotational speed, and service factor. We chose a service factor of 0.8 for light duty since the system will only be used for short times. Also, because the torque on the gears is low at high speeds (when the accumulator is full after stopping and before launching), we calculated the maximum horsepower using the maximum RPM speed and a ¼ full high pressure accumulator. This would only occur if the rider brakes and slightly charges the accumulator and then petals back up to maximum speed.

To find the horsepower ratings, we used the tables given by the gear manufacturers [8]. Boston gear’s website also provided information on how to calculate horsepower ratings that were not given on the charts. An example of this is shown in the Appendix. It is also noted that the Martin

Sprocket gear selection is an AGMA class 6, and they do not recommend rotational speeds over 1800 RPM. Thus, the axle gears cannot be from Martin Sprocket. Boston Gears may have a pitch line velocity of 1000 ft/min. Some of our gears surpass this by up to 38%, but these will be rare occurrences at low torques, so we think they will suffice for our prototype. However, a higher gear grade is recommended for a final product design. Finally, the main gear must be steel to have enough strength, which is not offered by Boston Gear. Therefore, we will order our gears from both Martin Sprocket and Boston Gear.

Gear Ordering Problem and Analysis: Throughout this design process, we were confronted with an unforeseen difficulty regarding gear selection due to the small, metric size of the pump and motor axle (6mm diameter with 2mm wide keyway). Standard gears are manufactured from stock already having a minimum bore size that is larger than our axles. We performed exhaustive research to determine our best option for finding axle gears with the correct bore. Our most promising options are as follows:

1. Order custom axle gears. These would be $300 each with a 5 to 6 week lead time.
2. Order all metric gears. The overall cost of gears would be approximately $1000 with a 3 to 4 week lead time.
3. Get custom work done by Ann Arbor Machine. They have done custom work for free for this project in the past, but did not receive proper gratuity and are hesitant to work with us again.
4. Get standard English gears as chosen before, and use a reducer bushing to adapt the gear to the shaft.

We chose a combination of options 1 and 4. The bushing option will compromise our torque capacity, however we have recently learned that our pump and motor lead times will extend beyond the final design expo and, therefore, may use a bushing as an adapter to show our prototype. We then may still order custom axle gears which will be ready at approximately the same time as the pump and motor. We are also still hopeful that Ann Arbor Machine will be willing to assist us in this custom work at a lower cost.

Clutches, Shafts, Bearings: Following from the gear design is the diameters of the clutches, shafts, and bearings.

The satellite gear is too small to contain the one way locking bearing, thus the one way locking bearing is pressed into the motor connector gear. The bearing must withstand 5.4 ft-lbs of torque as shown in Table 3. The minimum bearing size that meets this requirement is ¾” outer diameter and ½” inner diameter. The bearing RPM limit is 15,000; well above our range.

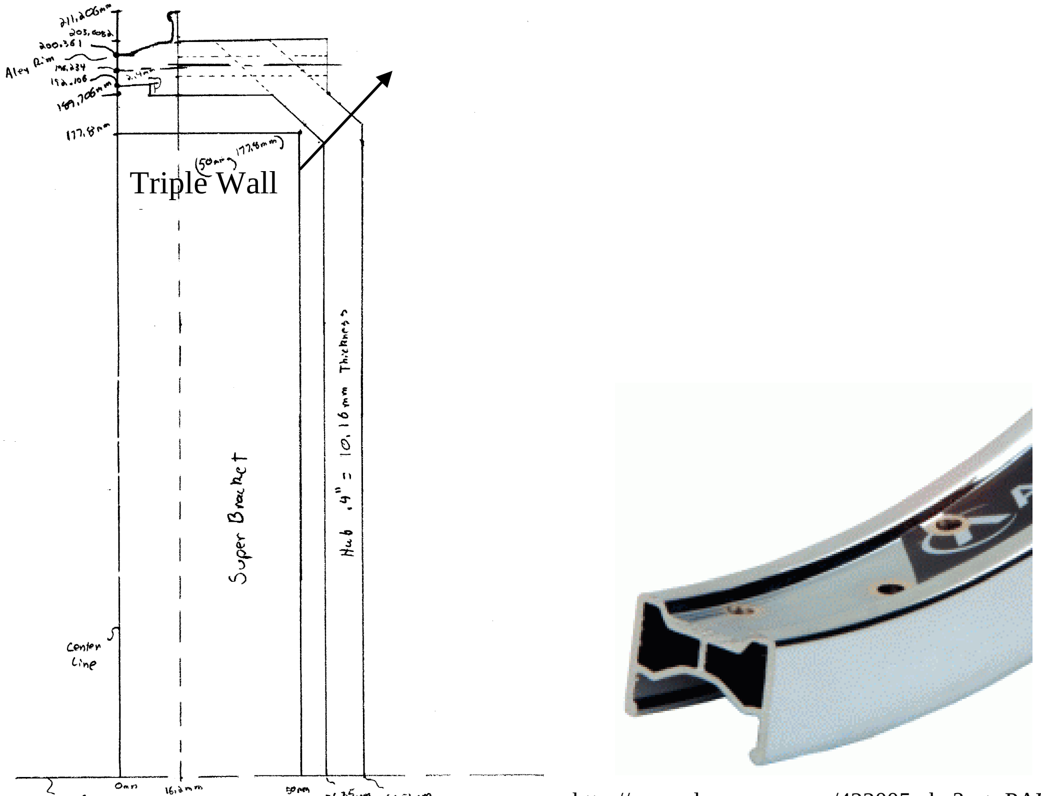
To reduce the number of different parts, we made both of the shafts ½” based on the inner diameter of the one way bearing. Following from that, the electromechanical clutch must have a ½” inner diameter. Again, the clutch must withstand 5.4 ft-lbs of torque, so we chose the clutch rated at 6.25 ft-lbs. This clutch is rated at 1400 RPM. Our maximum shaft speed is at 1920 RPM, however, because this is at rare speeds and at low torques, we think that this will be ok for our prototype. Future final designs may want to consider finding a new clutch.

Finally, we chose “cantilever flanged shafts” to mount onto the superbracket for our thrust gears. These will not impede the plumbing for the pump and motor. We chose bearing sized to fit the inner diameter of the standard size ½” bore on the thrust gears so we will not have to machine the bores. We chose a shaft diameter to fit the 3/8” inner diameter of these needle roller bearings.

We double checked the bearing max RPM and load ratings to be sure that all would operate well within their limits.

Low Pressure Accumulator: We chose the low pressure accumulator to be a honey bottle with a wide mouth as previous teams have done. We sized the bottle to be greater than twice the change in the high pressure accumulator to assure enough room for fluid and some air. Our calculations, shown in Appendix B, establish a minimum low pressure accumulator volume of 7 fluid ounces. Our accumulator volume is 8 fluid ounces which meets this requirement.

Wheel Hub Design: Following the establishment of the final layout and dimensions of the interior components, the final model of the hub was designed. Our alpha design included the basic shape of the wheel hub. We also have chosen a BMX bicycle rim from the Alex Rim company because of its triple wall cross section. Below (Fig 17) is a quarter cross-section of the Alex Rim, Superbracket components and hub. With this drawing it is easy to see that there is not much clearance between the superbracket (14”) and the inside of the rim (15”). In order to properly secure the hub to the rim, a design had to be constructed that allowed a flush mount to the side wall of the rim in the area where a triple wall exists. This area is only 0.325 inches thick and has to be able to contain a ¼” diameter bolt that will properly secure the hub to the rim. In order to reduce stress and allow for minimum width, the hub has a 45 degree beveled edge connecting the horizontal part to the vertical part.



http://www.danscomp.com/422005.php?cat=PARTS#

Figure 17: Quarter cross-section of the superbracket, Alex Rim, and hub (dimensions in mm); Cross section of Alex Rim

In order to provide extra strength to the area of the hub that bolts into the rim a ½” extrusion was created at 12 different locations spaced 30 degrees apart around each bolt that is fastened to the rim. In addition to having a raised area there will also be collars inserted in the hub during fabrication that will be 3/8” outer diameter and ¼” inner diameter so when the bolts are tightened the hub will not crush due to the concentrated force. The force will be transferred through the hub via collars and into the rim.

The hub must rest on the axle to transfer the downward force of the bike and occupant. In order for the hub to transfer force smoothly it must rest on a bearing. It will use a thrust bearing so that the sides of the hub can be bolted together without fear of binding the bearing. Below in Figure 18 there is a CAD drawing that shows the major dimensions and locations of the bolts and bearing and a 3D view of the hub bolted to the rim.

Based on previous prototypes and availability of material, we have chosen fiberglass as our hub shell material.

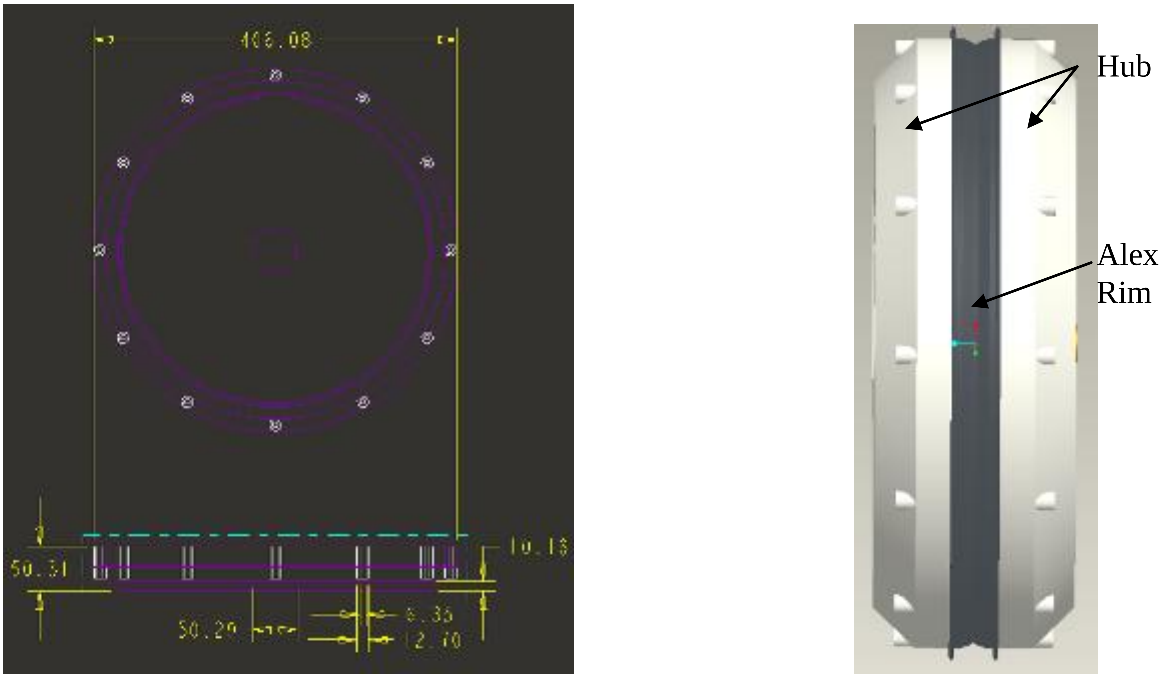


Figure 18-19: CAD drawing of major dimensions of Hub shows bolt and bearing locations. 3D CAD model shows hub bolted to rim

Spider Bracket: In choosing fiberglass for the hub material, a bearing cannot be pressed directly into it. The solution for this is a metal bracket that will be connected to the hub with layers of fiberglass. The name of this component is the spider bracket. It can be seen in Figure 21. It is 5” in diameter (equal to the main gear pitch diameter) and has triangular slots so that the fiber sheets can intertwine and firmly secure the bracket into place. The middle of the bracket is a raised hollow cylinder that is 1.98” in diameter so that the thrust bearing can be pressed into it.

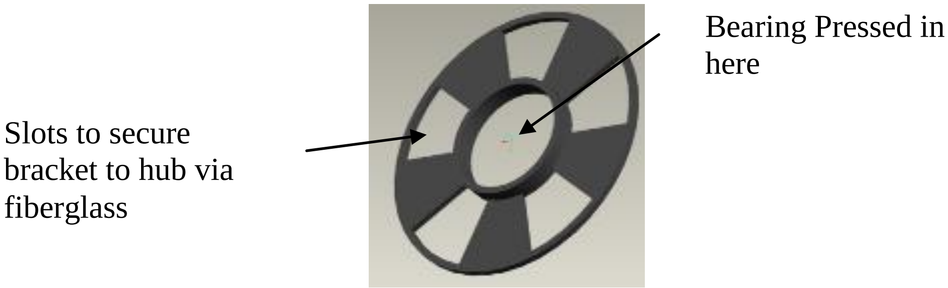


Figure 20: Spider bracket that connects to the hub and houses thrust bearing so the hub can transfer weight and spin freely on the 1 inch axle

In addition to transferring weight through the axle the hub must also transfer torque from the main gear in the hydraulic circuit. Since fiberglass is not strong enough to bolt through, a different version of the spider bracket will be used that will bolt directly to the main gear. The main difference between this bracket (spider bracket driver) and the spider bracket is that it has raised ¼” bolt threads that extend out from the bracket and to the gear, so that the gear can be bolted and firmly secured to the hub (Figure 22).

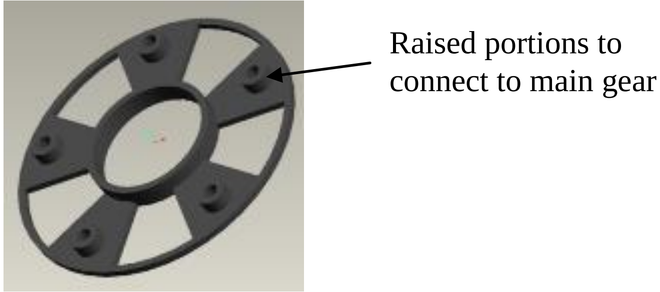


Figure 21: Spider bracket driver that houses the thrust bearing and connects to the main gear

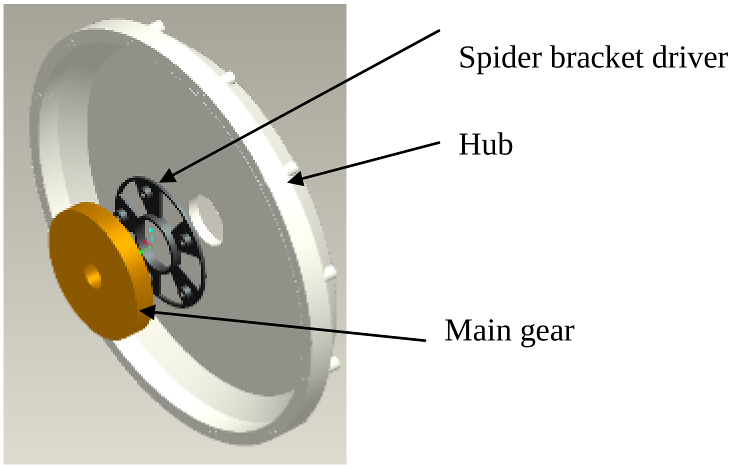


Figure 22: Main gear, spider bracket driver and hub exploded assembly

7.2 Strength and Failure Analysis

Wheel Hub Material Selection: We analyzed the preliminary shape of the hub, including the thickness, to determine whether it will withstand the forces encountered during use. To do this, we employed finite element analysis of the hub design using Altair Hypermesh© software.

Figure 23 shows a static force diagram of a bike with a 20” wheel. Included are the static forces on the bike from the rider, the bike itself, and our modified front wheel. A detailed analysis of the process used to lump the individual components at one center of gravity can be found in Appendix C. At this point we calculated the static forces on the bike. From there we moved to a dynamic force analysis. For a rigorous analysis of the bike, we chose to analyze the forces on the hub that would result from a ten degree downward grade and a maximum braking event. This will be very close to the maximum forces that will act on the front wheel during the life of the bike.

Figure 23: Static free body diagram of the 20” bike

The dynamic analysis of the front wheel yielded a force on the front axle of 422 N, acting at a fifty degree angle (see appendix for equations and diagram). From here we constructed our FEA model in Hypermesh©. Once the appropriate loads were put in place, we had to choose a material to make our hub. Since the machine shop at the College of Engineering has an epoxy/fiberglass mix that can be obtained for free, we decided to evaluate this material to determine if it would function within our design. Pulling the material attributes from the CES Material Universe software (see appendix for attributes), we inputted the appropriate values into Hypermesh©. Figure 20 shows the resulting FEA stress analysis of one-half of the hub.

From our analysis, we determined the maximum stress on the hub to be 45.02 MPa. This is well below the yield strength of 110 MPa, with a resulting factor of safety of 2.44. Therefore, this design is more than satisfactory for our needs.

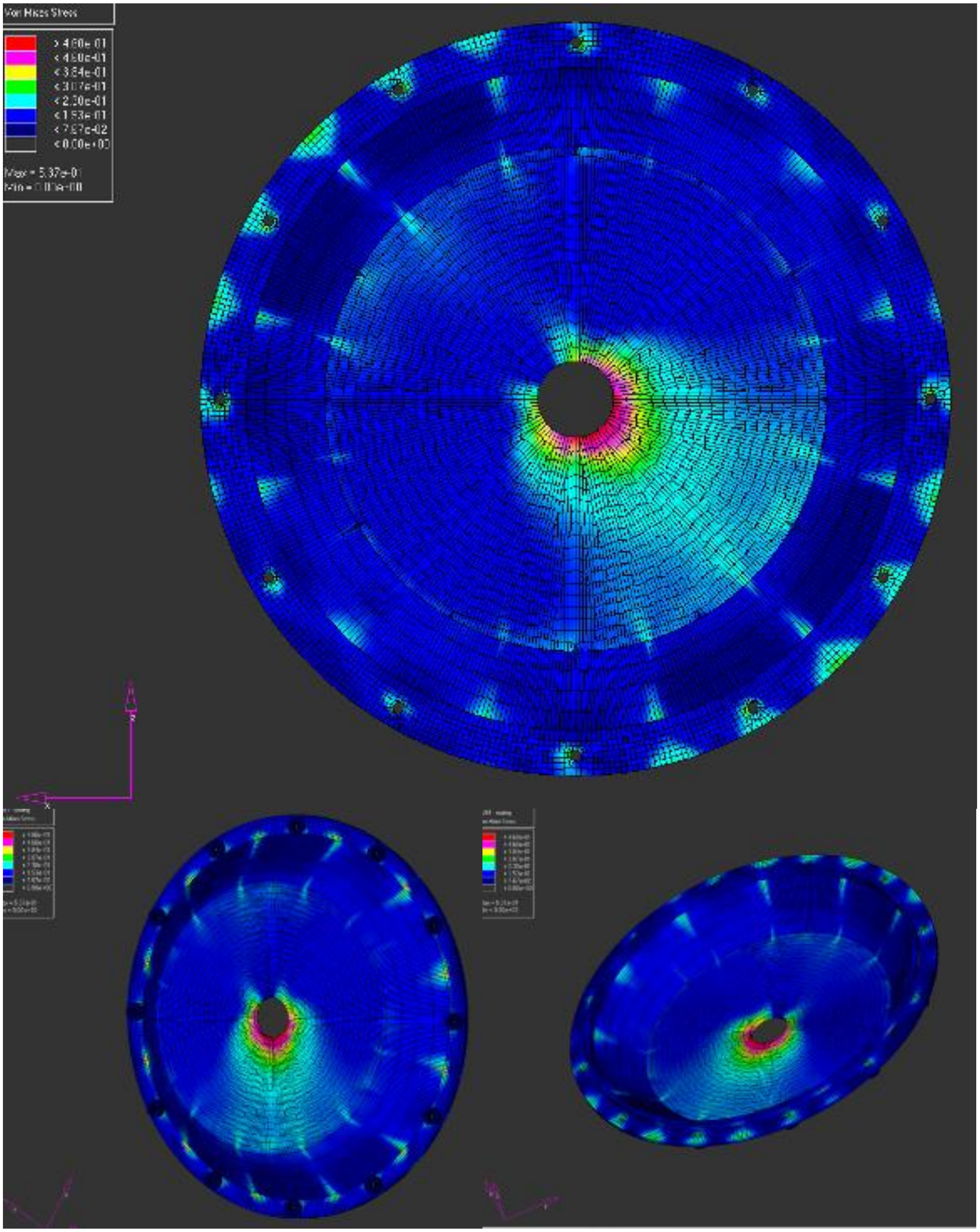


Figure 24: Hypermesh© screenshots of stress analysis of the hub

7.3 Final Design Analysis

Material and Manufacturing Process Selection: Part of our parameter analysis was a rigorous exploration of the options available for two of our system components, as well as the subsequent manufacturing processes. The principle tool used for this analysis was the Granta CES© software. In addition, personal group experience from our prototyping stage and our collective educational background were utilized. The components we chose to evaluate were the thrust gear shafts (four per bike assembly) and the bike hub wheel shell (two per assembly). These components were chosen based on the critical loading requirements specified for each as well as the relatively large amount of material used per wheel assembly.

Appendix E.1 gives a detailed account of our material selection process for both the thrust gear shafts and the wheel hub shell. To begin, we outlined the function, objective, and constraints for the individual material selection processes. From the objective and constraints, we were able to formulate material indices that could be numerically optimized to highlight the best choices for each component. Using the hard constraints and material indices with the Granta CES© software, we narrowed our choices to five top selections for both parts. Finally, cost analysis of each of the five choices yielded the best options. For the thrust gear shafts, we recommend using low alloy white cast iron (BS grade 1A). The shell should be made of an epoxy resin/aramid fiber mixture. These selections are based not only on the software's recommendations but also on our engineering background and experience with these components. We believe that total reliance on the software should be avoided and any final decisions were evaluated separately using our combined engineering knowledge. It is important to remember that the software is a tool that cannot think for itself.

With a material recommendation for both of these components, we could proceed to selecting an appropriate manufacturing process for producing these parts. The first step was to determine a projected production volume for our final design. We believe there is a market for an initial outlay of 1000-10000 of our final product. Using this condition as our base, we also specified the material, necessary tolerance, and shape for both parts. The Granta CES© then returned the suitable processes for our manufacturing conditions. Based again on a cost analysis, we were able to select shell casting for the fabrication of the thrust gear shafts and resin transfer molding for the hub shell. Again we were also able to apply our engineering knowledge and familiarity with these components (from our prototyping stage) to help us to select the appropriate process. We believe this is a necessary extra step when working with software of this nature. The details of our process selection are available in Appendix E.2.

Design for Assembly: From the use of Design for Assembly (DFA) charts, we were able to not only list the order of assembling components correctly but also calculate the amount of assembly time required to complete the construction. From the amount of time for each component compiled together, we found design efficiencies for each sub-system involved with the hydraulic bike hub assembly. Each of the sub-systems analyzed was found to be within a 35-52% efficiency which is exceptional considering this project is a first-time manufactured product. We were able to see that there will be room for improving the assembly time in future semesters by reducing part numbers and re-organizing the order of assembly.

Due to the intricate design of the bike as a whole, each assembly process was not thoroughly examined using the DFA charts, however the most important and overall wheel along with superbracket structure was examined. Please see Appendix E.3 for a detailed description of each sub-assembly and the result charts which include all specific design efficiencies.

Design for Environmental Sustainability: Part of a thorough analysis of any engineering system is an investigation into its environmental impact. In order to complete this analysis, we utilized the SimaPro 7.1© software available to ME 450 students. We began by calculating the mass of material for each of the two components used in our material selection that would be necessary to build one bike wheel assembly. Based on these numbers, we used SimaPro to evaluate the environmental footprint that the use of these materials would leave. This evaluation included a sum of the emissions generated for each material, a summary of the impact for each of ten EcoIndicator 99 damage categories, a relative comparison between each materials impact in three EI99 meta-categories, and a summation of each material's EI99 point values for each meta-category. The details of each of these analyses are given in Appendix E.4. From this evaluation of recommended materials, we determined that the aramid fiber would have the biggest environment footprint compared to the cast iron and epoxy resin. However, the total numbers do not indicate that a reevaluation of our material choices is necessary. Despite the fact that the aramid fiber performed poorly compared to the other two materials, we believe that it is still well within the acceptable limits for environmental consequences.

Design for Safety: Using the DesignSafe© Software provided by the University of Michigan, we were able to perform a risk analysis on each of our bike's components, whether that is mechanical, hydraulic, electrical, or ergonomically related. The results of our risk assessment showed that the main hazards associated with our product are related more commonly to malfunctions which would affect future riders. The highest risk levels were registered with mechanical malfunctions of the two-way valve causing an unwanted launch, or if the clutch were to malfunction and the rider were unable to brake the bike for safety. Other hazardous concerns that were discovered by the assessment include hydraulic fluid leaks or water from outside leaking into the system, electrical surges caused by too much voltage supply or too high of impact pressures if the rider were to put such stress on the front wheel (where the components are all located).

The results of our assessment allowed us to analyze potential risk reduction methods that will help reduce levels of risk to an acceptable point. There is no such outcome as a zero risk for any component. Therefore, taking preventative measures such as labeling hazardous actions on the bike or suggesting frequent inspections will help eliminate failures that are inevitable with time. Appendix E.5 shows the design for safety software analysis.

7.4 Future Analysis

We recognize that there is much analysis that time restrictions this semester did not allow for. Because of the complexity and number of parts in the design, there are many more strength and failure analyses left for future work. This includes all of the forces on the superbracket, the shear stress on all of the bolts, the force from the main gear on the shafts and standoff brackets, and the torsion and shear stress of the superbracket connection to the axle and axle in the fork. We recommend looking at the similar work for the 26" wheel done by the Fall 2007 team to apply their calculation methods for our design. This will verify sufficient strength of the components, and also allow an objective justification of removal of material from the superbracket for weight reduction. We have attempted to overdesign on strength of the components as an initial prototype of our design.

8 Final Design Description

Here we present our final design description, its functionality and materials used. We also present a bill of materials for our components, and a list of in house parts that will be made.

8.1 Interior Component Layout and Function

Based on all of our design constraints discussed under Engineering Parameter Analysis, we have established the final layout design shown in Figures 25 through 31. Also not shown in these figures is a bracket to support the other side of the shafts near the satellite gears. Figure 27 shows the direction of rotation for each of the gears. Because the main gear is aligned with the pump and motor, this configuration also allows for the absolute minimum width of the interior components equal to the width of the pump and its axle, as shown in Figure 30 and 31. Figure 25 shows the direction of fluid flow during braking and during launching. As discussed previously, the electromechanical clutch engages the satellite gear to the connector and thrust gears that turn the pump and force fluid to the high pressure accumulator. When launching, the check valve assures that fluid will not flow in reverse through the pump, and the 2-way valve opens to allow flow through the motor instead, driving the shaft in the one way locking bearing to power the main gear and propel the wheel.

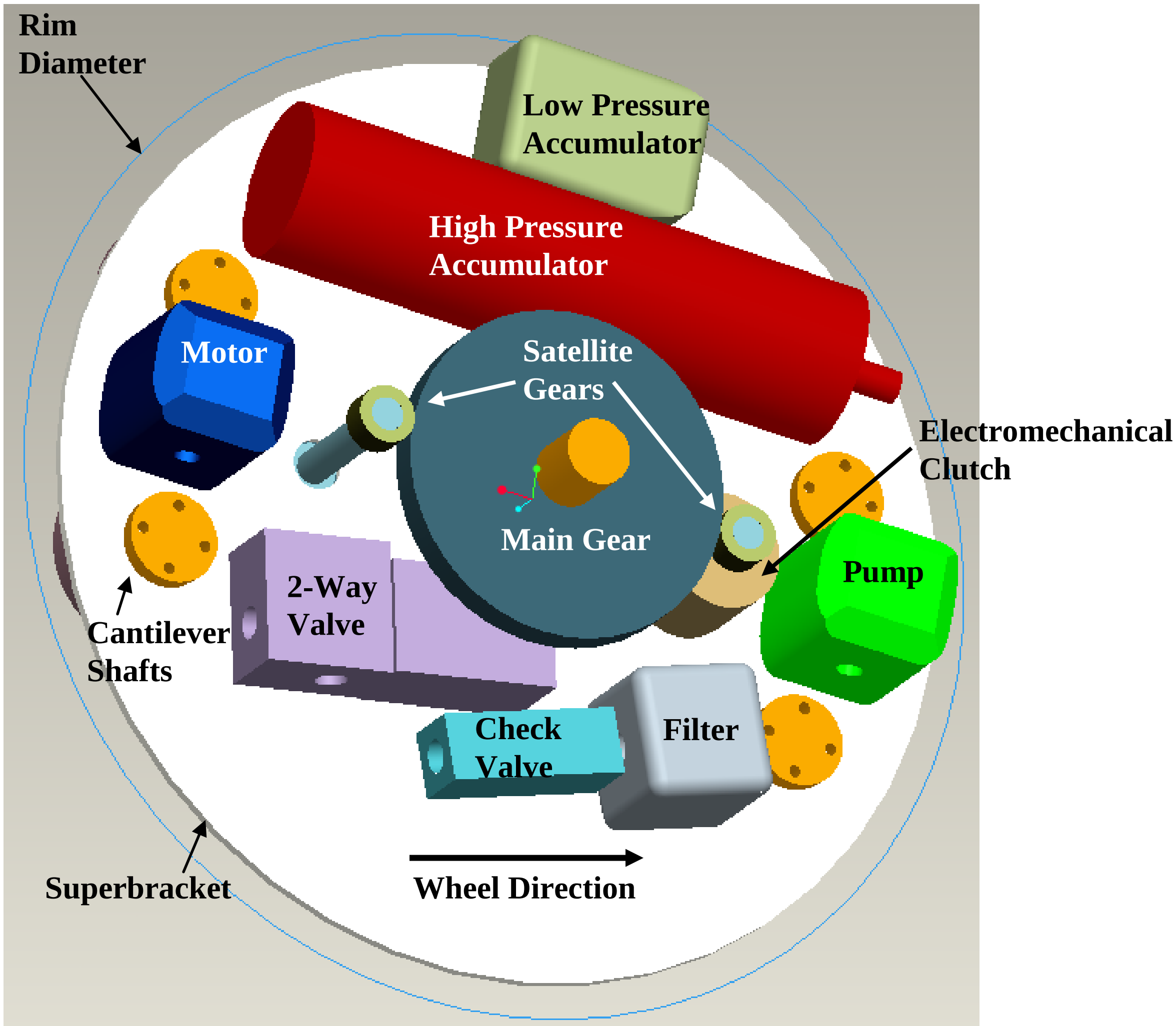


Figure 25: Layout of main gear side of superbracket

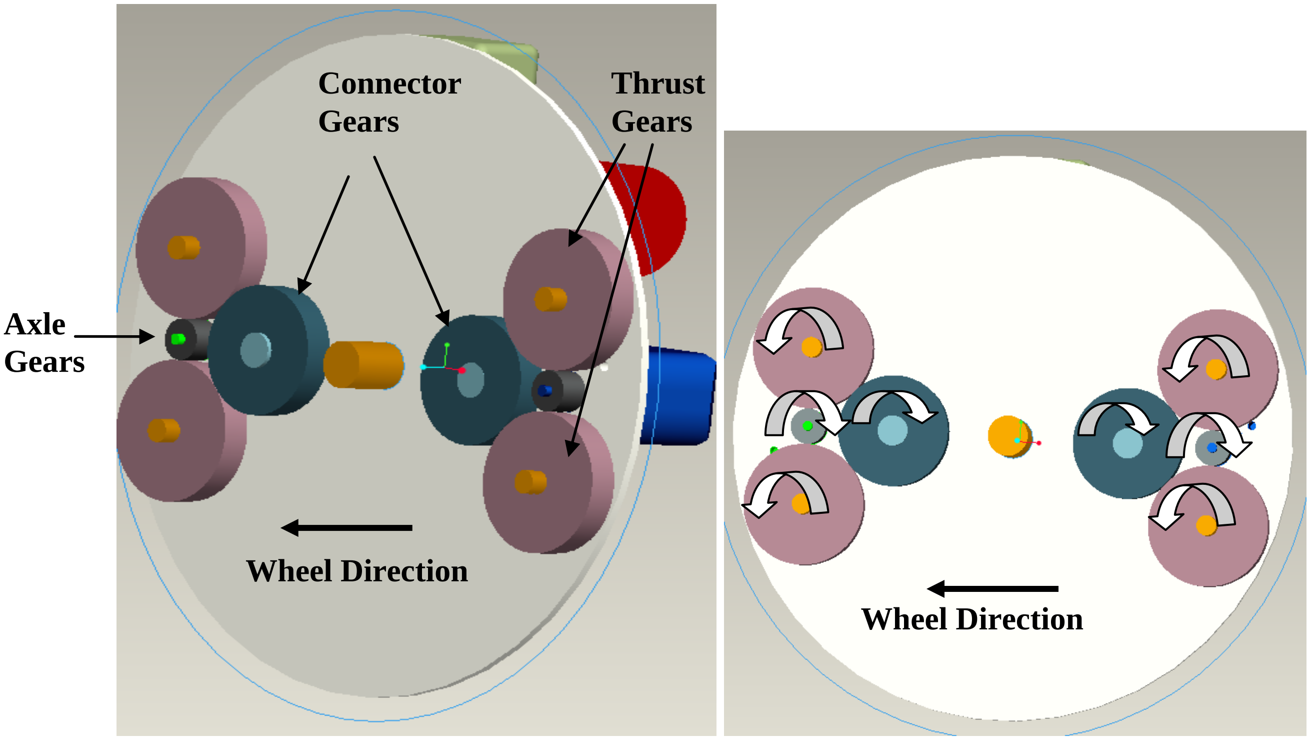


Figure 26-27: Layout of gear side of superbracket and rotation directions

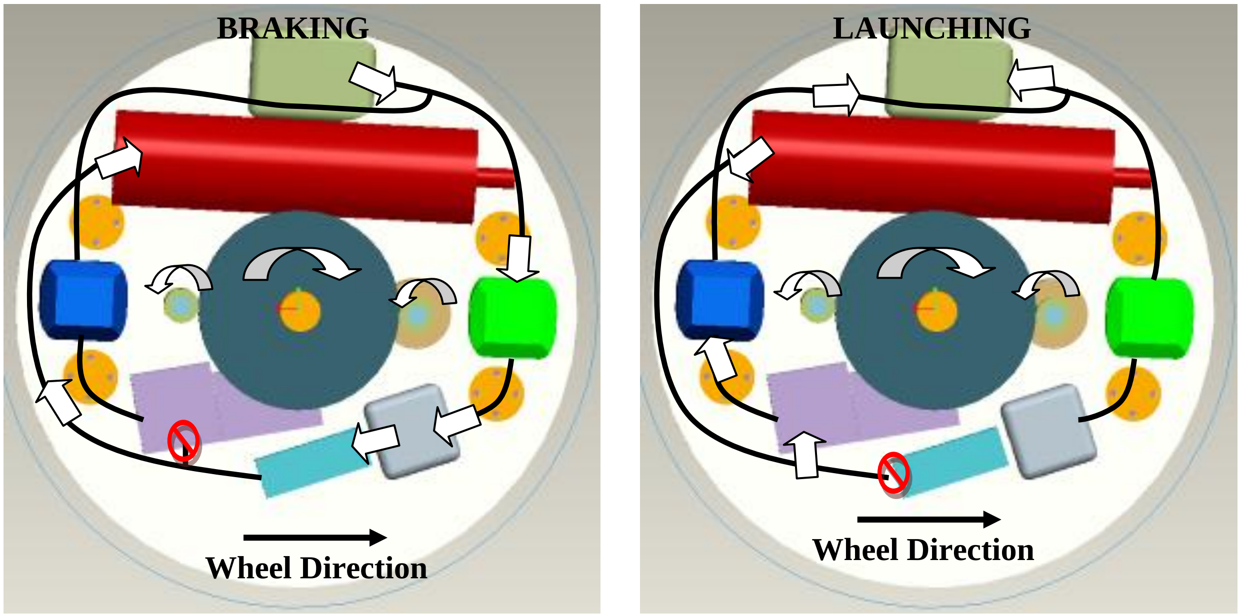


Figure 28-29: Direction of gears and plumbing while braking (left) and launching (right)

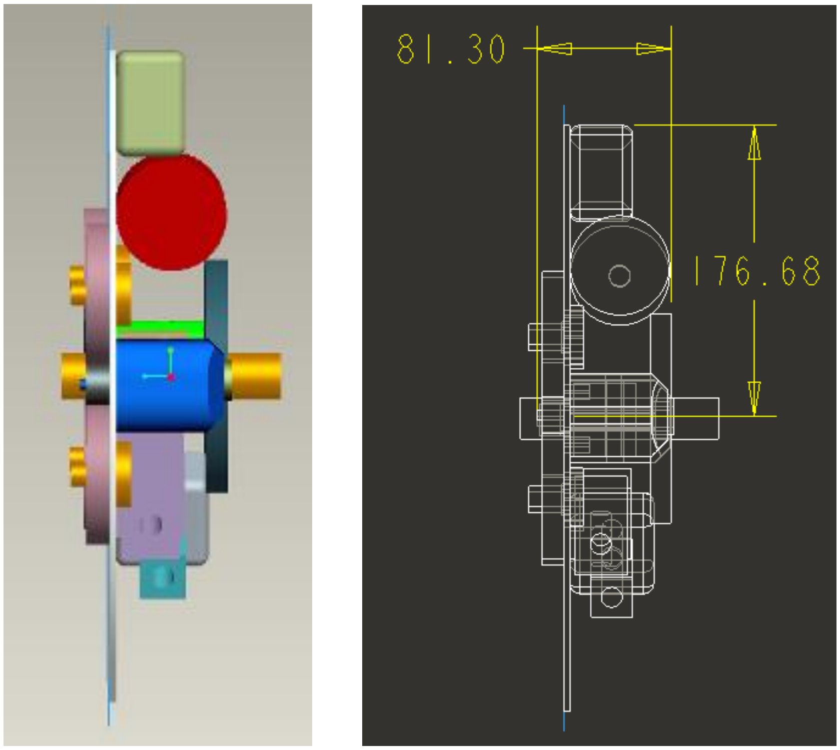


Figure 30-31: Side view of layout with dimensions in mm: Interior components contained within 3.2" wide and 14" diameter

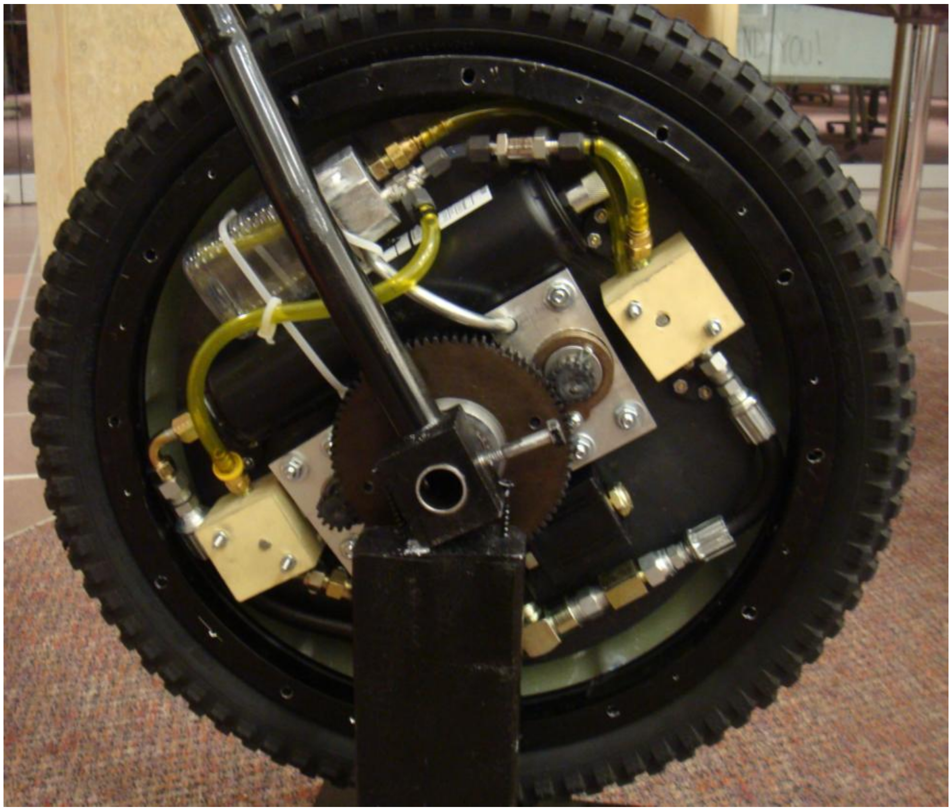


Figure 32: Full bike assembly; final product

Superbracket: The superbracket is a 4 mm thick sheet of steel. This is so that we can weld the superbracket to the axle rather than weld fixtures to the axle and bolt the superbracket to the fixtures. The weld will save space, simplify the design, and have approximately equal weight to the bulky fixtures and thick plastic superbracket. The standoff support brackets for the shaft and electromechanical clutch are made of 3/8” thick aluminum plates. The superbracket and the aluminum plate for the shaft on the motor side have miniature steel radial ball bearings pressed in to support the shafts. The aluminum plate on the pump side is around the clutch and is bolted to it. The cantilever shafts are put through the holes in the superbracket and bolted through the countersunk holes on the gear side of the superbracket. The pump, motor, 2-way valve, and c-clamp holding up the high pressure accumulator and low pressure accumulator are bolted to the superbracket. The c-clamp for the high pressure accumulator acts as one of the bolts through a standoff on the pump side due to space restrictions.

Wheel Axle: The wheel axle is a hollow 1” outer diameter steel pipe. The superbracket is welded to the axle off-centered, and a large hole is cut into the axle toward the back of the wheel. This allows us to run a pressure gauge line and electric wires for the electromechanical clutch and the 2-way valve up to the handlebars of the bicycle. Again, we choose steel stock from the College of Engineering machine shop for our prototype because it is free and we can weld our superbracket to it.

Gears: The final gears are as described in the Parameter Analysis section. As stated previously, the final design will incorporate custom gears to the pump and motor axles. Our prototype will have the same gears with a steel reducer bushing to adapt the gear to the metric axle. The main gear bolts to the spiderbracket that is inlaid to the hub shell. To minimize width and weight, the hubs are taken off of all the gears. The satellite gears are welded to the shafts because the gear is too small for a keyway and there cannot be a set screw without a hub. All of the gears on the left side of the superbracket have needle roller thrust bearings between them and the superbracket for smooth rotation. They are kept on the shaft by a retaining ring rather than a screw on the shaft to reduce the width of the wheel.

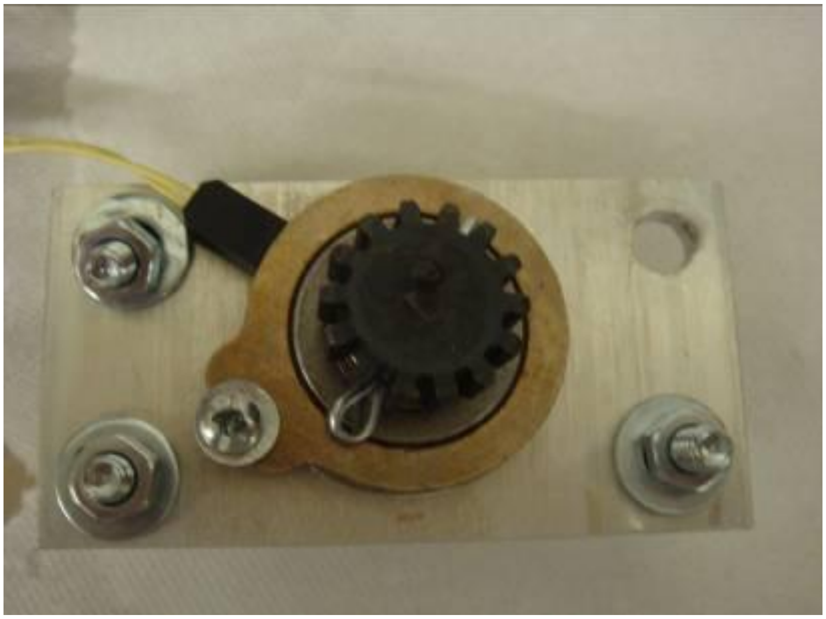


Figure 33: Top view of clutch showing pin through shaft (under gear) and bolt connecting clutch to the bracket

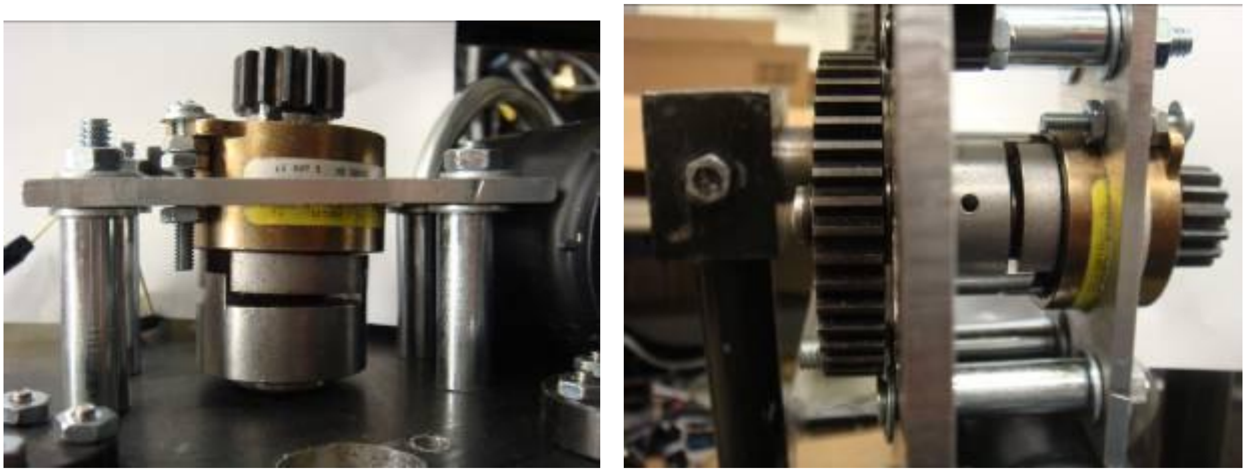


Figure 34: Clutch and coupler side views

Clutch: The shaft in the clutch has a pin through it and the pinhole on the clutch to transmit the rotational power from the clutch to the shaft (Figure 33). To keep the shaft from falling out, there is a retaining ring on the inner end of the clutch. There is a screw through the coupler and the other side of the shaft to transmit rotational power from the pump connector gear to the clutch (Figure 34, right). There is also a keyway and key in the pump connector gear to transmit rotational power from the gear to the shaft that leads to the clutch. A needle roller thrust bearing between the coupler and superbracket allows low friction rotation.

Figure 35: Low pressure accumulator with cap and fittings

Low Pressure Accumulator: An aluminum block with a space to epoxy the honey bottle's cap into provides a body to attach the hydraulic fittings without leaks. One fitting leads to the filter, pump, and motor. The other fitting is open to the air and on the inside of the low pressure accumulator connected to the same hole is a fitting with a tube to let the air in without letting the fluid leak out.

Filter: We have added a filter in our final layout to accommodate our customer and engineering requirements.

8.2 Hub and Exterior Design

Hub Design: Our hub design for a manufactured product would maintain approximately the same shape as our prototype shape, but would be more curved and incorporate the windows as discussed in our alpha-design. It would ideally be stamped out of the appropriate metal to provide the shape, strength, and minimize spatial requirements. This design in conjunction with the interior component layout design would guarantee a wheel width less than or equal to standard wheel widths. However, for our prototype we will be implementing the design discussed under the Parameter Analysis section. Also, due to the fiberglass prototype material, the incorporation of viewing windows will not be possible.

Connection to Fork: Our final design for fork attachment is to have essentially the same connection as standard bicycle wheels. Because of time restrictions, the prototype differs from our original hopes to make the axle attach to the fork in a similar way to standard wheels and having an arm attached to the fork to prevent the axle from rotating. To attach to the fork, steel blocks are welded to the fork arms and a hole for the axle is cut into the blocks. A pin sticking through the blocks and axle prevents the axle from rotating in the forks.

8.3 Electrical Circuit

Circuit Design: The final design will incorporate a full electrical circuit in order to trigger the launch of the bicycle and the regenerative braking system. A single-pole, single-throw switch ((on)-off) will be utilized for both the braking and the propulsion activation. Both switches are spring loaded to the "off" position, so the switch must be actively thrown in order for the respective braking or propulsion event to occur. One switch will trigger the electromechanical clutch that will effectively engage the pump and brake the bike. The other will open the two way valve to allow high pressure fluid through the motor and effectively propel the bicycle. The circuit can be cut by the master on-off switch, which will act as a safety feature. The system is powered by three 9-volt batteries connected in series. A 3-amp fuse is included so that the circuit is never overloaded. Figure 36 illustrates the arrangementof the circuit components.

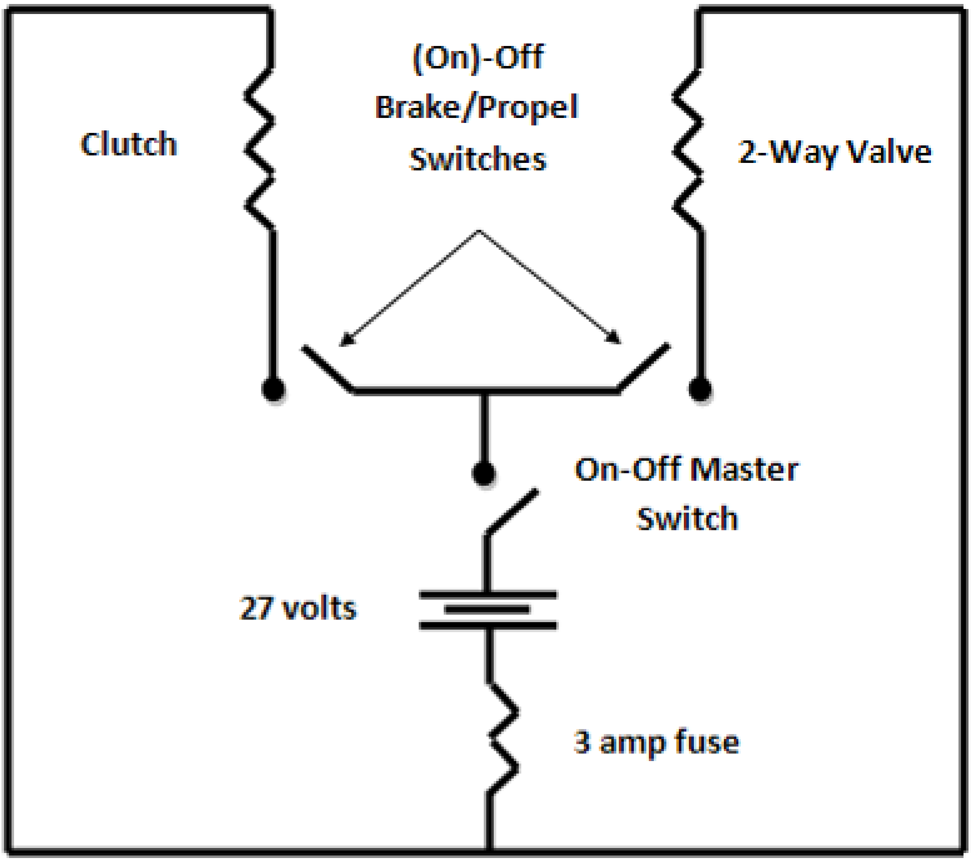


Figure 36: Diagram depicting the electrical circuit layout for hydraulic braking and launch equipment

Circuit Component Layout: Placement of this circuit on the final design is crucial to the aesthetics of the bicycle. For convience, the trigger switch will be located on the right handlebar of the bike. As already mentioned, the safety switch will not be be near this trigger switch forcing the user to purposely make an effort to switch it to the "on" position when ready to launch or regenerate power through braking. This switch will be on the left handlebar. The batteries will be located with the two (on)-off switches where they can be conveniently accessed to change them if necessary.

Our goal for the prototype is to have the circuit as discrete as possible so that the bike is still aesthetically pleasing to a potential buyer. The only discrepancy between the prototype and final design will lie in the switch boxes or battery box, which may be less pleasing to the eye than the ultimate final design would be.

8.4 Deviations From Final Design and Final Prototype

There were several last minute changes with the plumbing design. First, the filter we had planned to use was approximately 8 pounds and 6" long, including fittings. We recently found a 5µm inline filter that was purchased by the EPA for a previous semester and never used. We did not originally count on having this type of filter because of the cost. The fittings on the inline filter, unlike the original filter, are only rated for 1500 psi. Thus, we made use of it, but had to change the location of the filter to the low side, between the low pressure accumulator and the pump. Second, we had planned on using a Parker Hannifin C300S check valve, but did not have enough room for it and all of the other plumbing and fittings. We replaced it with a much smaller check valve, but its pressure rating is only 3000 psi. This will have to be replaced in the future.

Figure 37: The old filter (left) versus the smaller new filter (right)

We also did not anticipate the ½" wide coupler for the clutch. We did not realize that this was how the clutch connected or disconnected the two shafts, and did not account for this width in the original layout. Thus, the main and satellite gears had to be extended away from the superbracket by ½".

8.5 Bill of Materials

Most of our parts are power transmission and hydraulic components that we will order from various manufacturers and distributors. A summary of all of our parts can be found in Appendix F.

9 Fabrication and Assembly

This section details how to machine all of the necessary parts and how to assemble the prototype we have designed.

9.1 Fabrication Plan

Many of the parts on the bike hub can be manufactured in the undergraduate machine shop. Bob and Marve are excellent sources for information on tolerances, setting up mills and lathes, and ideas for how to go about machining different parts. Below is a detailed description of all parts fabricated and the fabrication process used.

Superbracket: The superbracket is the most important component of the entire hydraulic regenerative braking system assembly. It supports all of the components involved with propeling and slowing down the bike. This must hold all the components and the weight of the bike and driver. Show below are images of the superbracket after fabrication. Notice all holes are made, axle is welded with slots, and all edges are deburred before using in assembly.

Figure 38 Side view of super bracket

Figure 39: Top view of superbracket

The first step to assembly is to gather the raw materials. The super bracket has a diameter of 14in and an approximate thickness of 4mm (0.15748"). It is hard to find sheets of circular material in this diameter so it is wise to purchase a square sheet of 1080 steel that is at least 14" by 14" and 4mm thick. The axle is made from 1in tube steel.

Find the exact center of the 14" by 14" by 4mm sheet of steel. Place the sheet onto a piece of ply wood and secure it to the mill. Mark the center of the steel using a center drill. If you plan on not finishing it is smart to drill a ¼" hole that is one thousandth over for a doll pin to stick in so that you can find the center origin again. Use the center drill to mark the centers of all the holes. Zero the coordinate system on the center of the sheet of steel and find the centers of all the circles using the CAD drawing below.

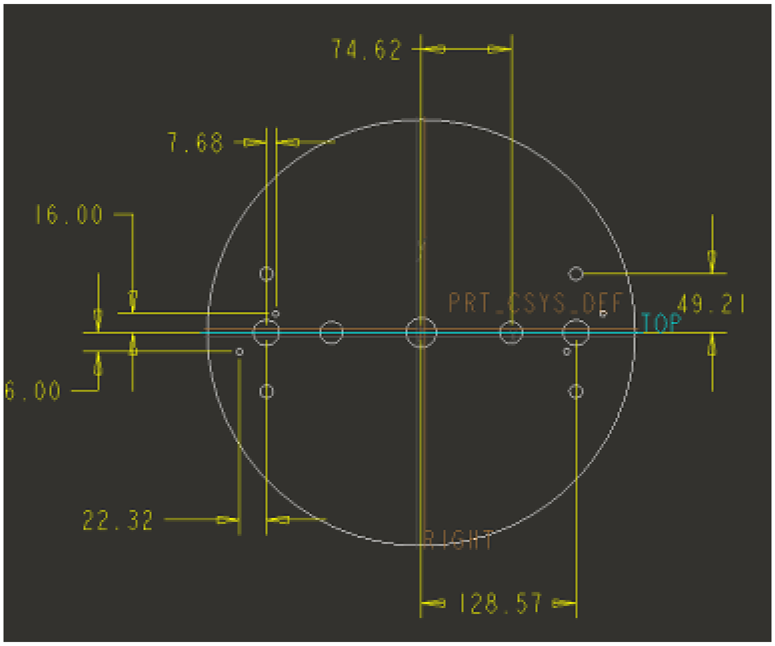


Figure 40: CAD of super bracket hole centers (all dimensions in mm)

After finding the centers, go back and drill out all of the holes with the correct drill bits except for the 19.05mm (satellite/transfer gear shafts). This is because a bearing must be pressed in here so the tolerances are very important. Measure the bearings that will be pressed into the hole. They will not necessarily be the dimensions given by the manufacturer. After all the holes are drilled, go back and use a ½" drill bit to drill out the 19.05 mm holes. Next, use a boring bar to make the hole one thousandth smaller than the bearing diameter. Use the CAD drawing below for the hole diameters.

In order to make the hub circular, you must use a rotating table for the mill. Secure the super bracket to the rotating table, find the center using a dial indicator, use a ¾" end mill and move the inside of the mill 7" away from center. Mill out the bracket by rotating and raising the table.

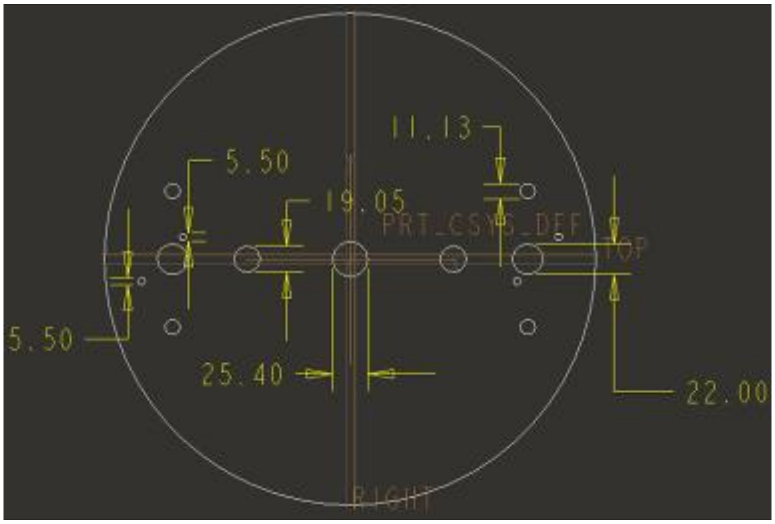


Figure 41: CAD of super bracket hole diameters (all dimensions in mm)

Cut the 1" tube steel to 6.5", put it in the lathe and make it to the 1" tolerance needed for the hub bearings to slide on. Next, cut a ½" slot 3" onto the axle so that the plumbing and wires can be routed out the sides. Finally, weld the tube to the super bracket. Be sure when welding that the orientation of the superbracket allows for the low pressure accumulator bottle mouth to be facing slanted down toward the ground in front of the bike wheel.

Hub: The hub must support the entire weight of the bike and all of its components, seal the internal components of the regenerative braking system, and freely rotate about the axle. The first step for fabrication of the hub is to make a cavity so that fiberglass can be layered in to form the hub. The CAD drawing below shows the necessary dimensions to make the hub. The best way to make the cavity is to use a mill with a rotating table attached. Place a slab of yellow board cut to 18” in length. Find the center of the slab and mount it in the mill using ½” bolts. First drill a ¼” on thousandth over hole for a doll pin in order to locate the center later. Drill this hole almost all the way through the board.

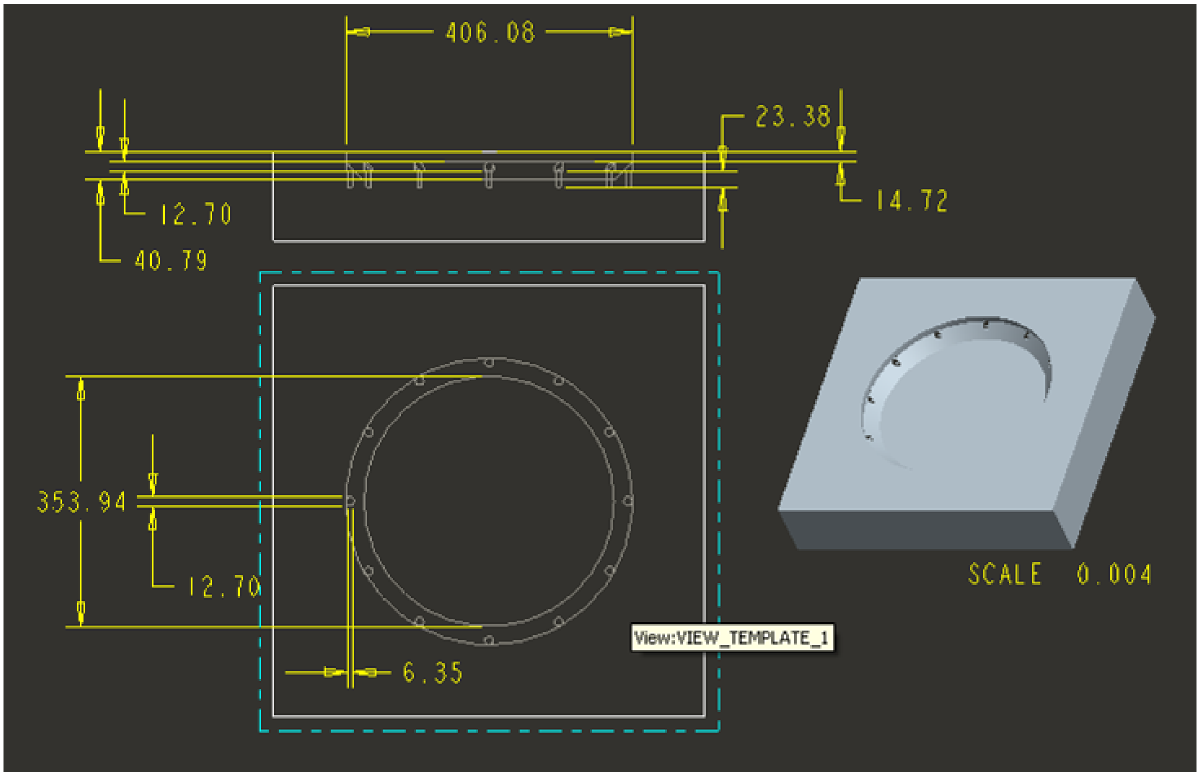


Figure 42: CAD of hub cavity, labeling all dimensions needed to manufacture a replica cavity

The cavity can be broken up into three different volumes, the inner cylinder, outer cylinder, and 45 degree ring. Use a ¾” 4 edge flat end mill to mill out the center cylinder taking ¼” steps all the way out to a radius of 6.97”. Move the mill up to cut the outer cylinder to the correct depth, move the mill out to a radius of approximately 8”.
Now use a ½” end mill to make twelve ½” deep holes that are 30 degrees apart around the cavity. Repeat this for a ¼” one thousandth oversized hole in the exact same locations with a depth of ½” deeper than the ½” hole.

Use the 45 degree ¾” end mill to make the 45 degree bevel in the cavity. Next, cut twenty four 3/8” OD, ¼” ID steel tube to the correct length of 1.1”. Insert doll rods in all of the ¼” one thousandth oversized holes and place steel tube (collars) over each one. Cut a piece of cylindrical PVC to 1” OD so that a spider bracket can fit around it. The cavity is finished, it is now time to lay fiberglass.

First wax the mold to prevent the fiberglass from sticking. Apply resin then fiberglass layers to build up a surface of 1/8” thick (approximately 15 layers). Place a spider bracket in after three layers have been placed down. Below are pictures of the finished hub.

Figure 43: Inside view of hub and spider Bracket

Figure 44: Outside view of hub

Forks: The forks are made of 1” tube steel with machined blocks using the mill on the ends so that it can house the axle and superbracket. Bend (Go to a muffler store to bend pipes) the forks so that they can fit in the bike tree and axle. The bottom width should be at least 5.25” apart. Cut to correct length and paint black to match bike.

Figure 45: Side view of custom bent axle

Figure 46: Front view of both axles on bike

Standoff Brackets: The standoff brackets for the clutch and motor shaft are made of aluminum and have 3/8” oversized holes for easy placement to line the shafts up correctly. The clutch bracket has a 2in diameter hole cut out and the shaft brace has a hole cut out for the shaft bearing. Figure 47 shows the bracket for the clutch. Drill a ¼" hole in place for the clutch to bolt to the standoff bracket.

Figure 47: Clutch bracket

Spider Bracket: The spider bracket is part of the hub that houses the bearing. Use a ¼" thick and 5" diameter plate of steel. Use the mill to take off 1/8" of material around inner cylinder. Use boring arm on lathe to take the inner cylinder to tolerance. The holes in the bracket are for the fiberglass to grip when riding, they do not have to be trapezoids, drill random holes around it and that will be sufficient to secure in the hub. Measure the bearings for the axle and bore the center hole a thousanth inch under to press fit the bearing into the bracket.

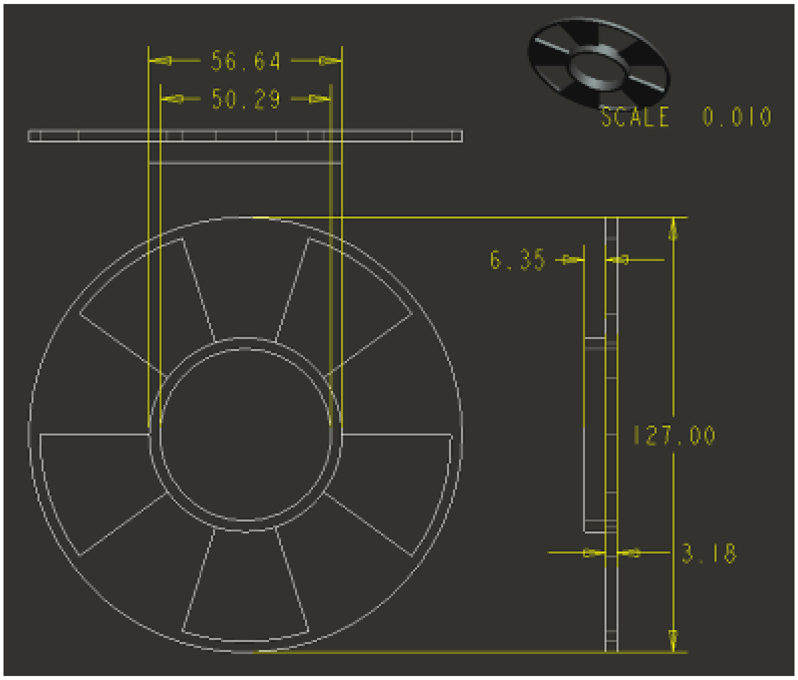


Figure 48: Spider bracket CAD dimensions

Spider Bracket Driver: This is the same as spider bracket but leave raised areas for ¼" tapped holes to attach to main gear.

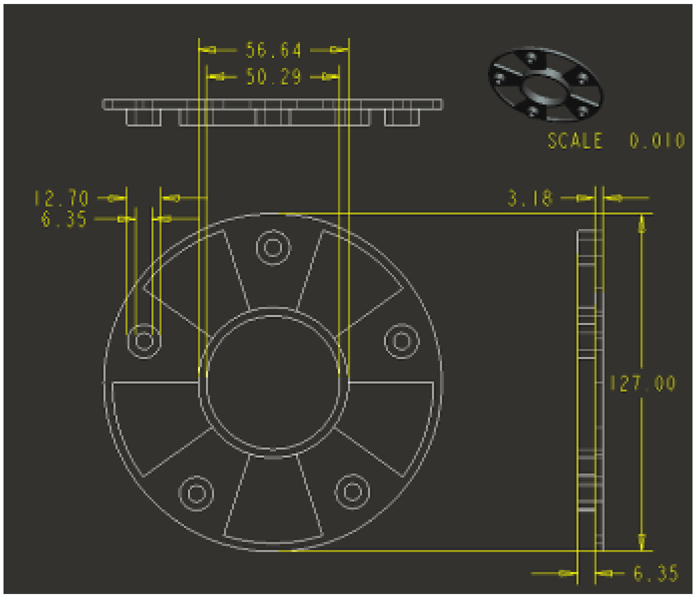


Figure 49: Spider bracket driver CAD dimensions

Main Gear Holes: Drill ¼” through holes thropugh gear to attach it to the spider bracket driver. Bore the center hole to fit on the axle bearing.

Figure 50: Main gear 1/4in hole locations

Wheel: The best way to drill the holes into the rim is to lay the hub over the rim and mark the holes. Use a drill press to drill 1/4in through holes. The rim with holes is shown below.

Figure 51: Alex Rim hole locations

Shafts: Cut the shafts to the correct length, leaving about 1/8" excess sticking past the gears. Lathe a groove in the shaft for the retaining ring.

9.2 Assembly

Do not attempt to assemble until all parts are fabricated, all bearings are pressed in, all plumbing/fittings are in place, and you have at least 2 straight hours to use for assembly.

Figure 52: Side view of regenerative braking system assembly

1. Layout out fully drilled and fabricated super bracket with axle welded on.
2. Place pump and motor on bracket and lightly tighten bolts.
3. Loosely bolt on shafts.
4. Assemble ½” shaft with satellite gear and shaft brace. Use ¼” -20 bolts, ¼” collars, ½” washers, and ¼” bolts.
5. Assemble clutch and clutch brace. Use ¼” -20 bolts, ¼” collars, ½” washers, and ¼” bolts. Make sure the satellite gear is in the same plane as gear in step 4. This is crucial for alignment purposes. To adjust height, add/remove ½” washers. The clutch must be perfectly inline (perpendicular to super bracket) so that it can engage/disengage.
6. Secure accumulator to super bracket with ½” C-clamp, one piece of the c-clamp goes through a hole in the clutch brace in step 5. Do not over tighten, this may misalign clutch.
7. Bolt on two way valve tightly.
8. Secure low pressure reservoir with zip ties. Not much force is applied to this bottle, but make sure it cannot move.
9. Check all plumbing connections to make sure they are tight.

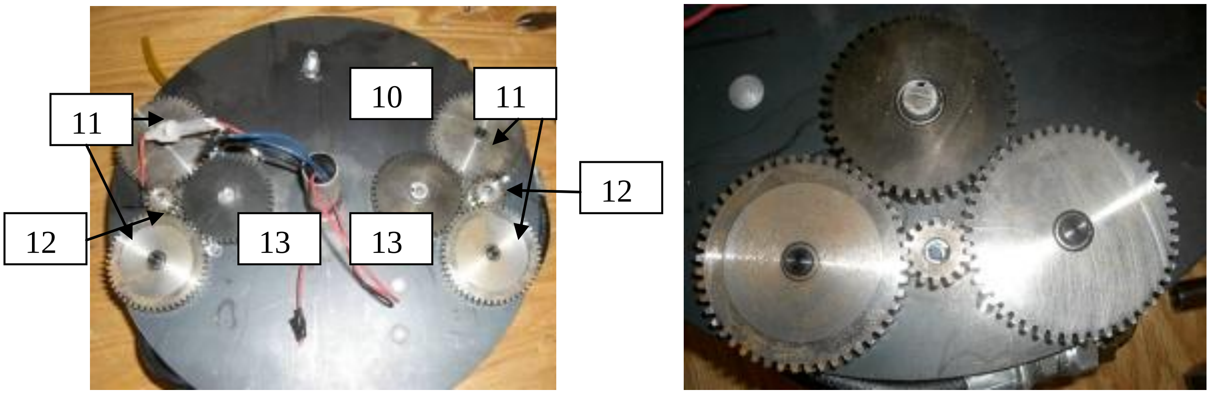


Figure 53: Side view of backside of super bracket assembly and close up of thrust, satellite, and axle gears.

10. Flip super bracket over, use 2x4’s (wood) to prop up the super bracket (this secures the bracket in place and still allows you to access all components)
11. Put thrust gears onto the four shafts (keep shafts loose). Secure the gears with C-clips.
12. Put pump and motor axle gears on, it is a close fit so it helps to rotate the thrust gears until teeth line up correctly. Secure gears with retaining rings.
13. Put on connector gear connected to one way bearing and clutch. Since the thrust gear shafts are loose you should be able to line up the teeth by rotating the gears. Rotate shaft so that the key is lined up with the key in the gear, press in key. Secure gears with retaining ring.
14. Tighten all shafts, motor, pump, clutch brace, and shaft brace.

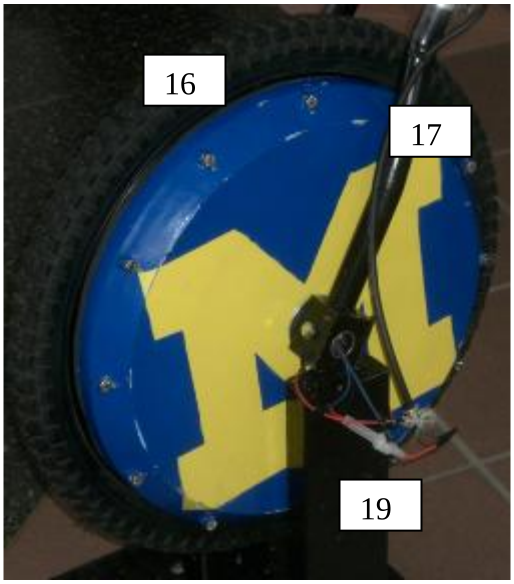


Figure 54: Side view of hub, rim, and fork assembly

Figure 55: Front view of assembly

15. Tilt super bracket assembly on its side with low pressure accumulator on top. Make sure all plumbing and electrical is routed out through the axle.
16. Sandwhich alex rim with the two hub halves that slide onto the axle. Secure hubs and rim together with ¼” – 20 bolts and nuts.
17. Keep the orientation of the assembly the same as in step 15. Place the forks on the axle so that the low pressure accumulator is on the right hand side of the bike (pretend you are

sitting on the bike). If this is put on incorrectly, the bike will work in reverse. Secure forks with 1/4in – 20 bolts and nuts.

18. Slide forks into handle bars making sure to keep the correct orientation, secure forks with handle bar bolts.
19. Place bike onto bike stand, this makes wiring easier and you can spin the hub to make sure everything clears.

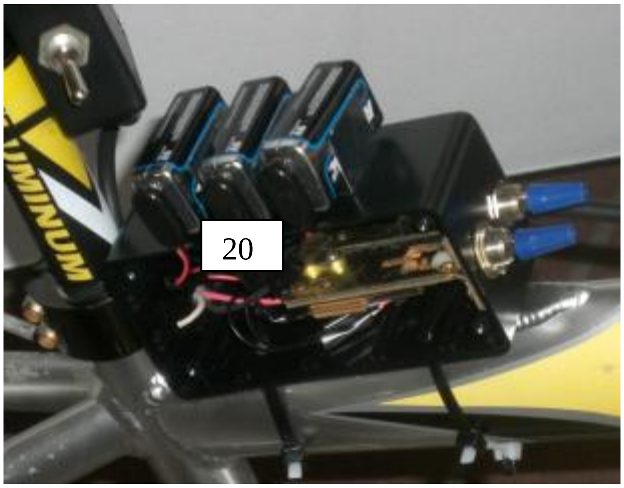


Figure 56: Switchbox assembly

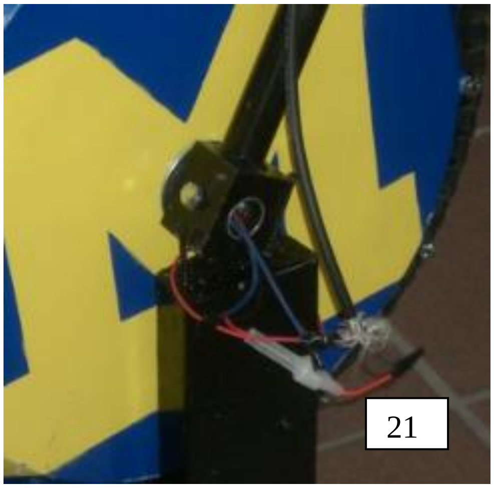


Figure 57: Wire assembly

20. Secure switch box, override switch, and batteries to bike frame with zip ties.
21. The wire running out of the control box has a white, black, and red wire. Connect the red to the positive clutch wire, black to the positive 2-way valve wire, white to the fuse, and then the fuse to bothe the negative (ground) wires of the clutch and 2-way valve. Check to see which switch powers which device; label these immediately.
21. Your bike is assembled, time to trouble shoot!

10. Validation Results and Critique

As we have discussed, we could not have a working prototype due to the extensive lead time of the custom ordered pump and motor. In addition, the four months of designing and fabricating our prototype required extensive parameter analysis to arrive at a final design that met the space and strength limitations. Thus, we have developed a system that currently meets some of our targets, but has not yet advanced to the testing stages required to validate others. Here we discuss which targets have been met, which haven't, and what can be done to tweak the prototype such that the targets can be met.

Maximum weight (target: less than 16 pounds): We found our final prototype to be equal to 38 lbs (without the fork) by weighing the overall interior part and adding the weight of two hubs. This is still over two times the target weight. However, we believe the weight of the gears (~ 8 lbs.) can be reduced to about 3 or 4 lbs if they are machined to be spoked. The superbracket, currently 5 lbs, may be reduced by about half by cutting away excess material, reducing the thickness to the minimum necessary dimension, and investigating the use of a lighter material and attachment to the wheel axle. The high pressure accumulator may also be made of carbon fiber, which reduces the weight from 5 lbs to about 1 lb.

Hub width (target: less than 4 inches): The final width of the interior components was 4”, resulting in an overall width of the wheel being 4.5” with the hub shell. As stated before, the width could meet the overall 4” and be as compact as possible with the given accumulator, pump, and motor if the clutch coupler was accounted for. To eliminate this excess width, the coupler could be pressed into the bore of the connector gear rather than having a shaft attached to the interior of the coupler and connecting to the gear.

Hub diameter (target: less than 16 inches): By fitting all of our components within the rim and hub shell, we have shown that our design has met the wheel diameter restrictions. There are a couple of areas that are very close to the rim and may make contact with it slightly; specifically, the hose between the pump and check valve, and the hose between the check valve and the high pressure accumulator. The hose connecting to the high pressure accumulator can be moved inward once the real motor is in place, which is slightly smaller than the model motor. The hose connecting to the pump may be moved inward by using a male fitting on the hose that connects directly to the pump port rather than using a swivel female fitting on the end of the hose.

We were not able to complete any further validation of our design at this point. Without any testing of the working prototype, we can only estimate the overall efficiency of the system. However, we have designed the system based on testing from previous prototypes such than the other target values may be met. The braking deceleration and launching acceleration, as stated earlier, may be adjusted by changing the charge in the high pressure accumulator. Our gear ratio of 18:1 has been incorporated in our design for comfortable and safe accelerations and final speed. Our working pressure has been chosen to provide ample energy storage. We have allowed for enough fluid to accommodate the change in volume of the accumulator and amount that will fill the plumbing. We have included a filtration system to prevent malfunction of the valves. Finally, our pump and motor displacement have been chosen to provide enough torque while still maintaining a small size. These values were applied to our design to give what we expect to be optimal performance.

11. Recommendations

Universal Application: To improve upon the universal application, our only recommendations for future work is, as we already stated, to design it such that the coupler for the clutch is pressed into the gear bore rather than connecting the two with a shaft to achieve the minimum width possible with this accumulator, pump, and motor. Also, the female hose end connecting to the pump can be replaced by a male hose fitting that will prevent the hose from contacting the rim. A small issue to watch out for is to make sure all of the bolts on the superbracket are properly countersunk so that there is no interference with the gears. Finally, we suggest finding a more compact method of attaching the high pressure accumulator to the superbracket.

Safety: The major issue making this system unsafe is the lack of restriction on having a full charge in the accumulator while the bike is moving at a relatively high speed. There is nothing keeping the rider from braking to charge the accumulator and petaling back up to speed. The result would either be a hard brake from a fast speed, throwing the rider off the bike, or launching from a high speed to dangerously higher speeds. We recommend incorporating a pressure release valve of some sort to act as a failsafe.

Lightweight: We reiterate the areas with drastic potential for weight reduction in this design. The gears may be spoked to cut out about half of their weight, the superbracket can lose much unnecessary area and thickness, an analysis of different superbracket material options would be helpful, and the high pressure accumulator can be replaced with one made of lightweight carbon fiber.

Aesthetics: The most obvious change to improve the aesthetics would be to have the hub stamped out of the appropriate metal. This is not likely to be possible within the scope of ME450, but we recommend exploring options of using a thin, lightweight metal as the hub material. The incorporation of shielded viewing windows, as in our original design, would also help. Finally, the electric circuit component placement has much room for redesign.

Natural Rate of Braking: We have done our best to achieve a comfortable braking rate through estimation of the weight of the bike and rider, and the speeds of travel. However, currently the system only provides two rates of braking: the maximum at which only the pump is engaged, and a second rate at which the pump and motor are both engaged. Because the 2-way valve can trigger within 2 ms, we suggest that a pulsing of the motor (pulse signal to the 2-way valve) would allow a graduated braking rate based on a pressure sensitive activation of the switch. This, however, is not a project for ME450 as we believe it would be better suited for an electrical engineering project.

Easy to Use: The placement of the switch will greatly enhance the ease of use.

Reliable: As we discussed previously, we did not have proper time to analyze the forces and failure analysis. We recommend a rigorous analysis of the critical parts of the prototype such as the forces on the shafts and standoff brackets, the torsion on the axle and shear stress at the weld joint between the axle and superbracket. We also ran into some problems with the retaining rings staying on the shafts. The precision and care of assembling the retaining rings onto the machined groves is something to take note of.

Easy to Service: Our prototype has an immense number of parts that are all bolted, welded, or fit together. There is much room for improvement in simply reducing the number of required parts and improving accessability.

12. Conclusions

Our project is currently extending upon previous semesters' attempt to apply a hybrid human-hydraulic powered system completely contained within a bicycle wheel that may be retrofit to operate on any bicycle. The motivation for this is to encourage the use of bicycles over other methods of transportation that contribute to pollution and the use of oil. Our project goal for this semester is to now apply the system to a child's bicycle. The top priority is to build a working prototype that is aesthetically pleasing and fits this standard size. Our second priority is concerned with how the prototype functions, such as efficiency and ease of use.

We have completed the prototype in so far as possible. The pumps and motors have not arrived, but the rest of the prototype is complete. Do to the lack of pumps and motors we were unable to build a working prototype, but everything else that was put together is functional and ready to be tested as soon as the pumps and motors arrive. The bike is aesthetically pleasing with painted components and all fit inside the 20" wheel. We were unable to fit the wheel hub into a width of

3” and instead had to make custom forks with a width of 5”. The weight goal of 16lbs was also not achieved. The entire hub assembly weighed 43lbs, 27lbs more than the goal. We were unable to test the functionality of the prototype because it does not work as of yet. These shortcomings are very minor in comparison to what we have achieved. The prototype that is fabricated is a great starting point for the next semester of students to take over and further engineer into the optimal design for a hydraulic regenerating braking wheel hub.

13. References

[1] http://en.wikipedia.org/wiki/Greenhouse_gas_emissions_in_the_USA#Transportation

[2] http://en.wikipedia.org/wiki/United_States_Environmental_Protection_Agency

[3] www.RevoPower.com

[4] Steve Katsaros, inventor of the RevoPower gasoline retrofit bike wheel, personal correspondance, 2/5/08

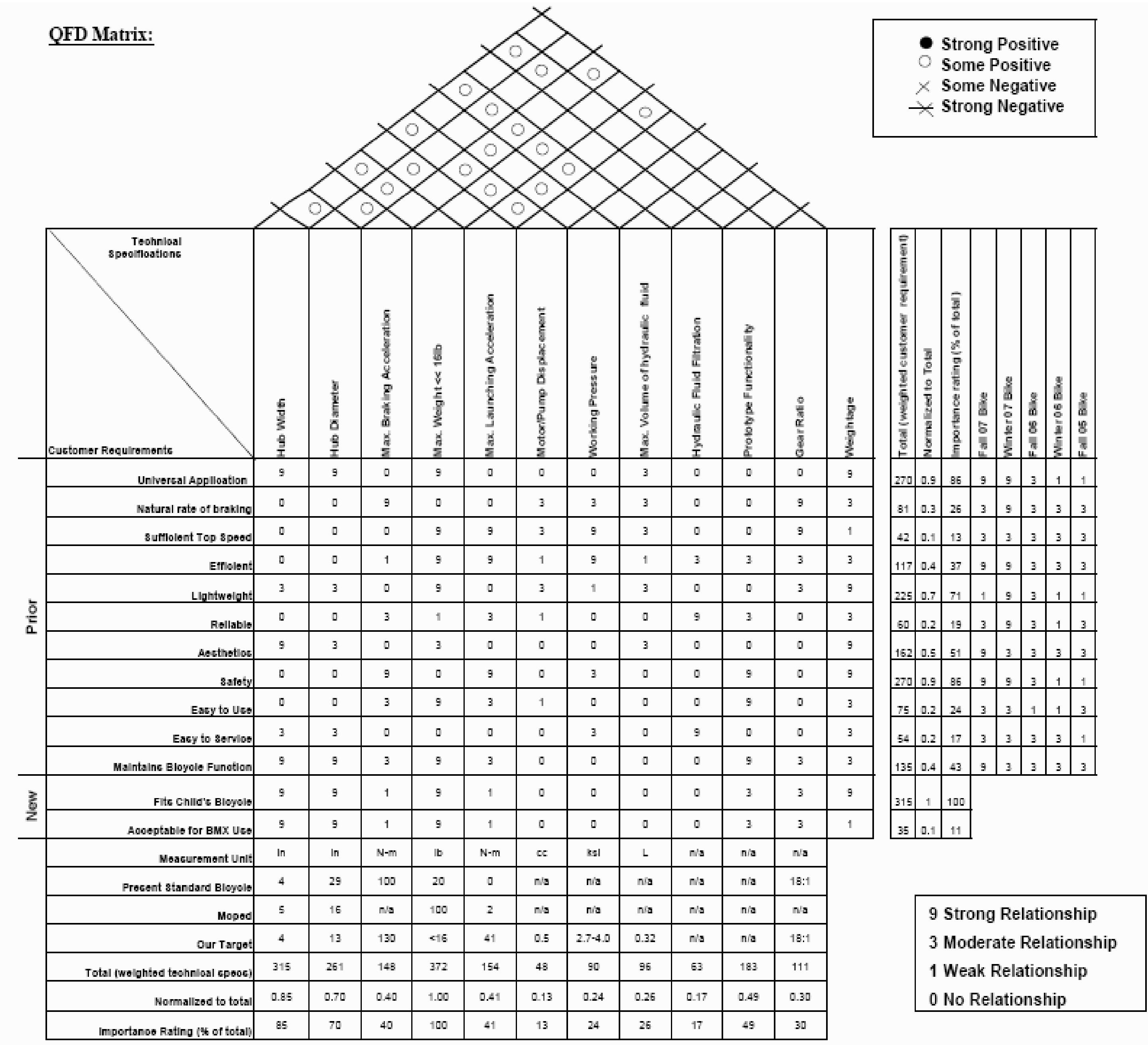
[5] David Swain, E.P.A., project sponsor, personal correspondance, numerous occasions

[6] August Brimer, Marzocchi Pumps U.S.A., personal correspondance, 2/8/08

[7] Chad Langdon, Motion and Controls Sales, personal correspondance, 2/12/08

[8] www.BostonGear.com

14. Appendix A: Quality Function Deployment Diagram



	Technical Specifications / Customer Requirements	Hub Width	Hub Diameter	Max. Braking Acceleration	Max. Weight << 16lb	Max. Launching Acceleration	Motor/Pump Displacement	Working Pressure	Max. Volume of hydraulic fluid	Hydraulic Fluid Filtration	Prototype Functionality	Gear Ratio	Weightage	Total (weighted customer requirement)	Normalized to Total	Importance rating (% of total)	Fall 07 Bike	Winter 07 Bike	Fall 06 Bike	Winter 06 Bike	Fall 05 Bike
Prior	Universal Application	9	9	0	9	0	0	0	3	0	0	0	9	270	0.9	86	9	9	3	1	1
	Natural rate of braking	0	0	9	0	0	3	3	3	0	0	9	3	81	0.3	26	3	9	3	3	3
	Sufficient Top Speed	0	0	0	9	9	3	9	3	0	0	9	1	42	0.1	13	3	3	3	3	3
	Efficient	0	0	1	9	9	1	9	1	3	3	3	3	117	0.4	37	9	9	3	3	3
	Lightweight	3	3	0	9	0	3	1	3	0	0	3	9	225	0.7	71	1	9	3	1	1
	Reliable	0	0	3	1	3	1	0	0	9	3	0	3	60	0.2	19	3	9	3	1	3
	Aesthetics	9	3	0	3	0	0	0	3	0	0	0	9	162	0.5	51	9	3	3	3	3
	Safety	0	0	9	0	9	0	3	0	0	9	0	9	270	0.9	86	9	9	3	1	1
	Easy to Use	0	0	3	9	3	1	0	0	0	9	0	3	75	0.2	24	3	3	1	1	3
	Easy to Service	3	3	0	0	0	0	3	0	9	0	0	3	54	0.2	17	3	3	3	3	1
	Maintains Bicycle Function	9	9	3	9	3	0	0	0	0	9	3	3	135	0.4	43	9	3	3	3	3
New	Fits Child's Bicycle	9	9	1	9	1	0	0	0	0	3	3	9	315	1	100					
	Acceptable for BMX Use	9	9	1	9	1	0	0	0	0	3	3	1	35	0.1	11					
	Measurement Unit	In	In	N-m	lb	N-m	cc	ksi	L	n/a	n/a	n/a									
	Present Standard Bicycle	4	29	100	20	0	n/a	n/a	n/a	n/a	n/a	18:1									
	Moped	5	16	n/a	100	2	n/a	n/a	n/a	n/a	n/a	n/a									
	Our Target	4	13	130	<16	41	0.5	2.7-4.0	0.32	n/a	n/a	18:1									
	Total (weighted technical specs)	315	261	148	372	154	48	90	96	63	183	111									
	Normalized to total	0.85	0.70	0.40	1.00	0.41	0.13	0.24	0.26	0.17	0.49	0.30									
	Importance Rating (% of total)	85	70	40	100	41	13	24	26	17	49	30									

Figure 58: Revised QFD matrix reflecting updated customer requirements and technical specifications

15. Appendix B: Calculations

For Safety:
Max speed = 20mph
Min weight = 50 kg
Motor ~ 20% smaller than pump
Based on previous testing: ~80-85% efficiency

Bike Kinetic Energy at max speed:

$$\frac{1}{2}mv^2 = \frac{1}{2}(50kg)(20mph * \frac{\frac{1}{2}}{2.24mph})^2 = 1990J$$

@ 82.5 efficiency, potential energy max must be:

$$\frac{1990J}{0.825} = 2410J$$

We chose 4000 psi max accumulator which is one pressure rating smaller than the previously used 5000 psi accumulator to store enough energy with the small size accumulator, we chose the 0.32L accumulator.

Thus our minimum pressure in the accumulator or "precharge", $P_{Pcharge}$, can be read off the figure as 2700 psi.

Potential Energy $= P_{average} * \Delta V_{accumulator} = \left(\frac{P_{max} + P_{Pcharge}}{2}\right) * (V_{max} - V_{\min})$

$$2410J = \left(\frac{4000psi + P_{Pcharge}}{2}\right) * \left(\frac{6.895Kpa}{psi}\right) * \left(0.32L - \frac{P_{Pcharge} * 0.32L}{4000psi}\right)$$

$$P_{Pcharge} = 2700psi$$

The change in volume from 2700 to 4000 psi is:

$$\Delta V = V_{max} - \frac{P_{Pcharge} * V}{P_{max}} = 0.32L - \frac{2700psi}{4000psi} * 0.32L = 0.104L$$

Approximate volume hydraulic fluid needed:

$$V = 3 * \Delta V = 3 * 0.104L = 0.312L$$

Minimum volume of low pressure accumulator:

$$V = 2 * \Delta V = 2 * 0.104L = 0.208L * \frac{33.8floz}{1L} = 7.0floz$$

For a "stiff," comfortable brake rate:
Based on testing previous prototypes at various "precharge" of high pressure accumulator:

$$\frac{pump\ fluid\ displacement}{rev} = \frac{3.458cc}{rev}$$

Gear ratio 12:1
26” wheels
Weight bike+rider=100kg
Optimum precharge found to be 2000 psi
Thus at P=$P_{Pcharge} = 2000psi$

$$Minimum\ Torque = Pump\ Disp * \frac{P_{Pcharge}}{2\pi} = \frac{3.458cc}{rev} * \frac{L}{2000cc} * \frac{2000psi}{\frac{2\pi}{rev}} * \frac{6.895kpa}{psi}$$

$$= 7.6n - m$$

$$Minimum\ Torque\ on\ Wheel = 7.6n - m * 0.825 * 12 = 75.2n - m$$

@ Minimum torque on wheel

$$T_{min} = Mass * deceleration * wheel\ radius$$

$$75.2n - m = 100kg * decel * 13" * 0.0254m$$

$$Min\ Decel = 2.3\frac{m}{s^2}$$

We chose a pump of $\frac{0.64cc}{rev}$based on a balance of size restrictions and maintaining torque ability.

Thus, our minimum torque at the pump will be:

$$\frac{0.64cc}{L} * \frac{L}{1000cc} * \frac{2700psi}{\frac{2\pi}{rev}} * \frac{6.895kpa}{psi} = 1.9n - m$$

Minimum torque at the wheel will be:

$$50kg * 2.3\frac{m}{s^2} * 10" * \frac{0.0254m}{1:} = 29.2n - m$$

Gear Ratio:

$$\frac{29.2n - m}{1.9n -, * 0.825} = 18:1$$

For safety, we choose a motor displacement ~20% less than the pump displacement:
$Motor\ Displacement = 0.80 * 0.64cc = 0.51cc$

Final Gear Ratio:

$$\frac{80teeth}{14teeth} * \frac{44teeth}{48teeth} * \frac{48teeth}{14teeth} = 18{:}1$$

Maximum RPM of each gear:
At max speed (20mph)

$$Wheel\ Rpm = 20mph * \frac{88\frac{ft}{min}}{mph} * \frac{12"}{ft} * \frac{rev}{\pi * 20"} = 336RPM$$

$$Wheel\ RPM = main\ gear\ RPM = 336RPM$$

$$\omega_2 = \omega_1 * \frac{N_1}{N_2}$$

$$Satellite\ RPM = 336RPM * \frac{80\ teeth}{14teeth} = 1920RPM$$

$$Balance\ Gear\ RPM = Satellite\ RPM = 1920RPM$$

$$Thrust\ Gear\ RPM = 1920RPM * \frac{44teeth}{48teeth} = 1760RPM$$

$$Pump\ and\ Motor\ gear\ RPM = 1760RPM * \frac{48teeth}{14teeth} = 6034RPM$$

Maximum Torque on Each Gear:

$$T_{pump\ max} = \frac{disp * P_{max}}{2\pi} = \frac{\frac{.64cc}{1000\frac{cc}{L}} * 4000psi * \frac{6.895kpa}{psi}}{2\pi} = 2.81n -,$$

$$2.81n - m * \frac{0.738ftlb}{1n - m} = 2.07ftlbs$$

$$T_{motor\ max} = \frac{\frac{0.51cc}{1000\frac{cc}{L}} * 4000psi * \frac{6.895kpa}{psi}}{2\pi} * \frac{0.738ftlb}{1n - m} = 1.65ftlbs$$

Maximum acceleration/deceleration of bike:

$$deceleration = 2.81n - m * 0.8258\frac{18}{1} = 50kg * deceleration * 10" * \frac{0.0254m}{1"}$$

$$deceleration_{max} = 3.29\frac{m}{s^2}$$

$$acceleration = 2.23n - m * 0.825 * \frac{18}{1} = 50kg * acceleration * 10" * \frac{0.0254m}{1"}$$

$$acceleration_{max} = 2.60\frac{m}{s^2}$$

Horsepower Calculations:

$$design\ HP = HP * servic\ factor$$

Service factor=0.80 for light shock, use

$$HP = \frac{Torque(ftlb) * RPM}{5252}$$

RPM essentially independent variable
Torque directly proportional to pressure in high pressure accumulator
Thus, assume maximum HP@maxRPM with 1/3 charge in accumulator

Example Calculation:

$$Pump\ Gear: \frac{\frac{0.64cc}{1000L} * \left[2700 + \frac{1}{3} * (4000 - 2700)\right] * \frac{6.895kpa}{psi} * \frac{0.738ftlb}{n-m} * 6034RPM}{2\pi * 5252} = 1.87hp$$

$$design\ HP = 1.87 * 0.80 = 1.49hp@6034RPM$$

Max @ all pump gears since as number of teeth changes, T*RPM=constant

Maximum Fluid Flow:

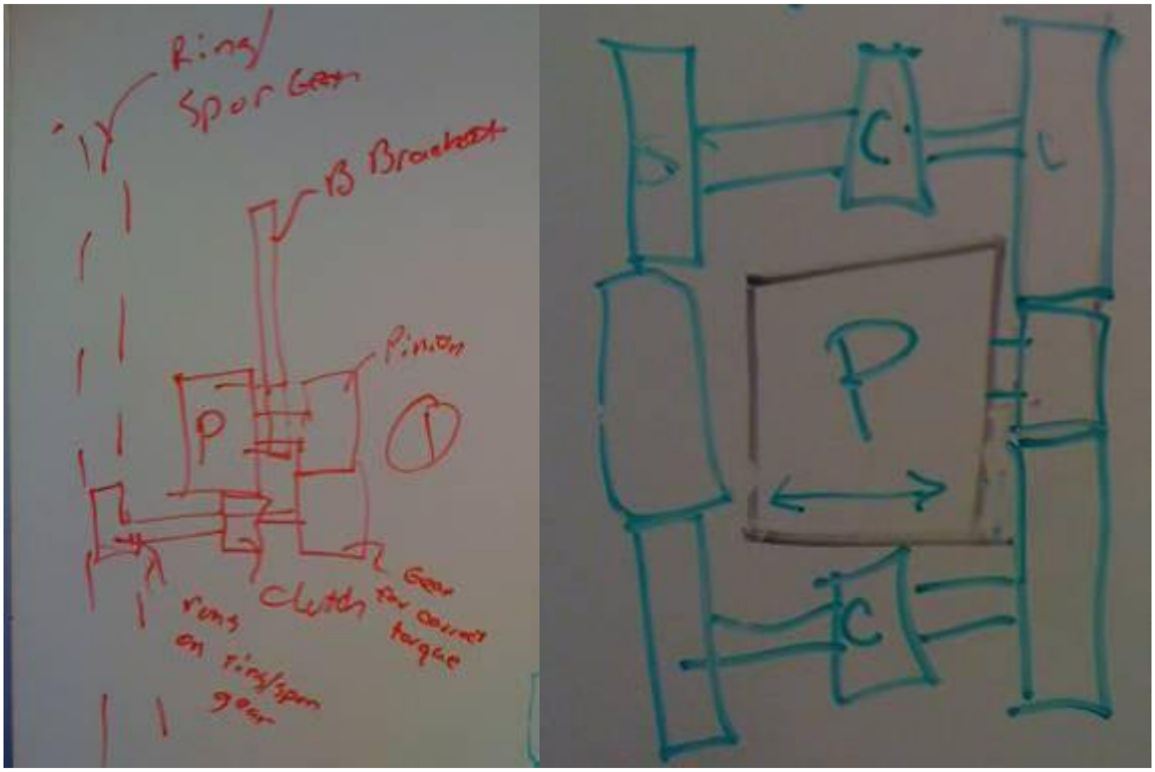
@6034RPM through pump with 0.64$\frac{cc}{rev}$

$$\frac{0.64cc}{Rev} * \frac{6034Rev}{min} * \frac{1Gal}{3785.4cc} = 1.0GPM$$

@6034 RPM through motor with 0.51$\frac{cc}{rev}$

$$\frac{0.51cc}{rev} * \frac{6034rev}{min} * \frac{1gal}{3785.4cc} = 0.81GPM$$

16. Appendix C: Concept Generation Drawings



Figures 59-60: Example drawings of generated concepts. Figure 35 shows power transfer system concept 2, where the pump/motor shaft is supported on one side by a bracket designed to alleviate radial load on the shaft. Figure 36 shows power transfer system concept 1, where the shaft is support on either side by two gears, which are clutched to the main spur gear on the opposite side.

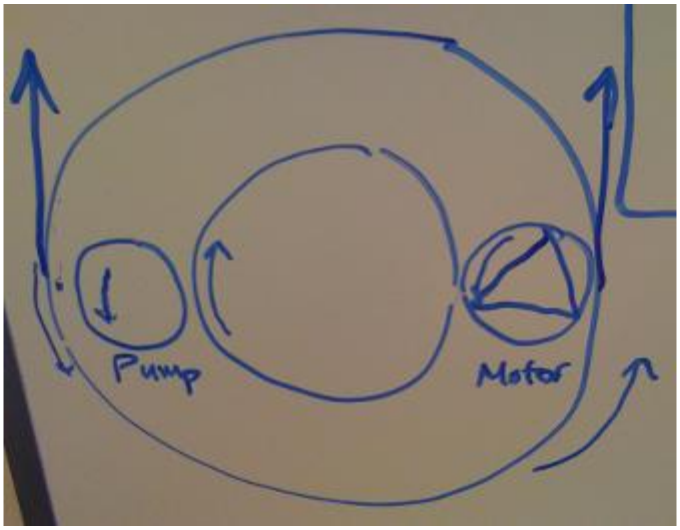


Figure 61: Power transfer concept 3, where the pump and motor gears are supported by the outer ring gear and sandwich an inner spur gear. This system leaves no area for a shaft to shaft clutch.

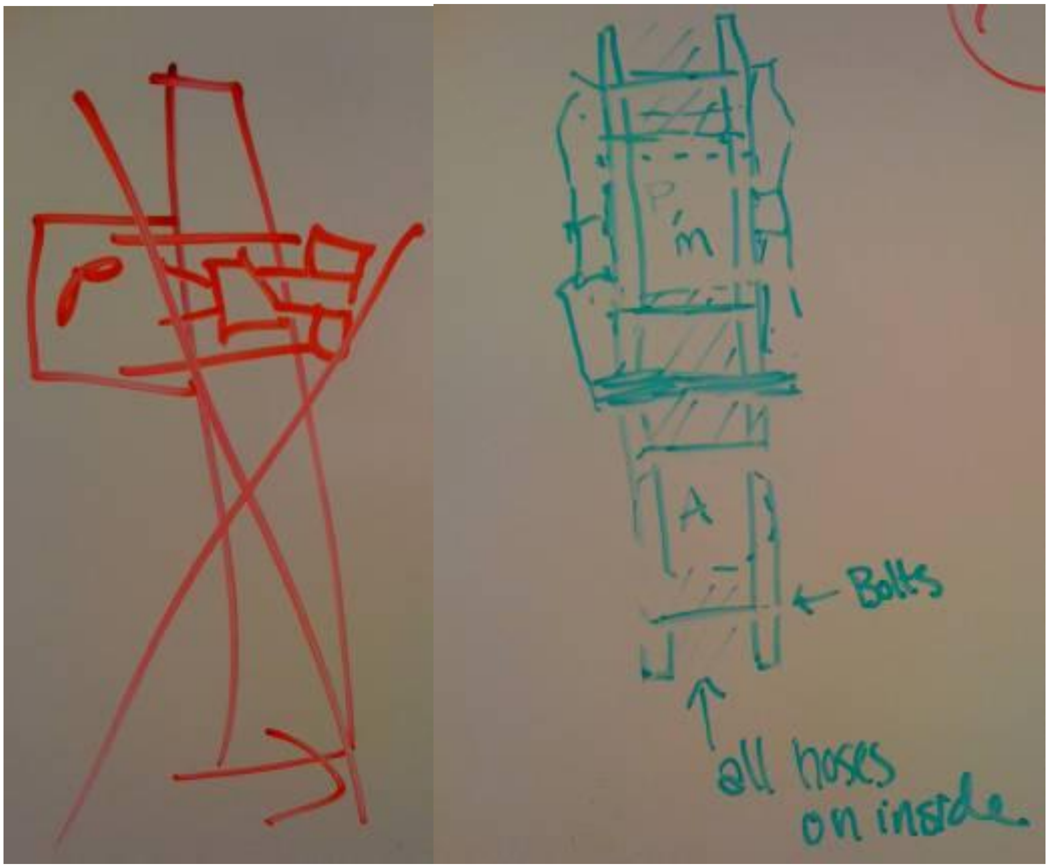


Figure 62-63: Figure 38 shows a rejected power transfer concept in which the superbracket holds roller bearings that encompass the pump shaft for support. Figure 15 illustrates superbracket concept 2, where the hydraulic components are sandwiched between two thin brackets.

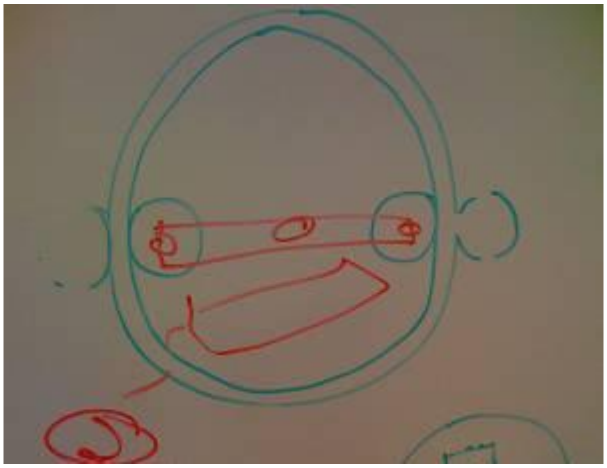
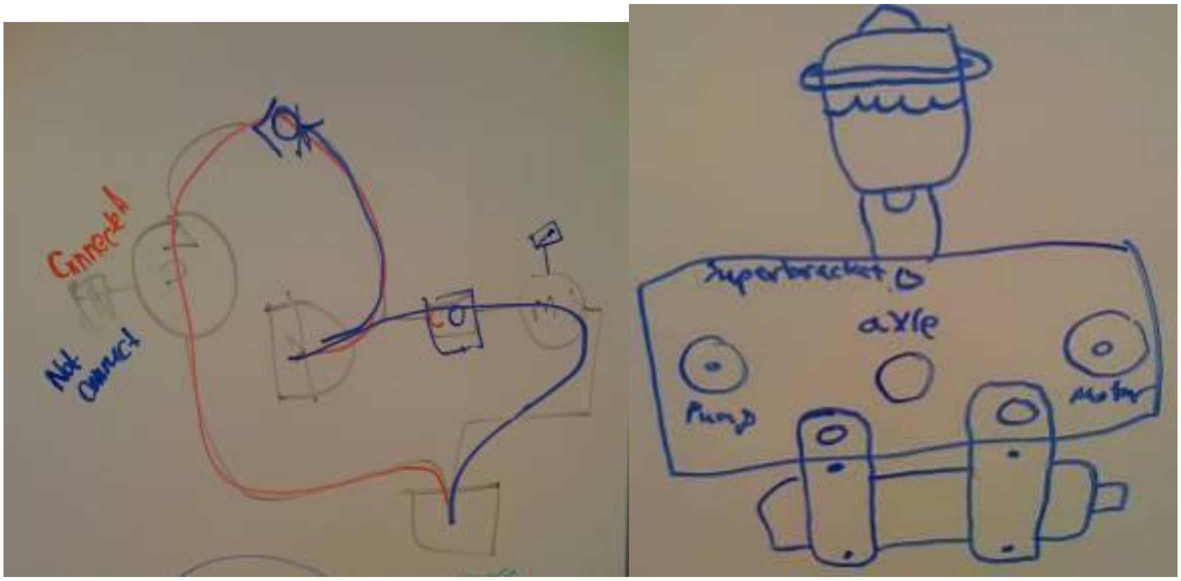


Figure 64: Rejected power transfer concept where a double sided bracket supports the pump and motor output shafts. This concept would not fit inside the wheel hub with enough room for the hydraulic circuit.



Figures 65-66: Figure 41 shows the final hydraulic circuit. Figure 42 shows superbracket concept 1 (selected with modifications) where the hydraulic components are supported by a bracket shaped to only provide material where necessary.

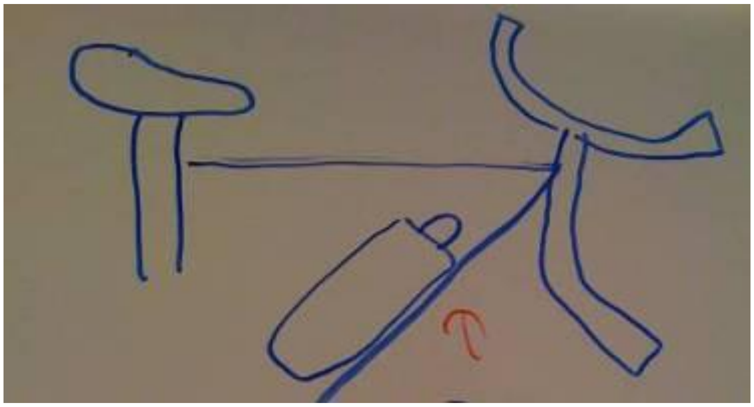


Figure 67: Rejected concept that allows for the high pressure accumulator to be mounted outside the front wheel on the water bottle holder. This design was partially inspired by the RevoPower gasoline-powered bicycle that retrofits a gasoline tank on the water bottle holder. [4]

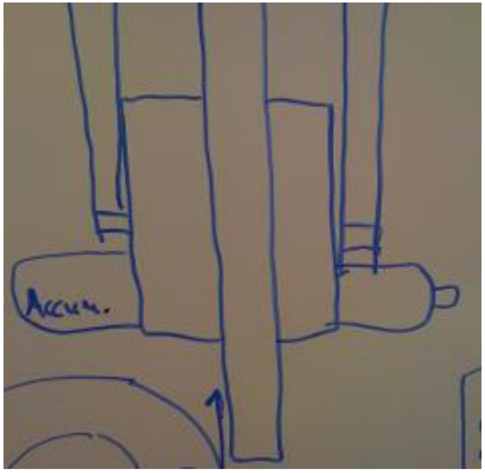


Figure 68: Side view of Figure 2. This system allows the accumulator to be placed transverse to the bike wheel to make the inner cylinder more compact.

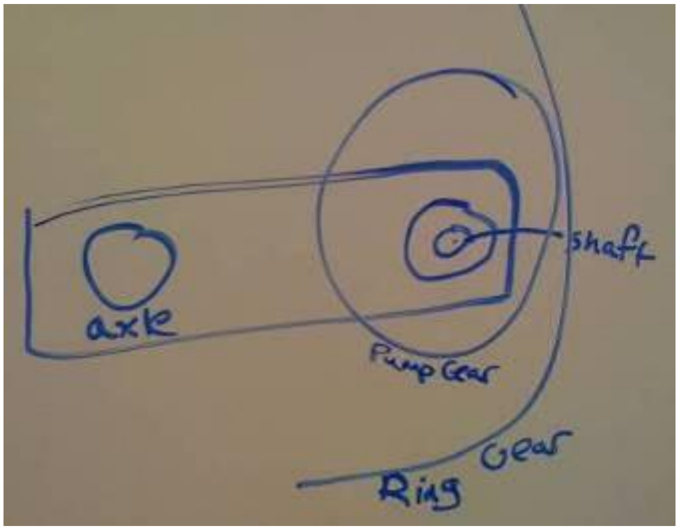


Figure 69: Side view of figure 38, where a bracket supports the pump shaft radially.

Figure 70: Hub design concept in which the spur gear is machined directly onto the side of the hub shell, to eliminate the extra spur gear purchase.

17. Appendix D: Finite Element Analysis of the Wheel Hub

$$x_{cg} = \frac{\sum_{i=1}^{3} m_i x_i}{\sum_{i=1}^{3} m_i} \qquad y_{cg} = \frac{\sum_{i=1}^{3} m_i y_i}{\sum_{i=1}^{3} m_i} \qquad m_{cg} = \sum_{i=1}^{3} m_i$$

Equation 3-5: X and Y coordinates of a combined center of mass, as well as the total mass of a system found by summing the individual masses of each component..

	xcg [in]	ycg [in]	mass [kg]	m*xcg	m*ycg
Rider	**15**	**31**	**50**	**750**	**1550**
Bike	**17.5**	**22**	**8**	**140**	**176**
Front Wheel	**35**	**10**	**8**	**280**	**80**
System	**17.7**	**27.4**	**66**	**1170**	**1806**

Table 3: Center of mass information for each of the system components and the system totals

$$F_{total} = m_{total} \times g = (66kg)(9.81m/s^2) = 647.46N$$

$$c = 17.7in$$

$$h = 27.4in$$

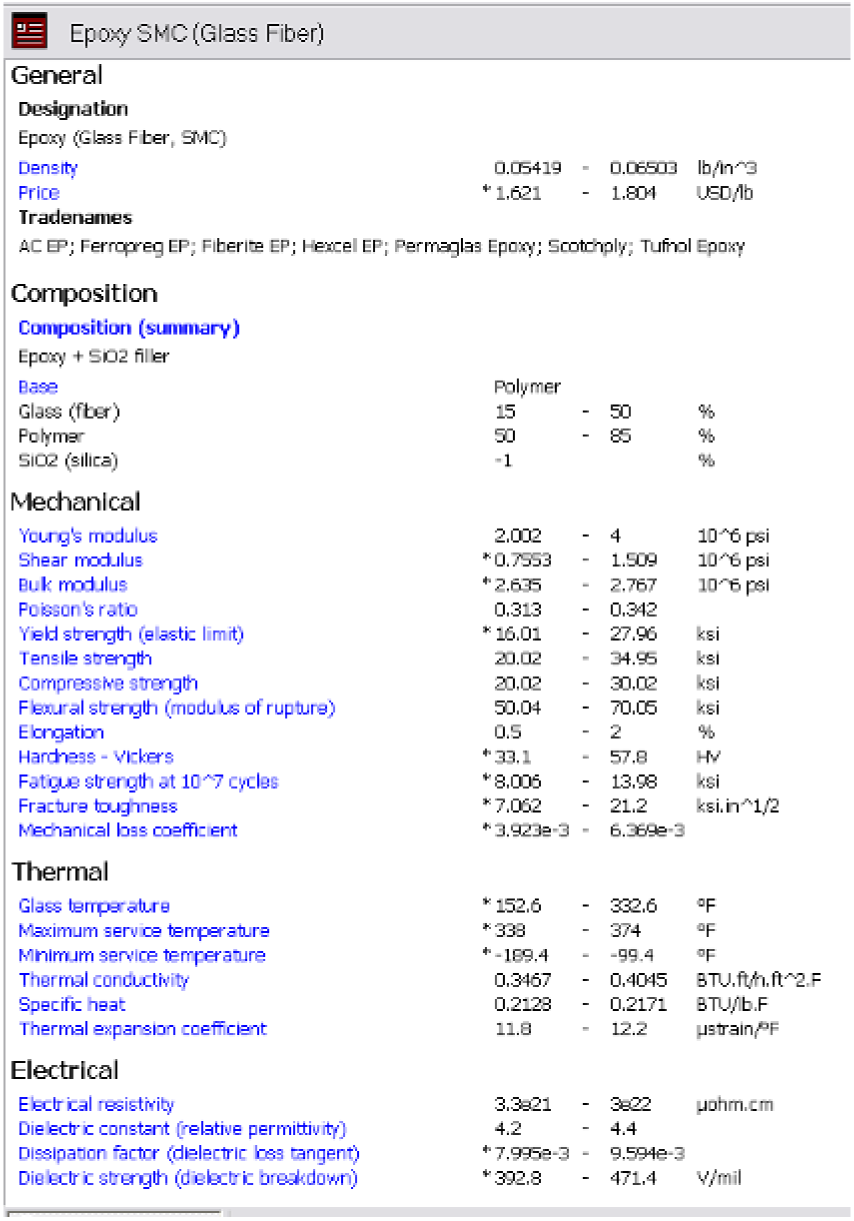
$$L = 35in$$

$$\theta = 10°$$

$$F_{axle} = \frac{F_{total}(c \times \cos\theta - h \times (a_x / g) - h \times \sin\theta)}{L} = 422.0N$$

Equation 6-7: Equation to find the static force of the bike as well as the force on the axle of the bike during a maximum braking event on a ten degree downward grade

Figure 71: Free body diagram of the forces acting on the braking bicycle. A close-up of the front wheel is also included with the forces acting on it



Epoxy SMC (Glass Fiber)

General

Designation

Epoxy (Glass Fiber, SMC)

Density	0.05419	-	0.06503	lb/in^3
Price	* 1.621	-	1.804	USD/lb

Tradenames

AC EP; Ferropreg EP; Fiberite EP; Hexcel EP; Permaglas Epoxy; Scotchply; Tufnol Epoxy

Composition

Composition (summary)

Epoxy + SiO2 filler

Base	Polymer			
Glass (fiber)	15	-	50	%
Polymer	50	-	85	%
SiO2 (silica)	-1			%

Mechanical

Young's modulus	2.002	-	4	10^6 psi
Shear modulus	* 0.7553	-	1.509	10^6 psi
Bulk modulus	* 2.635	-	2.767	10^6 psi
Poisson's ratio	0.313	-	0.342	
Yield strength (elastic limit)	* 16.01	-	27.96	ksi
Tensile strength	20.02	-	34.95	ksi
Compressive strength	20.02	-	30.02	ksi
Flexural strength (modulus of rupture)	50.04	-	70.05	ksi
Elongation	0.5	-	2	%
Hardness - Vickers	* 33.1	-	57.8	HV
Fatigue strength at 10^7 cycles	* 8.006	-	13.98	ksi
Fracture toughness	* 7.062	-	21.2	ksi.in^1/2
Mechanical loss coefficient	* 3.923e-3	-	6.369e-3	

Thermal

Glass temperature	* 152.6	-	332.6	°F
Maximum service temperature	* 338	-	374	°F
Minimum service temperature	* -189.4	-	-99.4	°F
Thermal conductivity	0.3467	-	0.4045	BTU.ft/h.ft^2.F
Specific heat	0.2128	-	0.2171	BTU/lb.F
Thermal expansion coefficient	11.8	-	12.2	µstrain/°F

Electrical

Electrical resistivity	3.3e21	-	3e22	µohm.cm
Dielectric constant (relative permittivity)	4.2	-	4.4	
Dissipation factor (dielectric loss tangent)	* 7.995e-3	-	9.594e-3	
Dielectric strength (dielectric breakdown)	* 392.8	-	471.4	V/mil

Figure 72: Material attributes for the fiberglass/ epoxy mix to be used to construct the hub

18. Appendix E: Design Analysis

E.1 Material Selection

Thrust Gear Shaft

Function: Torque transmission

Objective: Minimize mass (weight)

Constraints:

- Support torque of 9.63 N-m

$$Torque\ on\ pump = 2.81N - m$$

$$(2.81N - m) \times \frac{48\ teeth}{14\ teeth} = 9.63\ N - m$$

- Cost
- Length L specified

Material Index:

Since the loading on the shaft will be dominated by the torsion, we minimize the mass using the equation for critical torque as follows:

Minimize mass m:

$m = \pi r^2 l \rho$

Critical torque on the shaft:

$$\tau_{crit} = \frac{G\theta r}{l}$$

Solve for radius r and set equal:

$$\sqrt{\frac{m}{\pi l \rho}} = \frac{\tau_{crit} l}{G\theta}$$

$$m \geq (\pi \tau_{crit}{}^2)\left(\frac{l^3}{\theta}\right)\left(\frac{\rho}{G^2}\right)$$

Index:

$$M_1 = \frac{G^2}{\rho}$$

Using the CES software, we are able to use our material index to screen for the most appropriate material to fabricate our thrust gear shafts. With the stage 1 graph set to density against shear modulus, with logarithmic scale, material index 1 will be represented by a line of slope one half. The materials above the line will be those that satisfy the criteria greater than or equal to in the above equation. We further screen materials by lowering the cost/lb. By moving the line upwards and lowering the cost, we can eliminate materials until only the top choices remain.

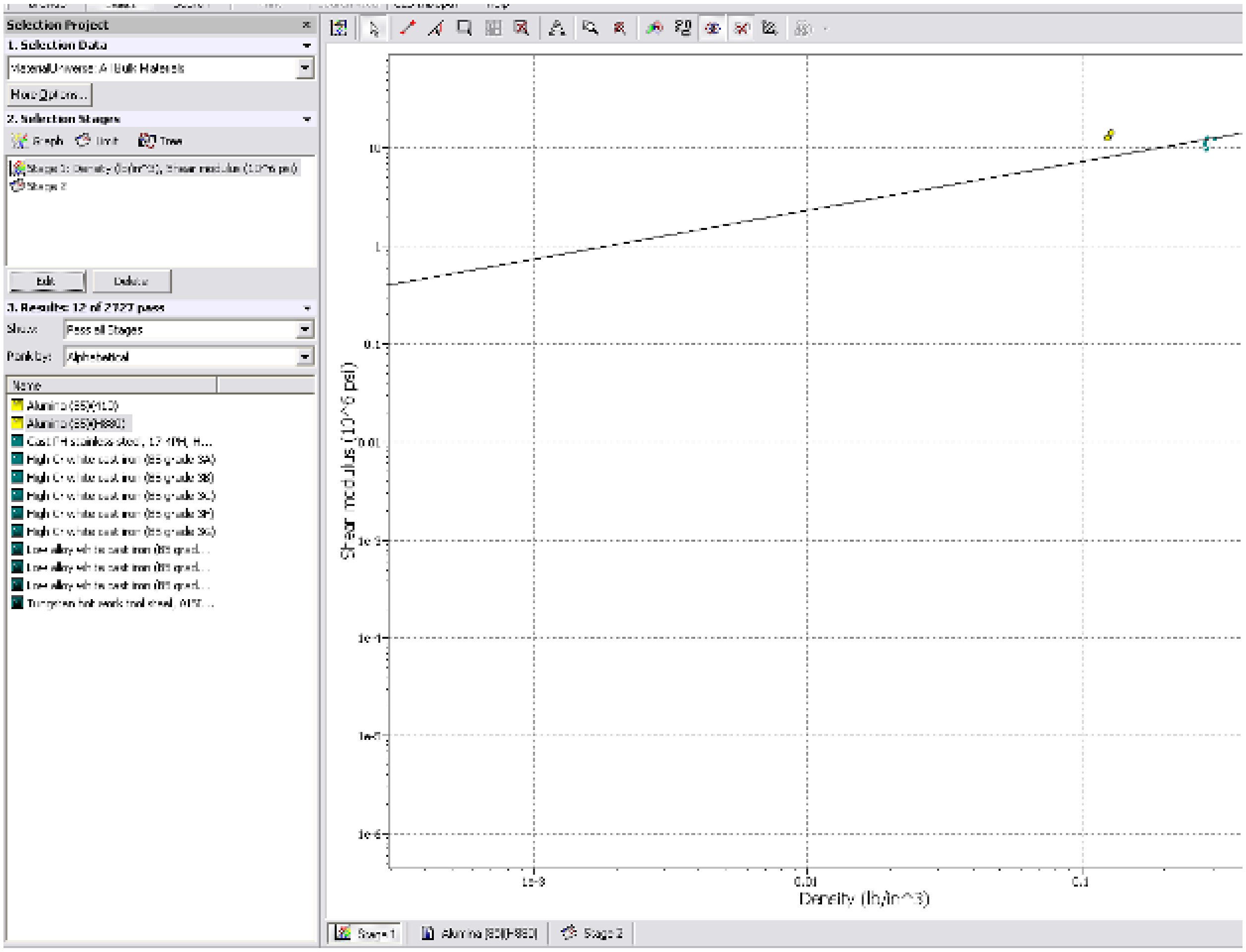


Figure 73: CES screenshot of material index 1 screening available materials for the thrust gear shaft.

From the CES software analysis, our top five material choices are:

- Alumina (85%)
- Cast pH stainless steel
- High CR white cast iron (various grades)
- Low alloy white cast iron (various grades)
- Tungsten hot work tool steel

Our final recommendation for this material is low alloy white cast iron (BS grade 1A). This is the lowest priced material out of all of the CES choices. In addition, this material is more easily machined than the other choices. It is more readily available than the alumina, the stainless steel, and the tool steel. Based on these details, we can confidently recommend this cast iron for the final design.

Wheel Hub Shell

Function: Support Load

Objective: Minimize mass (weight)

Constraints:

  - Support dynamic stress of 45.02 MPa (from FEA)
  - Cost
  - Length L specified (the shell can be modeled as a beam of length L)
  - Thickness

Material Indices:

From lecture, the material index for a light, stiff beam is:

$$M_1 = \frac{\sigma_Y{}^{2/3}}{\rho}$$

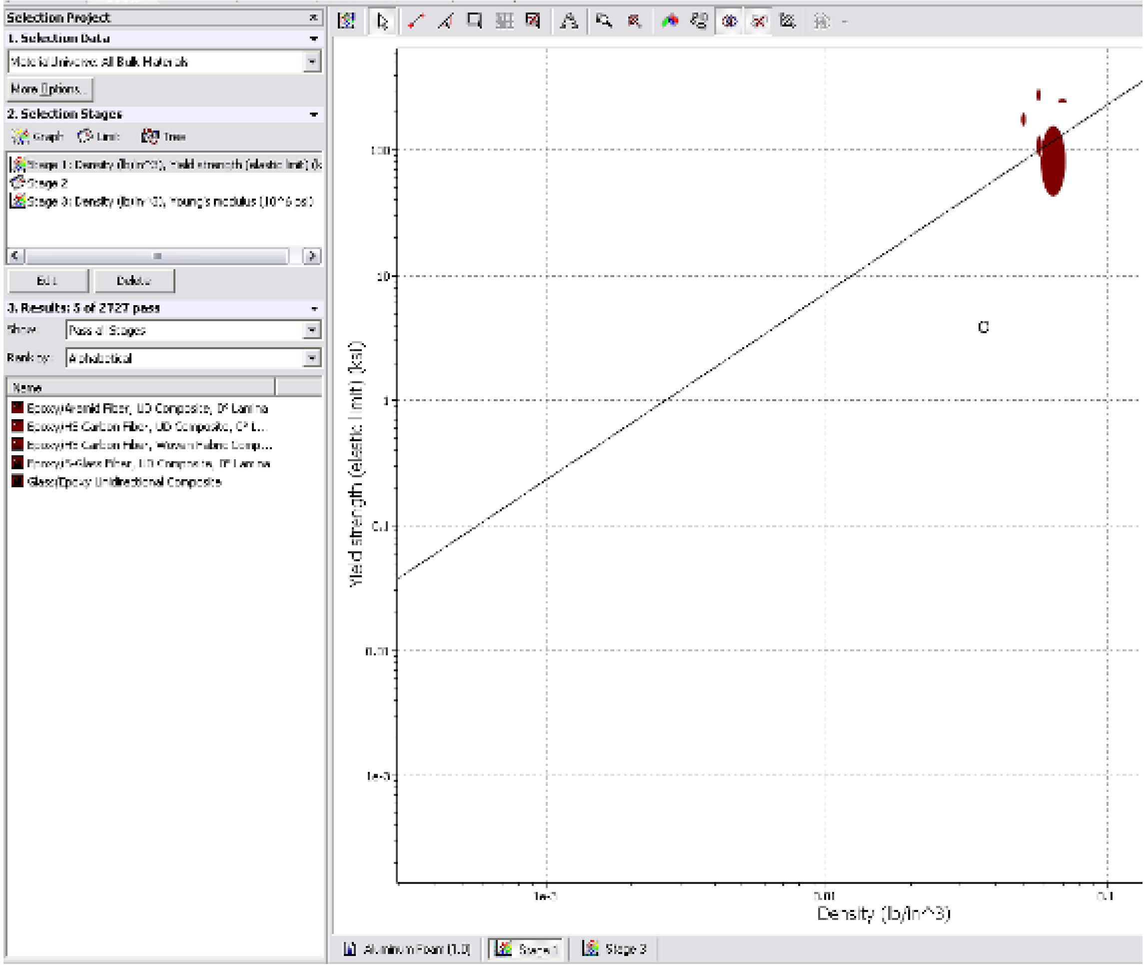
Also from lecture, the material index for a light, strong beam is:

$$M_2 = \frac{E^{1/2}}{\rho}$$

Using the CES software, we are able to use our material indices to screen for the most appropriate materials. The first stage graph is set to density against yield strength. The first index corresponds to a line of slope 3/2. We can eliminate any materials below the index line. The second index can be represented by a line of slope 2 on a graph set with density against Young's Modulus. From the cross section of these two graphs, we can adjust the two lines until we are limited to certain applicable materials. In addition, we can adjust the total cost/lb for the material until we have found the five most suitable materials. These are:

- Epoxy/aramid fiber
- Epoxy/high strength carbon fiber, unidirectional composite, 0 degree lamina
- Epoxy/high strength carbon fiber, woven fabric composite, biaxial lamina
- Epoxy/S-glass fiber, unidirectional composite, 0 degree lamina
- Glass/epoxy unidirectional composite

For our final recommendation, we would suggest using the glass/epoxy mix. This material is the lowest price of the five materials suggested by the CES software. In addition, private correspondence with Steve Katsaros , inventor of the RevoPower retrofit gasoline powered bicycle wheel reinforces this choice. Part of our consultation with Mr. Katsaros was on the subject of materials for his support hub on his prototype. Mr. Katsaros also uses a glass/epoxy mix for his bicycle wheel assembly. The fact that this real-world example reinforces our theoretical findings from the CES software makes us much more confident in our recommendation for our own project.



Selection Project

1. Selection Data

Material Universe: All Bulk Materials

More Options...

2. Selection Stages

Stage 1: Density (lb/in^3), Yield strength (elastic limit) (k

Stage 2

Stage 3: Density (lb/in^3), Young's modulus (10^6 psi)

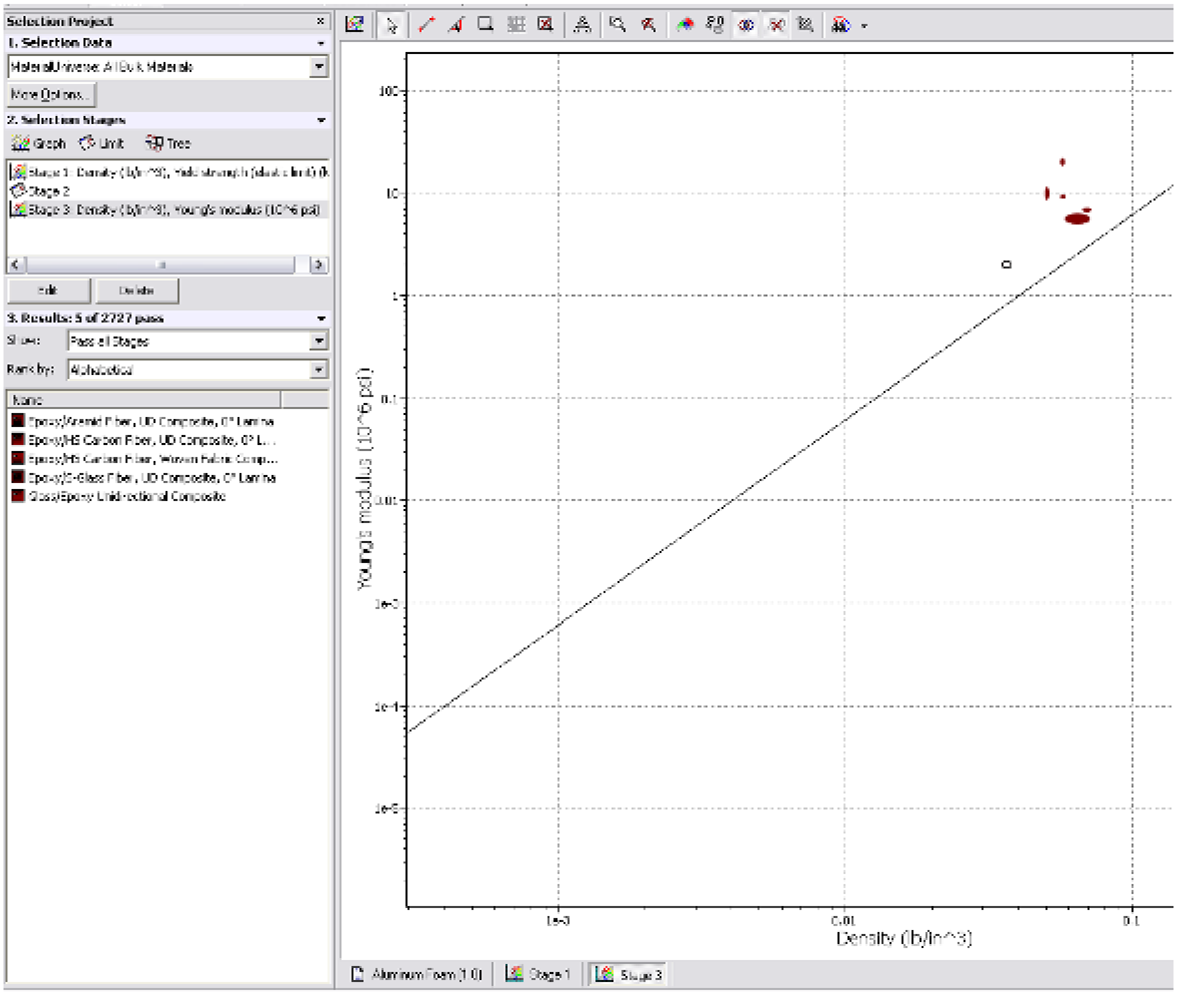
3. Results: 5 of 2727 pass

Show: Pass all Stages

Rank by: Alphabetical

Name
- Epoxy/Aramid Fiber, UD Composite, 0° Lamina
- Epoxy/HS Carbon Fiber, UD Composite, 0° L...
- Epoxy/HS Carbon Fiber, Woven Fabric Comp...
- Epoxy/S-Glass Fiber, UD Composite, 0° Lamina
- Glass/Epoxy Unidirectional Composite

Figure 74: Screenshot of the CES software recommendations based on the first material index for the wheel hub shell.



MaterialUniverse: All Bulk Materials

Stage 1: Density (lb/in^3), Yield strength (elastic limit) (k
Stage 2
Stage 3: Density (lb/in^3), Young's modulus (10^6 psi)

Show: Pass all Stages

Rank by: Alphabetical

Epoxy/Aramid Fiber, UD Composite, 0° Lamina
Epoxy/HS Carbon Fiber, UD Composite, 0° L...
Epoxy/HS Carbon Fiber, Woven Fabric Comp...
Epoxy/S-Glass Fiber, UD Composite, 0° Lamina
Glass/Epoxy Unidirectional Composite

Figure 75: Screenshot of the CES software recommendations based on the second material index.

E.2 Manufacturing Process Selection

In order to select a viable manufacturing process for our chosen materials, we first determined a set of requirements for each of the components (see Table 4). The analysis was based on the assumption of creating 1000-10000 units during the course of production.

Component	Batch Size (1000-10000 units)	Tolerance	Material	Shape
Thrust Gear Shaft	4000-40000 pcs. (four per unit)	0.01 in	Low alloy white cast iron (BS grade 1A)	Prismatic, axisymmetric, solid, stepped
Wheel Hub Shell	2000-20000 pcs. (two per unit)	0.01 in	Epoxy/aramid fiber, unidirectional composite, 0 degree lamina	3-D solid

Table 4: Manufacturing requirements for the thrust gear shaft and wheel hub shell components.

Based on these considerations, we used the Granta CES©software to perform an intersection analysis for possible manufacturing processes for each component. In order to do so, we created multiple stages for each component based on the conditions outlined in Table 4. For the thrust gear shafts, the software proposed five possible manufacturing processes:

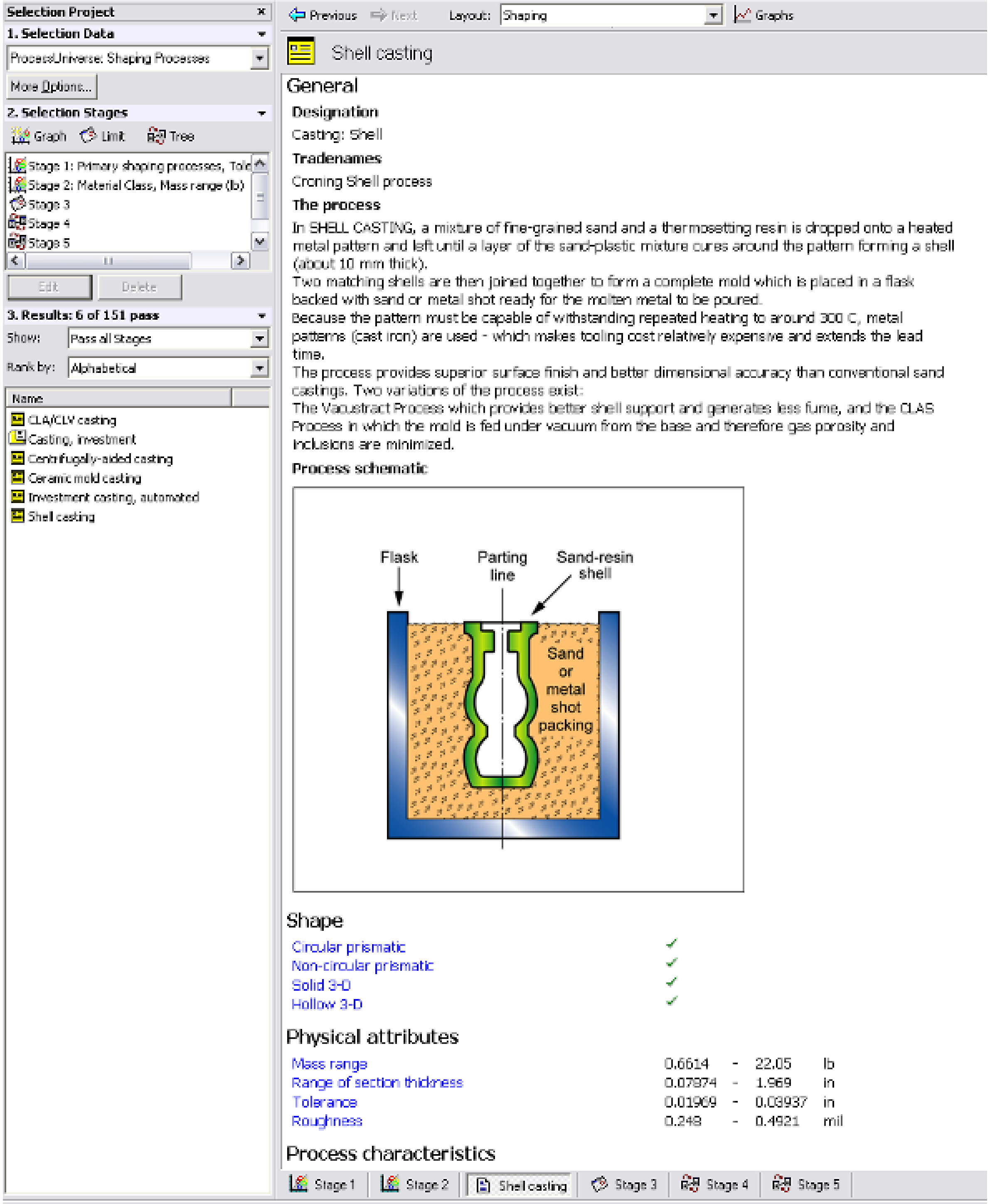
- CLA/CLV casting
- Centrifugally-aided casting
- Ceramic mold casting
- Investment casting, automated
- Shell casting

A short scrutiny of each of these processes based on the cost per piece yields shell casting as the most suitable process for fabricating the shafts. Figure 76 shows a screenshot of the CES synopsis for shell casting.

A similar analysis was performed for the ideal process to produce the wheel hub shells. Based on the material specified (aramid fiber/epoxy resin mix), the process selection was very limited in scope. Only two viable options were presented by the software:

- Centrifugal molding
- Resin transfer molding

Based on the cost per piece for each of these processes, we recommend using the resin transfer molding method for manufacturing the shells. This is also loosely based on our personal experience in fabricating the shell for our prototype. In our experience, use of partial vacuum pressure to press the resin/fiber mix to the mold was an unnecessary addition to the fabrication process that could be eliminated based on the simplicity of the part shape.



1. Selection Data

ProcessUniverse: Shaping Processes

2. Selection Stages

- Stage 1: Primary shaping processes, Tole
- Stage 2: Material Class, Mass range (lb)
- Stage 3
- Stage 4
- Stage 5

3. Results: 6 of 151 pass

Show: Pass all Stages

Rank by: Alphabetical

- CLA/CLV casting
- Casting, investment
- Centrifugally-aided casting
- Ceramic mold casting
- Investment casting, automated
- Shell casting

Layout: Shaping

Shell casting

General

Designation

Casting: Shell

Tradenames

Croning Shell process

The process

In SHELL CASTING, a mixture of fine-grained sand and a thermosetting resin is dropped onto a heated metal pattern and left until a layer of the sand-plastic mixture cures around the pattern forming a shell (about 10 mm thick).

Two matching shells are then joined together to form a complete mold which is placed in a flask backed with sand or metal shot ready for the molten metal to be poured.

Because the pattern must be capable of withstanding repeated heating to around 300 C, metal patterns (cast iron) are used - which makes tooling cost relatively expensive and extends the lead time.

The process provides superior surface finish and better dimensional accuracy than conventional sand castings. Two variations of the process exist:

The Vacustract Process which provides better shell support and generates less fume, and the CLAS Process in which the mold is fed under vacuum from the base and therefore gas porosity and inclusions are minimized.

Process schematic

Shape

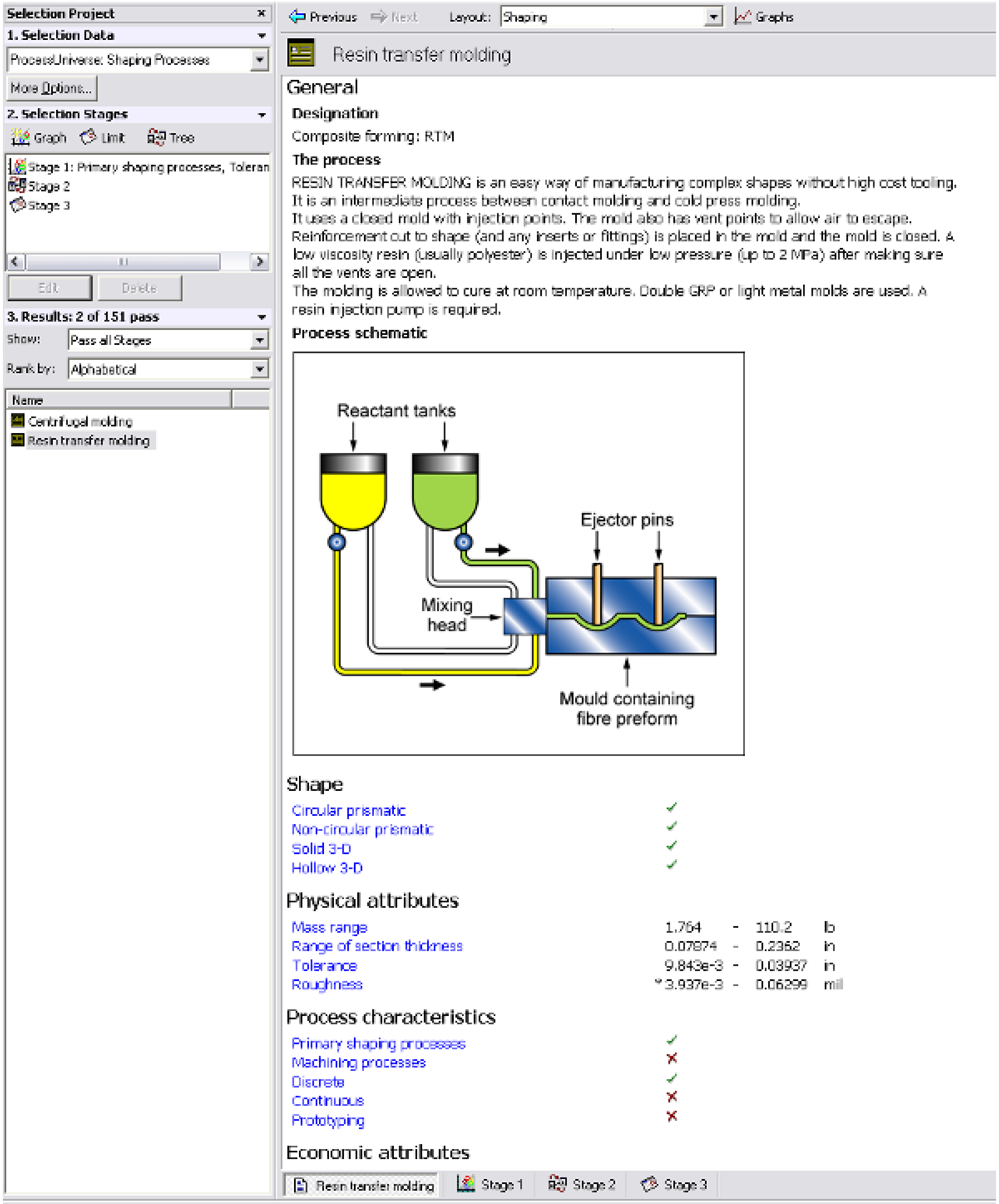
Circular prismatic	✓
Non-circular prismatic	✓
Solid 3-D	✓
Hollow 3-D	✓

Physical attributes

Mass range	0.6614	-	22.05	lb
Range of section thickness	0.07874	-	1.969	in
Tolerance	0.01969	-	0.03937	in
Roughness	0.248	-	0.4921	mil

Process characteristics

Figure 76: Screenshot of the CES software recommendation for use of shell casting to manufacture the thrust gear shafts, based on five stage screening of available processes.



ProcessUniverse: Shaping Processes

Stage 1: Primary shaping processes, Toleran
Stage 2
Stage 3

3. Results: 2 of 151 pass

Show: Pass all Stages

Rank by: Alphabetical

Centrifugal molding
Resin transfer molding

Layout: Shaping

Resin transfer molding

General

Designation

Composite forming: RTM

The process

RESIN TRANSFER MOLDING is an easy way of manufacturing complex shapes without high cost tooling. It is an intermediate process between contact molding and cold press molding. It uses a closed mold with injection points. The mold also has vent points to allow air to escape. Reinforcement cut to shape (and any inserts or fittings) is placed in the mold and the mold is closed. A low viscosity resin (usually polyester) is injected under low pressure (up to 2 MPa) after making sure all the vents are open. The molding is allowed to cure at room temperature. Double GRP or light metal molds are used. A resin injection pump is required.

Process schematic

Shape

Circular prismatic	✓
Non-circular prismatic	✓
Solid 3-D	✓
Hollow 3-D	✓

Physical attributes

Mass range	1.764	-	110.2	lb
Range of section thickness	0.07874	-	0.2362	in
Tolerance	9.843e-3	-	0.03937	in
Roughness	* 3.937e-3	-	0.06299	mil

Process characteristics

Primary shaping processes	✓
Machining processes	✗
Discrete	✓
Continuous	✗
Prototyping	✗

Economic attributes

Figure 77: Screenshot of the CES software giving a synopsis of the resin transfer method for production of the wheel hub shells.

E.3 Design for Assembly of Select Important Components

The design for assembly of the entire bicycle hub and all its components has not been altered during our project, since this has been the first time the assembly has ever been put together. The following charts describe the order of part assembly, the estimated time for manual assembly and then the overall design efficiency for each sub-assembly.

Clutch Assembly Order and Efficiency

			Size			**Thickness**					
Assembly Order	#	Part	0-6mm	6-15mm	>15mm	<2mm	>2mm	α	β	α + β	Estimated Time to manually insert
1	1.1	Small gear		X			X	0	360	360	4.35 sec
2	1.2	Spacing washer		X		X		0	360	360	3.86 sec
3	1.3	Thrust bearing		X		X		0	360	360	3.86 sec
4	1.4	Spacing washer		X		X		0	360	360	3.86 sec
5	1.5	Electromechanical Clutch			X		X	0	360	360	4.80 sec
6	1.6	Spacing washer		X		X		0	360	360	3.86 sec
7	1.7	Thrust bearing		X		X		0	360	360	3.86 sec
8	1.8	Spacing waster		X		X		0	360	360	3.86 sec
9	1.9	Support plate			X		X	0	0	0	4.80 sec
10	1.10	Holding screw	X				X	0	360	360	4.05 sec
11	1.11	Standoffs (x4)		X			X	0	360	360	17.4 sec
12	1.12	Bolts (x4)		X			X	0	360	360	17.4 sec
13	1.13	Washer		X		X		0	360	360	3.86 sec
14	1.14	Nuts (x4)	X				X	0	360	360	16.2 sec
15	1.15	Locking Pin	X			X		0	360	360	4.01 sec
									Total Time		100.03 sec
									Design Efficiency		44.98%

The design efficiency found for the assembly of the clutch to the superbracket including all parts assembled to achieve this is roughly 44.98%. The clutch activates the braking gear to produce the cycle of regenerative braking, or cycle of the hydraulic fluid building pressure into the high-pressure accumulator.

Accelerating Gear/One-Way Bearing Gear Order of Assembly and Efficiency

			Size			**Thickness**					
Assembly Order	#	Part	0-6mm	6-15mm	>15mm	<2mm	>2mm	α	β	$\alpha + \beta$	Estimated Time to manually insert
1	2.1	Small gear		X			X	0	360	360	4.35 sec
2	2.2	Spacing washer		X		X		0	360	360	3.86 sec
3	2.3	Thrust bearing		X		X		0	360	360	3.86 sec
4	2.4	Spacing washer		X		X		0	360	360	3.86 sec
5	2.5	Support plate			X		X	0	0	0	4.80 sec
6	2.6	Standoffs (x4)		X			X	0	360	360	17.4 sec
7	2.7	Bolts (x4)		X			X	0	360	360	17.4 sec
8	2.8	Washer		X		X		0	360	360	3.86 sec
9	2.9	Nuts (x4)	X				X	0	360	360	16.2 sec
									Total Time		75.59
									Design Efficiency		35.71%

The accelerating gear is the attachment that uses the energy stored in the high pressure accumulator and is released from the activation of the two-way valve. The efficiency of assembling these parts is roughly 35.71%. The lower percentage is regarded from the time spend tightening the bolts down to the support plate.

6-Gear System Assembly Order and Efficiency

			Size			**Thickness**					
Assembly Order	#	Part	0-6mm	6-15mm	>15mm	<2mm	>2mm	α	β	$\alpha + \beta$	Estimated Time to manually insert
1	3.1	Cantilever beams		X			X	0	0	0	4.35 sec
2	3.2	Screws (x16)	X				X	0	360	360	16.8 sec
3	3.3	Spacing washer		X		X		0	360	360	3.86 sec
4	3.4	Thrust Bearing		X		X		0	360	360	3.86 sec
5	3.5	Spacing washer		X		X		0	360	360	3.86 sec
6	3.6	Thrust gears (x2)		X			X	0	360	360	8.7 sec
7	3.7	Connecting gears (x2)		X			X	0	360	360	8.7 sec
8	3.8	Clamping pins (x6)		X			X	0	360	360	8.7 sec
									Total Time		50.13
									Design Efficiency		47.8 %

This gear system is the remaining gears, aside from the previously discussed driving and braking small gears that are correlated with the assembly of the clutch and one-way bearing. The efficiency of assembling these parts is roughly 47.8%, where most time is spend attaching the cantilever beams which require four screws a piece.

Attachment of Remaining Parts to Superbracket Order and Efficiency

			Size			Thickness					
Assembly Order	#	Part	0-6mm	6-15mm	>15mm	<2mm	>2mm	α	β	$\alpha + \beta$	Estimated Time to manually insert
1	4.1	Superbracket			X	X		0	0	0	1.69 sec
2	4.2	Low pressure accumulator			X		X	0	0	0	5.03 sec
3	4.3	High pressure accumulator			X		X	0	0	0	7.24 sec
4	4.4	Motor			X		X	0	0	0	6.4 sec
5	4.5	Pump			X		X	0	0	0	6.4 sec
6	4.6	Two-way valve			X		X	0	0	0	7.34 sec
7	4.7	Fluid filter		X			X	0	180	180	2.43 sec
8	4.8	Fittings (x12)		X			X	0	360	360	20.4 sec
9	4.9	Low pressure tubing		X		X		0	180	180	3.7 sec
10	4.10	High pressure tubing		X		X		0	0	0	5.9 sec
11	4.11	Bearing for main gear			X		X	0	360	360	1.5 sec
12	4.12	Main gear			X		X	0	360	360	1.5 sec
									Total Time		69.53 sec
									Design Efficiency		51.77%

The remaining components of the inside of the hydraulic bike wheel comprise of several items which have been summarized in the above table in order in which they are to be assembled. The design efficiency is roughly 51.77%, with most time spent on applying the fittings to the low and high-pressure tubing.

Hub, Fork, Axle, and Rim Assembly Order and Efficiency

			Size			Thickness					
Assembly Order	#	Part	0-6mm	6-15mm	>15mm	<2mm	>2mm	α	β	α + β	Estimated Time to manually insert
1	5.1	Fork			X		X	0	0	0	5.7 sec
2	5.2	Axle			X		X	0	0	0	5.0 sec
3	5.3	superbracket assembly			X		X	0	0	0	2.13 sec
4	5.4	Rim			X		X	0	360	360	1.18 sec
5	5.5	Inner tube			X	X		360	360	720	1.27 sec
6	5.6	Tire			X	X		0	360	360	15.2 sec
7	5.7	Hub shell with spider bracket incorporated (x2)			X		X	0	360	360	4.3 sec
8	5.8	Axle pins			X		X	0	360	360	3.5 sec
9	5.9	Bolts (x12)			X		X	0	360	360	12.3 sec
10	5.10	Nuts (x12)		X			X	0	360	360	12.3 sec
									Total Time		62.88 sec
									Design Efficiency		47.7%

The remaining parts to add to the overall design include the hub, fork, axle, and rim assembly. The design efficiency of this entire assembly is roughly 47.7%.

E.4 Design for Environmental Sustainability

In order to evaluate our final design for environmental sustainability, we carefully reviewed the materials highlighted by the Granta© CES material selection software. To do this, we used SimaPro 7.1©, a software package that, among other things, allows us to evaluate the environmental impact of the the use of certain quantities of manufactured materials. To begin, we determined the quantity of each material that we will be using in our final design:

Low alloy white cast iron (BS grade 1A)

$$4\,shafts \times 4in\ length \times \pi\left(\frac{1}{4in}\right)^2 = 3.142\ in^3 = 51480mm^3$$

$$51480mm^3 \times (7.70055E-6)\ \frac{kg}{mm^3} = 0.3964kg$$

Epoxy resin

$$\frac{146060mm^3\ per\ shell}{2} \times 2\ shells = 146060mm^3$$

$$146060mm^3 \times (1.1072E-6)\ \frac{kg}{mm^3} = 0.1617kg$$

Aramid Fiber

$$\frac{146060mm^3\ per\ shell}{2} \times 2\ shells = 146060mm^3$$

$$146060mm^3 \times (1.4394E-6)\ \frac{kg}{mm^3} = 0.2102kg$$

From here, we used the SimaPro 7.1© software to provide the total mass of air and water emissions, as well as mass of raw materials used and solid waste (see Figure 78). From Figure

78, we can readily see that the biggest impact will be in the raw materials used area (the other areas are neglible in comparison. Within this area, the aramid fiber has by far the largest impact, with roughly ten times the mass generated as the other two combined.

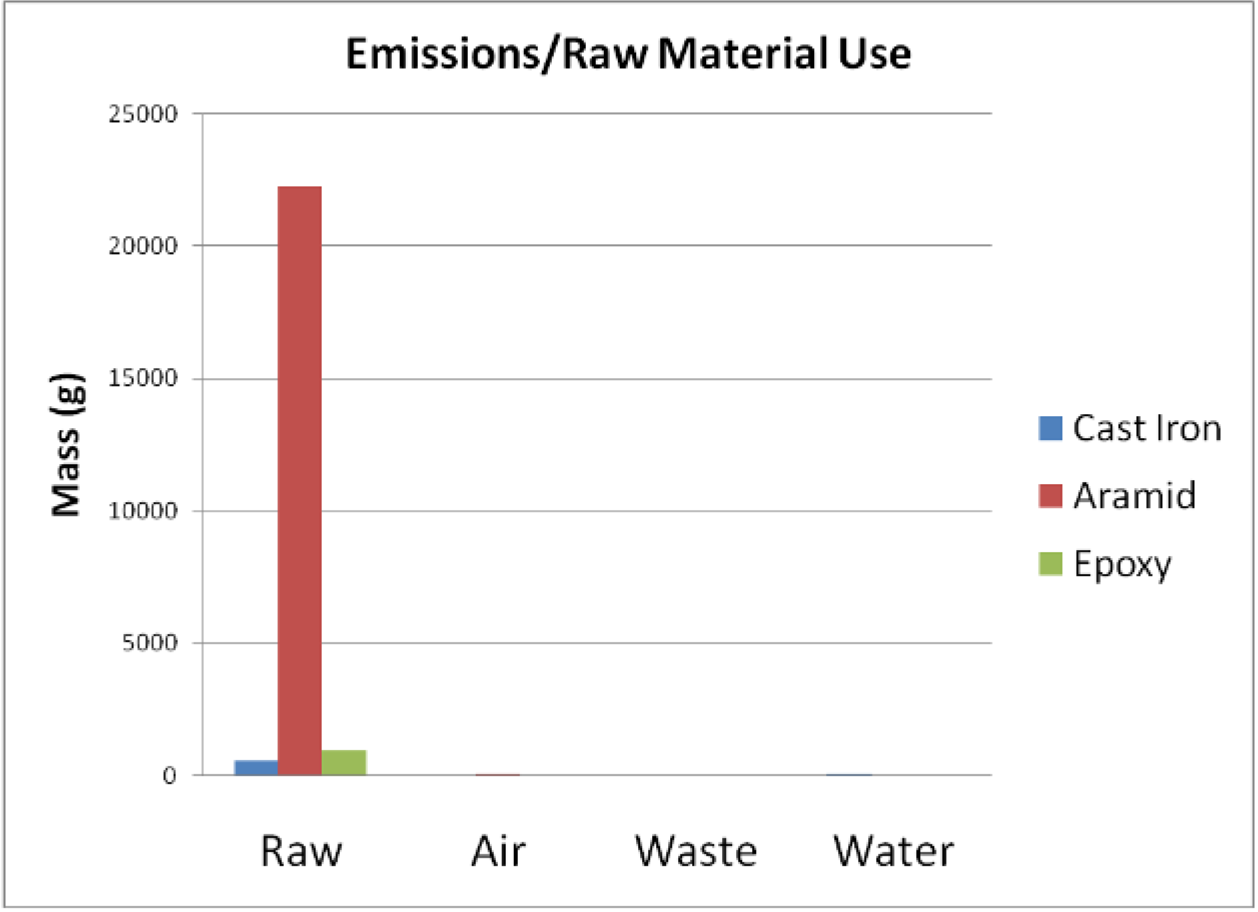


Figure 78: Total mass of raw materials used, and air, water and solid waste emissions generated for the necessary cast iron, aramid fiber, and epoxy resin to be used in one bicycle.

Next we evaluated the effect of each material in relation to one another for ten separate environmental categories. Figure 79 clearly shows the aramid fiber having the greatest impact in seven of the ten categories, and the highest relative impact overall. Figure 80 introduces three damage meta-categories for consideration: human health, ecosystem quality, and resources. From the figure we can see that all three materials have a smaller relative ecosystem impact, but aramid fiber has a strong influence on human health and cast iron scores poorly in the resources category. This is reinforced by Figure 81 that reconfigures this data into a "points" total for each of the three categories.

We can conclude from this analysis that the overall environmental impact of these materials will be better than most, they still cannot be discounted. In terms of relative impacts, the aramid fiber will have the greatest environmental footprint. It far and away uses the greatest mass of raw materials, and has a much greater influence in seven of the ten evaluated environmental categories. In addition, the use of the aramid fiber poses the greatest risk to human health out of the three. The only category in which cast iron shows a substantial advantage over aramid is in the natural resources consumed category.

Due to the high EcoIndicator 99 "point value" of aramid fiber compared to cast iron or epoxy resin, we can conclude that it's impact will be greatest over the entire life cycle of the product, even though the cast iron will have the greatest initial outlay in terms of resources used. This highlights the importance of considering the entire “big picture” of the life of the product, as it would be easy to assume the cast iron is the biggest culprit when considering only the manufacturing period for the bike wheel. This analysis does not necessarily target any of these materials being used as “bad” for the the environment. It merely provides a relative comparison between materials. The only indicator of absolute impact is the mass of emissions and raw materials used for each. Based on the low scores for emissions generated, we recommend that these materials do not show enough of an environmental footprint as to eliminate them from consideration. Therefore, we still endorse the use of all three of these materials.

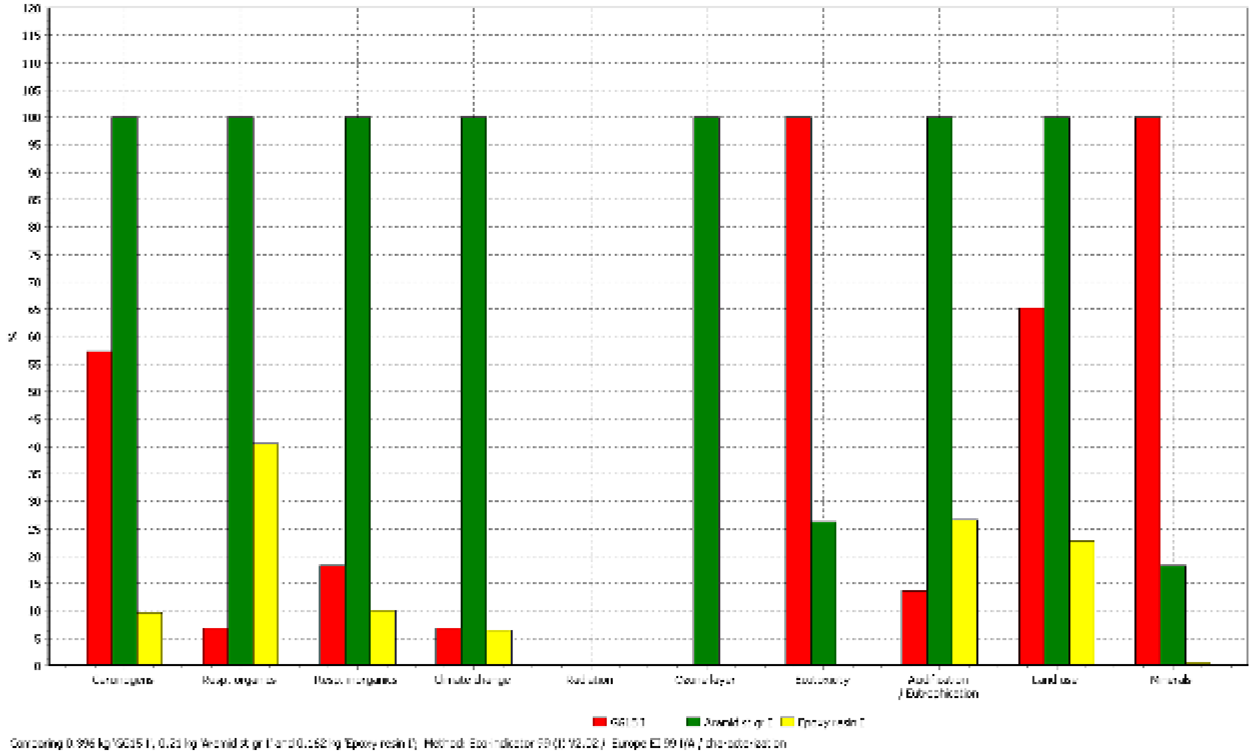


Figure 79: Relative environmental impacts of each of the three materials in each ten separate categories.

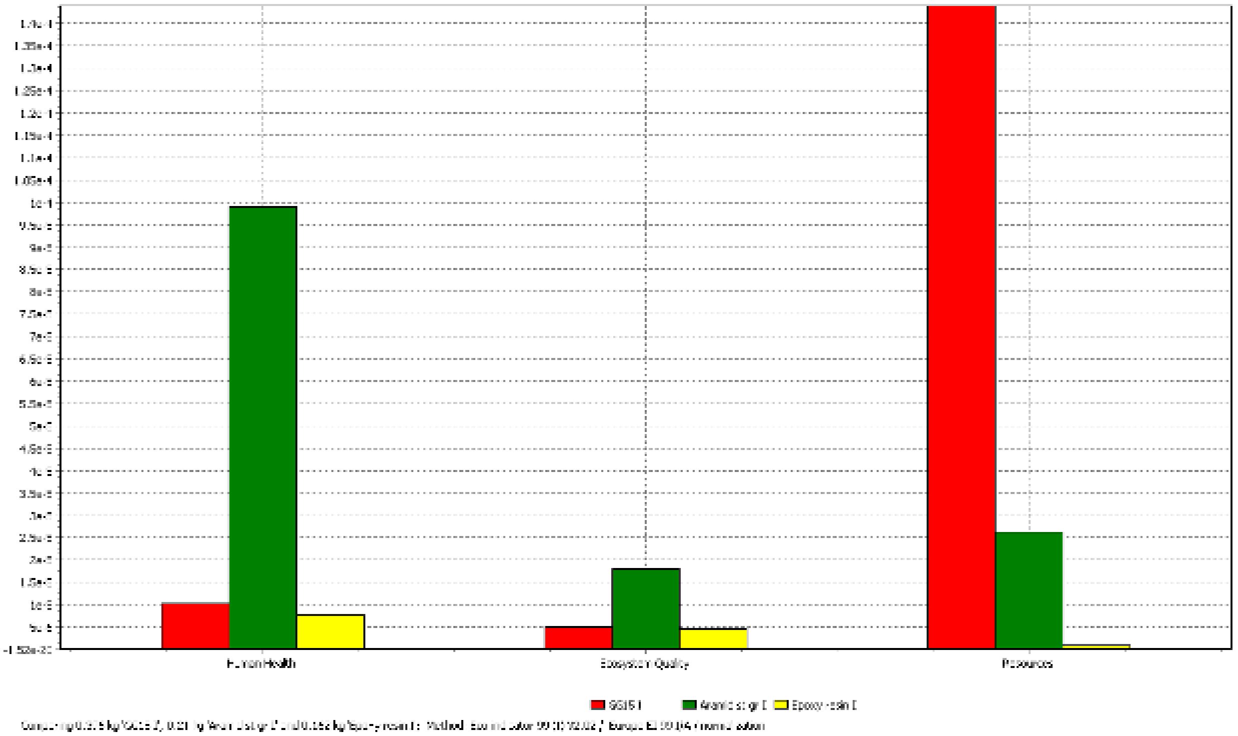


Figure 80: Normalized score for each material in 3 damage meta-categories: human health, ecosystem quality, and resources.

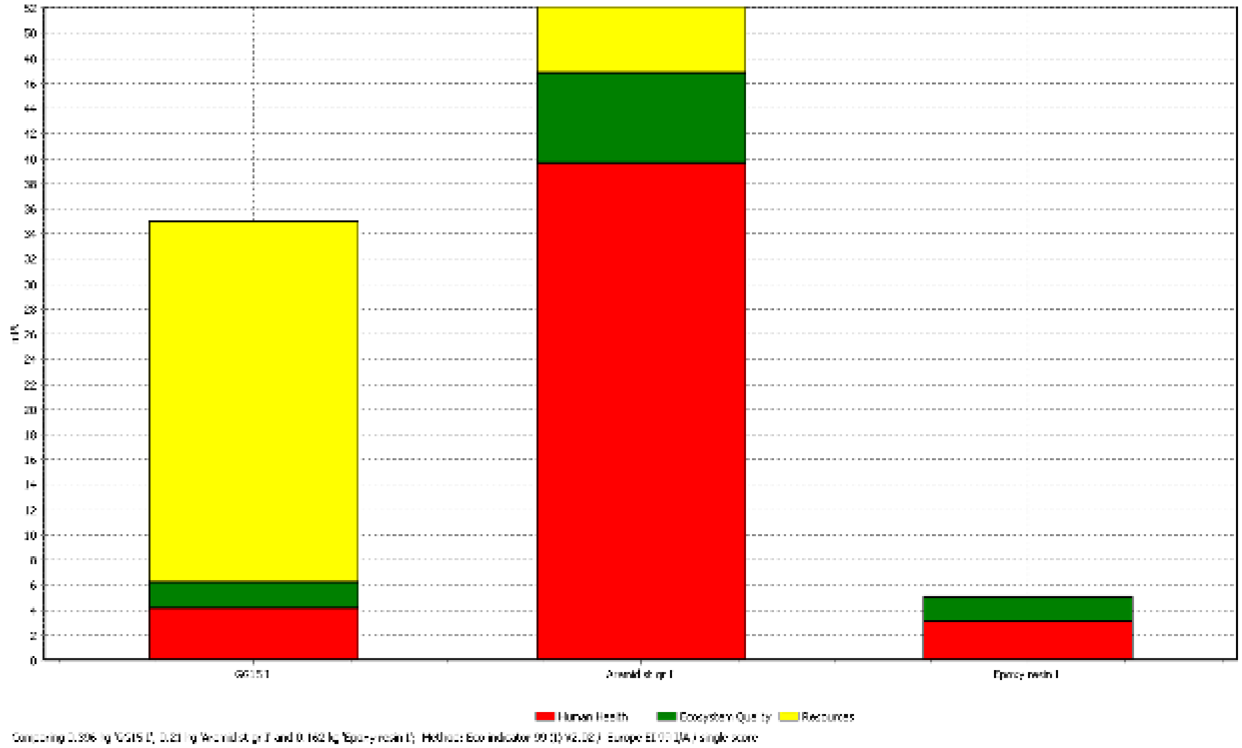


Figure 81: Single score "points" comparison between materials for each damage meta-category.

E.5 Design for Safety

The major risks involved with the 20” hydraulic regenerative braking bicycle are mostly directed towards the riders of the bike but also not limited to those who assemble the systems. One of the most hazardous failures the bike may encounter is an accidental launch, which can be triggered from a fault in the two-way valve activating unexpectedly or from an electrical surge sending unwanted power to the valve for launch. Also, if the electrical system were to malfunction or the electromechanical clutch, the biker may not be able to brake when needed, as this would be a hazardous situation as well.

The DesignSafe analysis shows that there are more mechanical hazards than electrical, fluid, or human factors. From this report which can be seen below, the highest risk levels pertain to valve malfunctions, loose parts that may cause damage to gears or other internal components, hydraulic hose entanglement, harmful impact of the bike, and ergonomic related stresses from riding or assembling. Other potentially hazardous elements for riders are electrical shorts with the clutch and valve, and fluid damage from hydraulic liquid leaks or unwanted water leaks from outside sources. Assembling the bike has the risk of sharp edges that weren’t filed down on the many steel components, such as the superbracket, axle, bolts, and clasping mechanisms. Assemblers also have the issues pertaining to the electrical wiring which may become hazardous if not grounded properly or soldered correctly.

Performing a risk assessment on our product is somewhat different than executing a Failure Modes and Effects Analysis (FMEA). FMEA is a risk analysis tool more focused on the development of a product rather than an overall risk assessment. This tool enables the analyzer to determine the level of risk associated with a specific part of the design and suggest areas of improvement. The benefit of using this system is that it helps to identify design weaknesses and define corrective action. Risk assessment on the other hand is a structured approach to achieve new design requirements and criteria. This acts as a continual improvement plan for risk reduction activities. Risk reduced is an acceptable risk.

Acceptable risk in regards to function of the bicycle are the risks that are determined to be unavoidable, such as unaccounted for damage from outside forces. Also, regular wear and tear on the mechanisms can be labeled as acceptable so long as the bike has gone through thorough testing and as much prevention of failure has been applied. When it comes to safety, there is no real acceptable risk. The bike will need to be distributed with information and labels pertaining to the potential hazards produced from the mechanisms and usage. If the bike were inspected regularly and used properly at all times, there will not be any definite safety issues. This also follows suit for the assembly procedure involved which also has some unsafe conditions. The assembly process will also need to have an explicit order and procedure to follow in order to reduce all risks to a potential zero. Overall, “zero risk” does not truly exist; however acceptable risks include those which protective measures have been taken into account fully.

designsafe Report

Application: Hydraulic Regen Bike
Description:
Product Identifier:
Assessment Type: Detailed
Limits:
Sources:

Analyst Name(s): Team 14
Company:
Facility Location:

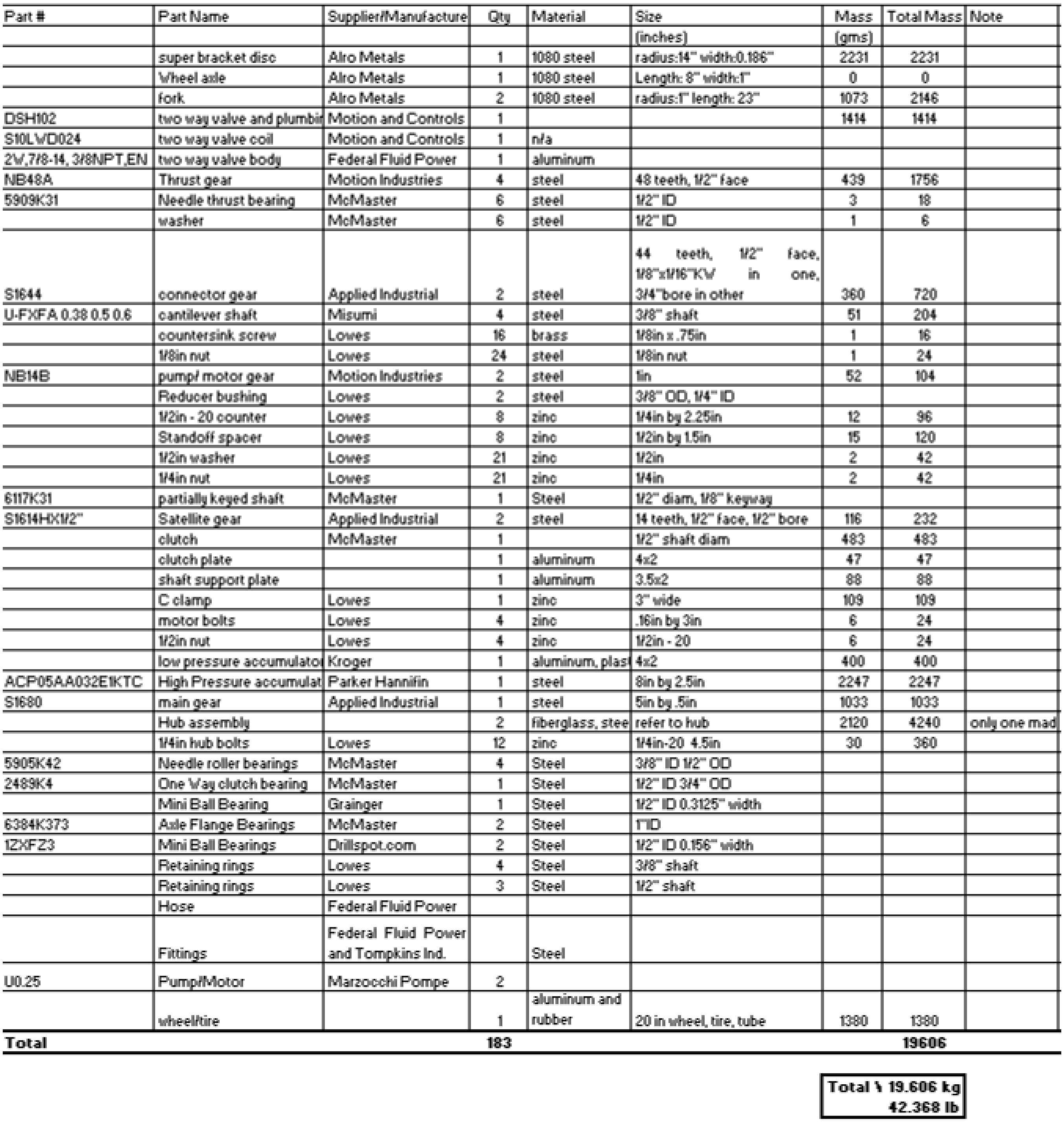
Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	mechanical : cutting / severing Edges of brackets and bolts may be sharp and cut a user or manufacturer	Slight Occasional Possible	Moderate	sand/file down all edges before assembly	Minimal Occasional Possible	Moderate	
All Users All Tasks	mechanical : drawing-in / trapping / entanglement the low pressure hydraulic hoses may become trapped or tangled in the restraint bolts/metal pieces and therefore kinked	Serious Occasional Possible	High	make sure all hydraulic tubes are out of reach of bolting down mechanism	Slight Occasional Possible	Moderate	
All Users All Tasks	mechanical : unexpected start the valve malfunctions and releases hydraulic fluid when not called for, and therefore accelerating the bike without notice	Serious Occasional Possible	High	check valve functioning frequently	Serious Occasional Unlikely	Moderate	
All Users All Tasks	mechanical : break up during operation Parts, gears, or bolts may become loose due to inconsistent motions and therefore cause the system to malfunction or break down	Serious Frequent Possible	High	check all nuts and bolts frequenctly	Slight Remote Possible	Moderate	
All Users All Tasks	mechanical : machine instability unaccounted torques causing pump/motor and gear instability; will ruin parts	Serious Occasional Unlikely	Moderate	systems should be thoroughly checked before implemented	Serious Occasional Probable	High	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	mechanical : impact if user were to drop bike or run into unaccounted for impacts, the mechanical parts and/or shell may be destroyed	Slight Frequent Probable	High	make sure users are well aware of the possibility of breaking the bike if placed under harsh conditions	Serious Occasional Possible	High	
All Users All Tasks	electrical / electronic : lack of grounding (earthing or neutral) ground wire was not established in electrical system; could cause shock to user	Slight Occasional Probable	High	ground the system!	Serious Occasional Possible	High	
All Users All Tasks	electrical / electronic : shorts / arcing / sparking over amplified circuit could cause a spark on or near the fuse; also improper soldering could cause bad connections between wires	Slight Occasional Possible	Moderate	reduce the battery power	Slight Remote Unlikely	Low	
All Users All Tasks	electrical / electronic : improper wiring bad soldering could cause lack of connection and therefore user may not be able to brake the bike or accelerate	Serious Remote Unlikely	Moderate	use a circuit board instead	Minimal Remote Unlikely	Low	
All Users All Tasks	electrical / electronic : water / wet locations hydraulic fluid leaks and/or water getting into the hub could cause damage to the electrical parts and wires	Slight Remote Possible	Moderate	seal hub best as possible, and make sure all valve connections are correct and sealed as well	Slight Remote Unlikely	Low	
All Users All Tasks	electrical / electronic : unexpected start up / motion malfunction of wire set up or if the valve breaks, the system could unexpectedlly launch the user and/or bike	Serious Remote Unlikely	Moderate	electrical checks performed somewhat frequently	Minimal Remote Unlikely	Low	
All Users All Tasks	electrical / electronic : overvoltage /overcurrent if resistors are broken or stop working, the battery supply will give too much current to 2-way valve	Slight Occasional Possible	Moderate	replace resistors on a time based frequency	Slight Remote Unlikely	Low	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	ergonomics / human factors : posture assembly of hydraulics not easy; also if a rider were to large for the bike it would be not comfortable	Slight Frequent Possible	High	avoid large riders; place notices on bike.	Slight Occasional Possible	Moderate	
All Users All Tasks	fluid / pressure : hydraulics rupture hydraulic rupture could cause electrical damage and mechanical damage.	Serious Remote Possible	Moderate	again seal valves, and have valve checks somewhat frequently	Slight Occasional Possible	Moderate	

19. Appendix G: Bill of Materials



Part #	Part Name	Supplier/Manufacture	Qty	Material	Size	Mass	Total Mass	Note
					(inches)	(gms)		
	super bracket disc	Alro Metals	1	1080 steel	radius:14" width:0.186"	2231	2231	
	Wheel axle	Alro Metals	1	1080 steel	Length: 8" width:1"	0	0	
	fork	Alro Metals	2	1080 steel	radius:1" length: 23"	1073	2146	
DSH102	two way valve and plumbi	Motion and Controls	1			1414	1414	
S10LWD024	two way valve coil	Motion and Controls	1	n/a				
2W,7/8-14, 3/8NPT,EN	two way valve body	Federal Fluid Power	1	aluminum				
NB48A	Thrust gear	Motion Industries	4	steel	48 teeth, 1/2" face	439	1756	
5909K31	Needle thrust bearing	McMaster	6	steel	1/2" ID	3	18	
	washer	McMaster	6	steel	1/2" ID	1	6	
S1644	connector gear	Applied Industrial	2	steel	44 teeth, 1/2" face, 1/8"x1/16"KW in one, 3/4"bore in other	360	720	
U-FXFA 0.38 0.5 0.6	cantilever shaft	Misumi	4	steel	3/8" shaft	51	204	
	countersink screw	Lowes	16	brass	1/8in x .75in	1	16	
	1/8in nut	Lowes	24	steel	1/8in nut	1	24	
NB14B	pump/ motor gear	Motion Industries	2	steel	1in	52	104	
	Reducer bushing	Lowes	2	steel	3/8" OD, 1/4" ID			
	1/2in - 20 counter	Lowes	8	zinc	1/4in by 2.25in	12	96	
	Standoff spacer	Lowes	8	zinc	1/2in by 1.5in	15	120	
	1/2in washer	Lowes	21	zinc	1/2in	2	42	
	1/4in nut	Lowes	21	zinc	1/4in	2	42	
6117K31	partially keyed shaft	McMaster	1	Steel	1/2" diam, 1/8" keyway			
S1614HX1/2"	Satellite gear	Applied Industrial	2	steel	14 teeth, 1/2" face, 1/2" bore	116	232	
	clutch	McMaster	1		1/2" shaft diam	483	483	
	clutch plate		1	aluminum	4x2	47	47	
	shaft support plate		1	aluminum	3.5x2	88	88	
	C clamp	Lowes	1	zinc	3" wide	109	109	
	motor bolts	Lowes	4	zinc	.16in by 3in	6	24	
	1/2in nut	Lowes	4	zinc	1/2in - 20	6	24	
	low pressure accumulato	Kroger	1	aluminum, plas	4x2	400	400	
ACP05AA032E1KTC	High Pressure accumulat	Parker Hannifin	1	steel	8in by 2.5in	2247	2247	
S1680	main gear	Applied Industrial	1	steel	5in by .5in	1033	1033	
	Hub assembly		2	fiberglass, stee	refer to hub	2120	4240	only one mad
	1/4in hub bolts	Lowes	12	zinc	1/4in-20 4.5in	30	360	
5905K42	Needle roller bearings	McMaster	4	Steel	3/8" ID 1/2" OD			
2489K4	One Way clutch bearing	McMaster	1	Steel	1/2" ID 3/4" OD			
	Mini Ball Bearing	Grainger	1	Steel	1/2" ID 0.3125" width			
6384K373	Axle Flange Bearings	McMaster	2	Steel	1"ID			
1ZXFZ3	Mini Ball Bearings	Drillspot.com	2	Steel	1/2" ID 0.156" width			
	Retaining rings	Lowes	4	Steel	3/8" shaft			
	Retaining rings	Lowes	3	Steel	1/2" shaft			
	Hose	Federal Fluid Power						
	Fittings	Federal Fluid Power and Tompkins Ind.		Steel				
U0.25	Pump/Motor	Marzocchi Pompe	2					
	wheel/tire		1	aluminum and rubber	20 in wheel, tire, tube	1380	1380	
Total			**183**				**19606**	

Total \ 19.606 kg
42.368 lb