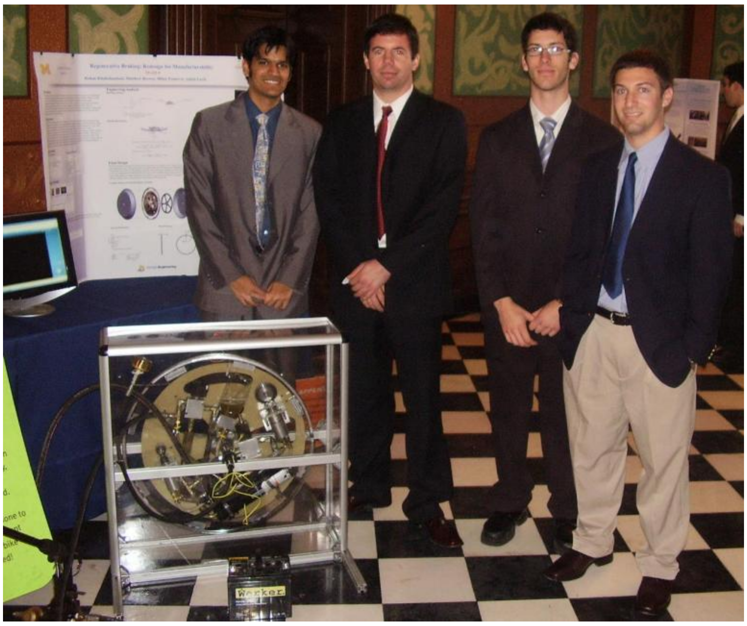
Final Design Review

Bicycle Regenerative Braking: Redesign for Manufacturability



ME 450: Design and Manufacturing III

Fall 2007

Team 9

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Contents

1. ABSTRACT

The Environmental Protection Agency (EPA) is producing vehicles which use conventional engines in combination with hydraulics for regenerative braking and propulsion. These are referred to as hydraulic hybrid vehicles. In the Winter of 2007, students in ME 450, in collaboration with the EPA, designed and assembled a lightweight regenerative braking system (RBS) for the front wheel of a bicycle. We have continued this project and our goals were to: reengineer the previous team's prototype to improve durability; redo the plumbing of the RBS to incorporate a higher safety standard in the high pressure hoses; reconfigure the positioning of hydraulic components to reduce the overall thickness and to facilitate the design of a hub shell; design and manufacture bicycle rim that will support the RBS; and to design a hub shell.

2. INTRODUCTION

The Environmental Protection Agency (EPA or sometimes USEPA) is an agency of the federal government of the United States which is responsible for protecting human health and safeguarding the natural environment: air, water, and land. The EPA began operation on December 2, 1970, and was established by President Richard Nixon. The EPA conducts research with three main aims [1, 2]. The three namely being to

- Reduce pollution
- Increase fuel efficiency
- Reduce Greenhouse gases.

In congested cities it is thought that cycling could be a better option than using a vehicle. Cycles are more environmentally friendly and at times can be quicker when there is a large amount of traffic. The EPA in conjunction with students from the University of Michigan has built a bike with a hydraulic braking system. The EPA is a research leader in the application of hydraulics. Hydraulics help to capture a large amount of energy that is wasted during braking. This energy is then transmitted back into kinetic energy during launch. Hydraulic hybrid technology does not pollute the environment and also helps increase fuel efficiency.

Our sponsor, Dr. David Swain from the EPA, has summarized our main task, which is to ensure the functionality of the current RBS and design an outer casing for the front hydraulic wheel of the bike. We also are responsible for the rearrangement of the internal components of the hydraulics, so as to make the assembly more compact. Our aim is to increase the manufacturability of the entire system and assemble a working prototype.

The RBS works on the following principle. When the bicycle rider squeezes the hand brake, the hydraulic pump thrusts fluid from the low pressure accumulator to the high pressure accumulator. Gears connect the main bicycle wheel to the pump shaft, which is used to increase pressure during braking, causing the bike to decelerate. In the launch phase, the valves redirect the fluid flow to actuate a hydraulic motor, accelerating the main gear and the front wheel. The fluid flows in circles through the system without pressurizing the accumulators when riding the bicycle at a constant velocity.

3. INFORMATION SEARCH

Our sources of information include: our sponsor, Dr. David Swain; Jason Moore, a graduate student with much exposure to this project; the research of previous teams who have worked on this same project; two US patents on RBS technology; and Jason Moore's application for a patent on his working prototype.

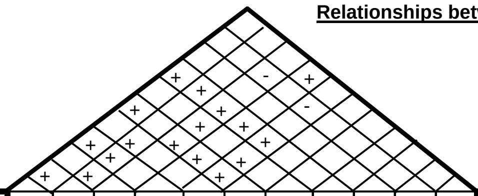
Dr. Swain has provided us with the underlying goals and customer requirements. He is also our source for project funding and overall questions as to the nature of our project. Jason Moore is our resource for technical questions concerning the inner workings of the current hydraulic RBS prototype and questions concerning the incorporation of the RBS into a bicycle. The documentation from previous teams also provides us with technical knowledge and understanding of the current prototype in addition to unresolved problems that will need to be addressed in our design.

US Patent No. 4942936 is a design for a hybrid bicycle that uses hydraulics and electricity [3]. The electro-hydraulic system can store energy in the form of hydraulic pressure or in compressed air. The system lies in the center of the bike, rather than in the front wheel hub, and the setup is large, awkward and heavy. US Patent No. 6959971 is a design that incorporates an electric braking system, a hydraulic braking system and an electric RBS into a vehicle [4]. The components of the hydraulic braking system are similar to our design, but the stored hydraulic pressure generated during braking is used to decelerate the rear tires instead of accelerating the vehicle. Lastly, US Patent Application No. 20070126284 is the design created by Jason Moore from his most recent prototype of a hydraulic RBS for a bicycle [5]. Included in Jason's Patent Application is a design for transferring power from the working fluid to the motor. Furthermore, this power is transferred through a series of gears to the shell housing which is rigidly connected to the front bicycle wheel. Jason's Patent Application also includes a design layout for mounting the hydraulic components within the desired enclosure. Our project is largely based off of this bicycle.

4. CUSTOMER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

This section describes, in detail, the customer requirements and corresponding engineering specifications for this project. The customer requirements were determined by our sponsor, Dr. David Swain, and are listed in our Quality Function Deployment diagram (QFD) in Figure 1 **(**p.5). The most recent team's prototype is shown in Figure 2 (p.5).

Figure 1: Quality Function Deployment



Relationships between technical requirements

- ++ Strong Positive
- \+ Medium Positive
- \- Medium Negative
- \- - Strong Negative

Most Important Requirements/Specifications (red)

	Technical specifications / Customer requirements	Weightage	Hub width [5]	Hub diameter	Max. sustained braking torque	Max. Weight << 22lbs	Max. sustained launching torque	Motor/pump displacement	Max. pressure [4]	Max. volume of hydraulic fluid [2]	Hydraulic fluid filtration [1]	Accumulator Pressure After Breaking	Shell Weight	Total (weighted customer requirement)	Normalized to total	Importance rating (% of total)	Winter 07 Bike	Fall 06 Bike	Winter 05 Bike	Fall 05 Bike
Old Requirements	Universal application	5	7	9	1	7	1	1	1	7	1	1	3	195	0.07	7	9	2	1	1
	Natural rate of braking	3	1	1	9	1	1	7	7	5	1	3	1	111	0.04	4	7	2	2	3
	Sufficient top speed	3	1	1	1	7	9	5	9	5	1	1	3	129	0.04	4	5	2	2	3
	Efficient	5	1	1	3	7	7	3	8	3	5	5	3	230	0.08	8	7	2	2	3
	Lightweight	5	3	3	1	9	1	5	3	5	1	1	9	205	0.07	7	9	2	1	1
	Reliable	5	1	1	5	3	5	3	1	1	9	1	1	155	0.05	5	7	2	1	3
	Aesthetics	5	7	5	1	5	1	1	1	5	1	1	1	145	0.05	5	5	2	2	4
	Safety	5	1	1	9	1	9	1	5	1	1	9	1	195	0.07	7	7	2	1	2
	Easy to use	3	1	1	5	9	5	3	1	1	1	7	1	105	0.04	4	5	1	1	3
	Easy to service	5	5	5	1	1	1	1	5	1	9	1	1	155	0.05	5	5	2	2	1
	Maintains bicycle function	5	7	7	3	7	3	1	1	1	1	1	1	165	0.06	6	5	3	3	3
New Reqs	Fix and test current prototype	9	5	5	5	1	5	5	1	1	1	7	1	333	0.11	11				
	Design and manufacture hub shell	7	7	7	3	7	3	1	1	1	1	1	9	287	0.10	10				
	Reconfigure RBS	9	9	9	3	3	3	1	1	1	1	1	1	297	0.10	10				
	Adapt prototype to bicycle	9	5	7	3	1	3	1	1	1	1	1	1	225	0.08	8				
	Measurement Unit		in	in	N-m	lb	N-m	cc.	kPsi	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	n/a							
	Moped		5	16	n/a	100	2	n/a	n/a	n/a	n/a	n/a	n/a							
	Our target		6	29	130	<22	90	1.5	5	1	n/a	n/a	n/a							
	Total (weighted technical specifications)		389	407	285	345	305	195	210	187	183	221	205							
	Normalized to total		0.13	0.14	0.10	0.12	0.10	0.07	0.07	0.06	0.06	0.08	0.07							
	Importance Rating (% of total)		13	14	10	12	10	7	7	6	6	8	7							

Figure 2: Previous Team's Prototype

Customer Requirements

We have the same requirements for this project as the previous team, but since the scope of the project has evolved we have some additional requirements. The new and old customer requirements are listed in Table 1 below. The customer requirements with the highest importance rating as determined from our QFD are: fix and test current prototype, reconfigure RBS, and design and manufacture hub shell.

Table 1: Customer Requirements

Old Requirements	**New Requirements**
Universal Application	Fix and Test Current Prototype
Natural Rate of Braking	Design CAD file of Hub Shell
Sufficient Top Speed	Reconfigure RBS
Efficient	Adapt Prototype to Bicycle
Lightweight	Reduce RBS system thickness
Reliable	
Aesthetics	
Safety	
Easy to Use	
Easy to Service	
Maintains Bicycle Function	

Engineering Specifications

We determined the engineering specifications based on the desires of the customer requirements in addition to the specifications set forth by previous design teams. These specifications are displayed in Table 2 below.

Table 2: Engineering Specifications

Description	**Parameters**
Hub Width	< 6”
Hub Diameter	< 29”
Maximum Sustained Braking Torque	130 Nm
Top Operating Speed	20mph
Approximate efficiency	>70%
Maximum sustained launching torque	90 Nm
Maximum system working pressure	5000 psi
Maximum weight of hydraulic system	< 22 lbs
Motor/Pump Displacement	1.5 cc
Maximum Volume of fluid	1 L
Hydraulic fluid filtration	Rated for 4500 Psi max pressure
Accumulator Pressure After Braking	< 3000 Psi
Shell Weight	< 15 lbs

The engineering specifications with the highest importance rating as determined from our QFD are: hub width, hub diameter, maximum sustained braking torque, maximum weight, and maximum sustained launching torque.

5. CONCEPT GENERATION

Our design goals for this project were determined from the rightmost sub-functions as shown in Figure 3 (p.8). The two sub-functions listed as “Obtain Working Fluid from Reservoir” and “Transmit Torque from Main Gear to Pump,” were already completed by the previous team. Therefore, we concentrated on the remaining four sub-functions. The design goal for the RBS was to reconfigure the hydraulic components in a more spatially efficient manner. To optimize arrangement of the morphological Chart, we decided to combine the “minimize width” and “Endorse RBS components within circumference”. Both of them could be achieved by performing the same operation.

Reconfiguring the RBS will not only reduce the overall thickness of the system, but also reduce the diameter of the shell that has to encompass it. Our design goals for the shell were to attach a bicycle tire to the shell and attach the shell to the main gear of the RBS.

In order to reduce costs and maintain simplicity, we decided to reuse as many parts as possible from the current RBS. This includes all of the RBS hydraulic components, which have been experimentally proven to operate correctly, the superbracket, which can be salvaged for our reconfiguration of the RBS, and the gearing components, which have been designed to optimize power transmission. The only exception is that we will machine new bevel gear connecting rods out of steel as the previous ones were made from aluminum and are not capable of handling the torques generated by the pump and motor.

The following morphological chart (Table 3, p.9) and FAST diagram explains, in detail, our design considerations.

Figure 3: Fast Diagram

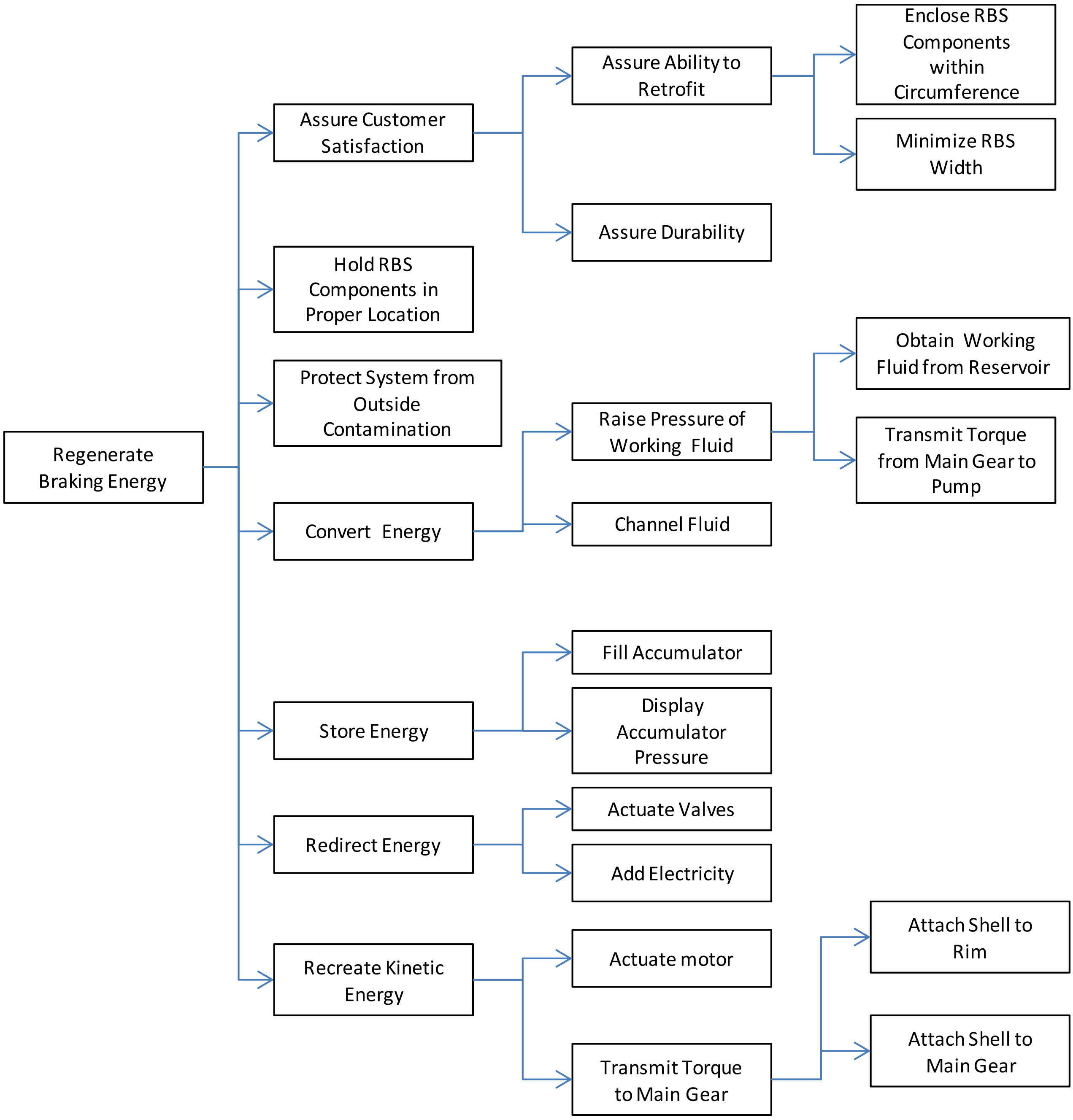
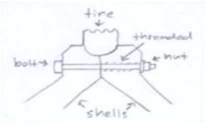
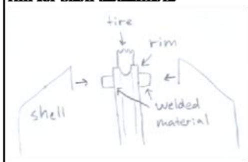
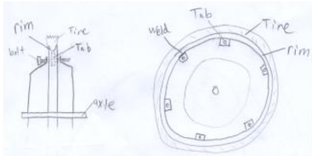
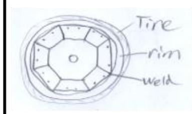
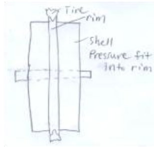
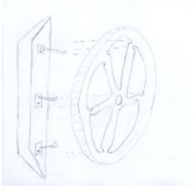
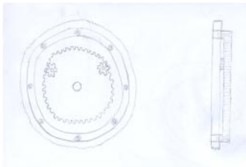
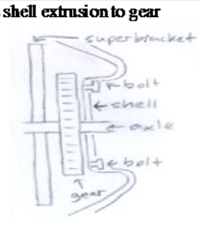


Table 3: Morphological Chart

Function	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Enclose RBS components within circumference and reduce width					
Attach rim to shell	Design rim into shell and bolt shells together 	Weld threaded cylinder to wheel rim for shell attachment 	Weld Tabs to rim, bolt shell to tabs 	Make individual hexagonal parts then glue together. Weld to rim 	Make large cylinder and pressure fit it into rim 
Attach shell to main gear	Grip gear with shell protrusions 	Embed gear teeth on inside of shell 	Bolts shell extrusion to gear 		

6. CONCEPT EVALUATION AND SELECTION

Reconfiguring RBS

One of our main goals was to reconfigure the RBS system. The first sketch, as displayed in the Pugh chart (Table 4, p.11), was the one which was designed by previous teams in ME 450. In addition to the system components being arranged in an inefficient manner, the parts protrude out of the existing superbracket. These workings extending beyond the superbracket would make manufacturing a shell for these dimensions, an extremely challenging task.

We thought of rearranging these components so that they all fit within the dimensions of the superbracket. Sketch 2 includes moving the high pressure accumulator and the low pressure accumulator within the diameter of the superbracket. This would use the space in a more efficient manner and also produce a more compact design. The compact design would increase aesthetic appeal and also provide better proportions for an outer shell design.

Sketch 5 would be the most optimal solution as determined by the Pugh chart. The low pressure reservoir would be placed upright instead of horizontal. The fifth design would use all the positive characteristics of sketch 2, and include a vertical reservoir. The low pressure reservoir is in fact a gravity fed system and the horizontal arrangement shown in sketch 2 could be a problem.

Attach the Rim to the Shell

Perhaps the hardest function to design for this project was how to attach our shell to the rim. We narrowed our ideas down to five concepts as depicted in Table 4 (p.11). In concept 1, we tried to skip the need of attaching the shell to a rim by incorporating the rim into the design of the shell itself. This would save us time and effort in the manufacturing process. However, when we tried to create this idea in a CAD file we found that it was impossible to machine a single mold capable of making the shell due an overhang caused by the incorporated rim. We also realized that this idea would be impractical for service and routine maintenance of the RBS system. Any time you need to remove the shell to service the system you would inadvertently remove the tire from the rim.

Sketch 2 involves attaching a separate spoke-less rim to the shell. This design would be heavier than sketch 1; however, a purchased separate rim is more reliable than a fabricated one. In addition this design is more serviceable because you do not have to remove the tire in order to access the hydraulic components. Sketch 2 uses threaded cylinders that would be welded to the inner rim of the wheel. This would extrude from the edges of the shell and would tacky.

Sketch 3 also uses a separate spoke-less rim and resultantly has the same benefits and drawbacks as previously discussed for sketch 2. However, sketch 3 uses tabs that will be welded to the inner rim of the wheel that will be covered up by the shell once assembled. Therefore, the unattractive attachments will not be visible as in sketch 2. Sketch 2 is also easier to manufacture than sketch 3 because it does not require tapped holes.

Sketch 4 uses a separate spoke-less rim and resultantly has the same benefits and drawbacks as previously discussed for sketch 2. However sketch 4 is not as reliable as sketches 2 and 3 due to the large number of thin, separate pieces that must be joined together. Therefore, sketch 4 is extremely difficult to manufacture. This design also provides the minimum amount of available volume with which to place the internal components of the RBS.

Sketch 5 uses a separate spoke-less rim and resultantly has the same benefits and drawbacks as previously discussed for sketch 2. However sketch 5 is not as reliable as sketches 2 and 3 because it uses the idea of pressure fitting the shell into the rim of the wheel. There is a possible safety concern for this design in that the placement of the shell could shift if subjected to a lateral impact and could cause additional stresses on the shell where it connects to the main gear.

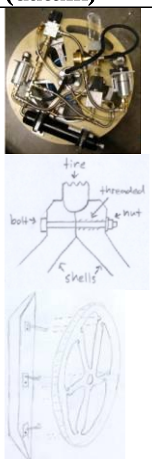
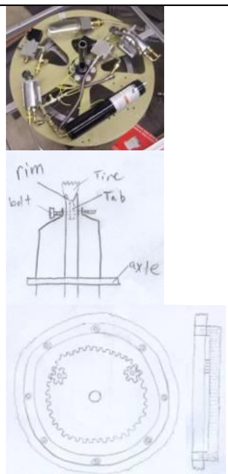
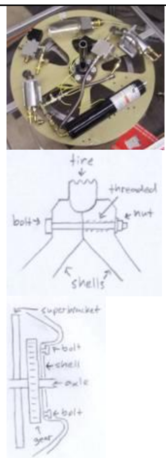
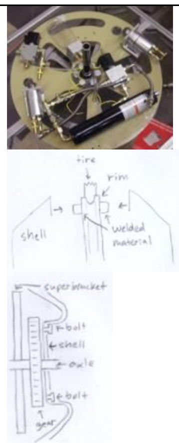
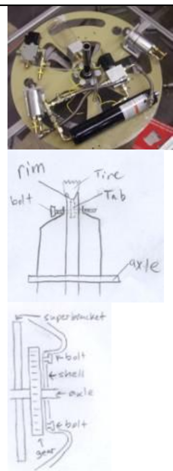
Attach Shell to Main Gear

We thought of a couple of ideas that could be creative and innovative solutions to the existing design problem. The first solution as seen in Table 4 (p.11) would entail creating a casing that has an extremely durable material attached onto it. This material, which would have high yield strength, will protrude into the existing open space of the gear. When the gear rotates, the attached outer casing and bicycle wheel turn with it, while the other internal components remain stationary. The shell half that covers the RBS components on the opposite side will be symmetrical but without the gear attachments. However, hooks are not reliable and this would not be visually pleasing.

The second solution is to replace the heavy main gear with a gear-shell hybrid. The new gear will have internal instead of external teeth and a flange to which the bicycle wheel rim can be attached. This would be a great solution however it would increase the weight of the system, because the ring gear tends to be heavy. The shell half that covers the RBS components on the opposite side will be as symmetrical as possible for aesthetic appeal but will only cover the components since there is no need for gear teeth. Manufacturing and re-Aligning the internal teeth in this gear system would be difficult.

The fifth solution would entail, just bolting the shell onto the existing gear. We feel that this solution is the most feasible as determined by the Pugh chart. The fifth concept is the easiest to manufacture, it's aesthetically pleasing, and it's the most reliable and robust design. Bolts are more reliable than hooks because there is virtually no movement of the gear relative to the housing.

Table 4: Pugh Chart for Attaching Shell to Gear

		Concept 1 (datum)	**Concept 2**	**Concept 3**	**Concept 4**	**Concept 5**
Customer requirement	**Weight**					
Universal application	**5**	**S**	**S**	**S**	**S**	**S**
Natural rate of braking	**3**	**S**	**S**	**S**	**S**	**S**
Sufficient top speed	**3**	**S**	**S**	**S**	**S**	**S**
Efficient	**5**	**S**	**S**	**S**	**S**	**S**
Lightweight	**5**	**S**	**- (ring gear is heavy) - (rim has additional weight)**	**S**	**- (rim has additional weight)**	**- (rim has additional weight)**
Reliable	**5**	**S**	**+ (gears more reliable than hooks) + (purchased rim more reliable than fabricated one)**	**+ (bolts more reliable than hooks)**	**+ (bolts more reliable than hooks) + (purchased rim more reliable than fabricated one)**	**+ (bolts more reliable than hooks) + (purchased rim more reliable than fabricated one)**

Aesthetics	**5**	**S**	**S**	**+ (inlaid bolts are more attractive)**	**+ (inlaid bolts are more attractive)** **+ (compact design)** **- (looks less appealing)**	**+ (inlaid bolts are more attractive)** **+ (compact design)**
Safety	**7**	**S**	**S**	**S**	**S**	**S**
Easy to use	**3**	**S**	**- (accumulator may leak)**	**- (accumulator may leak)**	**S**	**S**
Easy to service	**5**	**S**	**- (difficult to realign teeth)** **+ (can service without disassembling rim)**	**S**	**+ (can service without disassembling rim)**	**+ (can service without disassembling rim)**
Maintains bicycle function	**5**	**S**	**S**	**S**	**S**	**S**
Fix and test current prototype	**9**	**S**	**S**	**S**	**S**	**S**
Design and manufacture hub shell	**7**	**S**	**+ (easier to attach rim to shell)**	**+ (easier to attach gear to shell)**	**+ (easier to attach gear to shell)**	**+ (easier to attach rim to shell)** **+ (easier to attach gear to shell)**
Reconfigure RBS	**9**	**S**	**S**	**S**	**S**	**S**
Adapt prototype to bicycle	**9**	**S**	**+ (easier to retrofit)**	**S**	**+ (easier to retrofit)**	**+ (easier to retrofit)**
	Weighted Total +	**0**	**+31**	**+17**	**+41**	**+48**
	Weighted Total -	**0**	**-18**	**-3**	**-10**	**-5**
	Net	**0**	**+13**	**+14**	**+31**	**+43 (BEST)**

7. SELECTED CONCEPTS

RBS

We selected design solution 3 for reconfiguring the RBS component arrangement as seen in the Pugh chart (Table 4, p.11). The major gains of design solution 3 are that it is more aesthetically pleasing than the other two options, and that the RBS components are arranged in a more compact and efficient manner.

We need to purchase the following components: two 10in long high-pressure hoses, one to connect the upper 3-way valve to the one-way flow valve, the other to connect the one-way flow valve to the high pressure hose leading to the accumulator; one 14in long high-pressure hose to connect the lower 3-way valve to the motor high side; one 18in long high-pressure hose to connect the lower 3-way valve to the high-pressure accumulator; two 1in long fittings to convert from JIC8 to JIC6 to connect the one-way flow valve to attached high-pressure hoses; two 18in long low-pressure hoses, one to connect the motor low-side to the low-pressure reservoir, the other to connect the pump low-side to the low-pressure reservoir. In addition, we need to machine new holes in the RBS superbracket to modify the component mounting.

Shell

We selected design solution 5 for attaching the rim to the shell and design solution 5 for attaching the shell to the main gear (Tables 4, p.11). Below are preliminary CAD models for the shell (Figure 4, p.13) and detailed orthographic views (Figures 5 and 6, pgs. 13 and 14) that include both design solutions involved in the designing the shell.

Our outer shell design will be made out of carbon fiber. Carbon fiber is expensive but can be manufactured easily in a mold. In addition, it is extremely light weight, and has a high tensile strength. A possible molding material is foamboard, a dense composite often used in prototyping.

We need to purchase the following components: molding material, a bicycle rim, and bearings for the shell. We will weld material to the inside of the rim so that we can drill through it bolt the shells to either side, compressing the rim in between.

Figure 4: CAD model of the shell that will cover the RBS (left), the shell the will be attached to the gear (right), and the two shells assembled to the rim (middle)

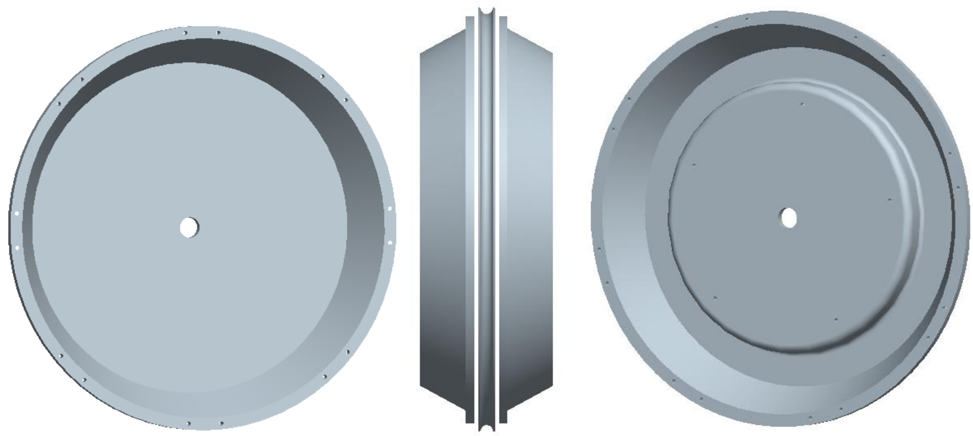


Figure 5: Drawing of Gear-Side Shell

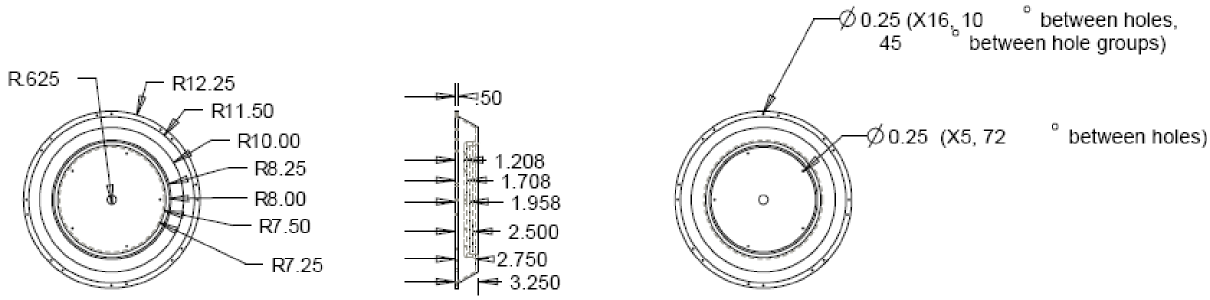
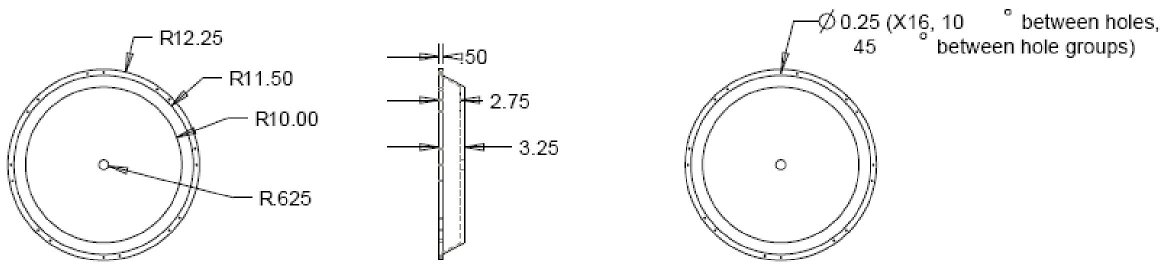


Figure 6: Drawing of RBS-Side Shell



8. ENGINEERING ANALYSIS

Our calculations included the following assumptions.

Table 5: Summary of Bicycle Component Weights

Weight	**Magnitude**
Maximum weight of bike rider	240 lbs
Weight of the bike	20 lbs
Weight of Regenerative Braking system	20 lbs
Weight of Shell	20 lbs
Total Weight	**300 lbs**

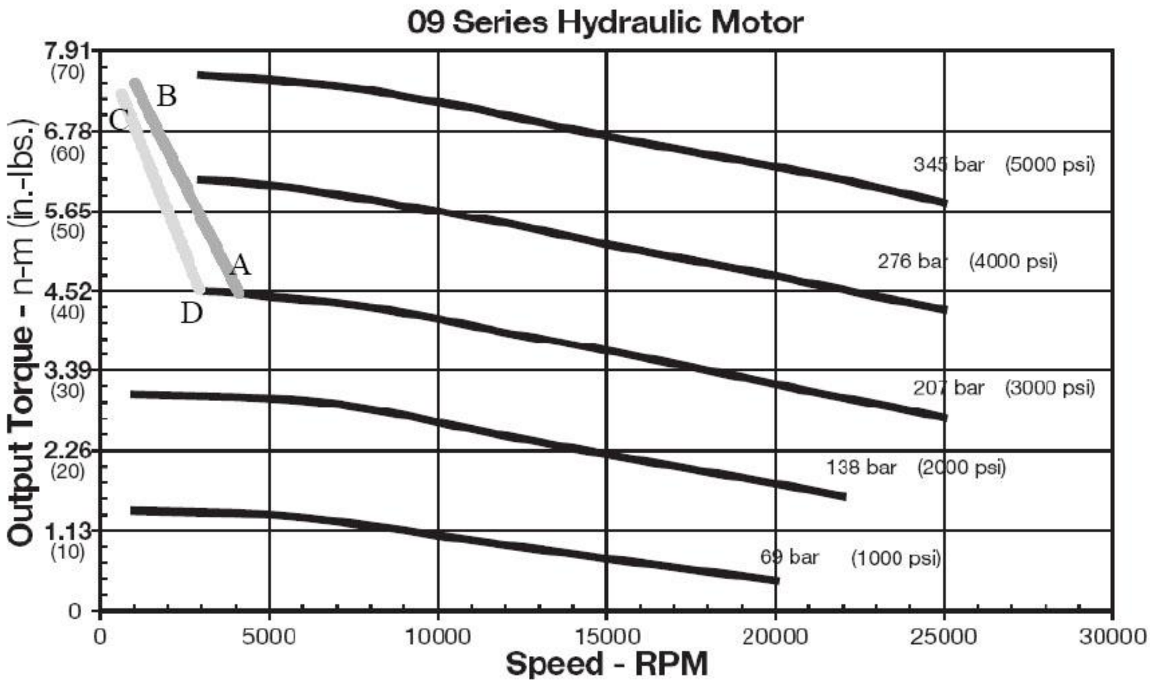
Figure 7: Free body diagram summarizing the various forces on the bike

Based on the free body diagram of the bike, we are assuming that total weight of the bike and the bike rider will be distributed equally, between the two wheels. This means that the front shell is going to experience a force of 150 lbs. When finding the maximum stress in the shell, the value of the force that we will use in our calculations will be 150 lbs.

Longitudinal Load Transfer During Braking

Given an initial velocity (v_i) of 20 mph (8.9408 m/s) and a outer tire diameter of 27" (0.6858 m), we used the equations below to find the corresponding revolutions per minute of the tire under these initial conditions. Using the 18:1 gear ratio of the pump gear train, we see that the angular speed of the hydraulic pump is 4482 rpm. Figure 8 illustrates that given an angular speed of 4482 rpm and a pre-charge working pressure of 3000 psi, then the initial output torque on the pump will be 4.52 N-m.

Figure 8: Braking Diagram for Hydraulic Pump / Motor*



The dark gray line shows the braking cycle; the light gray line shows the launch cycle. The peaks of each motor operation curve are the most efficient operating points at a given pressure. Graph provided by manufacturer.

***** This image is taken from W07 project 15 team's final report.

The deceleration analysis for points A and B in the braking cycle are shown below. We see that the bike achieves a maximum deceleration of 2.85m/s^2 at point B, just before the bike velocity reaches zero.

<u>Point A:</u>

$$\omega = \frac{v_i}{r} = \frac{8.9408m/s}{0.3429m} = \frac{26.07rad}{s} = 249rpm$$

$$18:1 \rightarrow 249rpm * 18 = 4482rpm$$

$$4482rpm \ @ \ 3000psi \xrightarrow{from\ Fig\ 8} 4.52Nm$$

$$18:1 \rightarrow 4.52Nm * 18 = 81.36Nm = \tau$$

$$F_x = \frac{\tau}{r} = \frac{81.36Nm}{0.3429m} = 237.27N$$

$$a_x = \frac{F_x}{m} = \frac{237.27N}{136kg} = 1.74m/s^2$$

ω = angular velocity, v_i = initial velocity, r = tire radius, τ = braking torque, a_x = deceleration, F_x = braking force, m = mass

Point B:

$$18:1 \rightarrow 7.38Nm * 18 = 132.84Nm = \tau$$

$$F_x = \frac{\tau}{r} = \frac{132.84Nm}{0.3429m} = 387.402N$$

$$a_x = \frac{F_x}{m} = \frac{387.402N}{136kg} = 2.85m/s^2$$

Figure 9 shows a free body diagram of our bicycle braking. This scenario corresponds to the maximum amount of longitudinal load transfer to the front axle of the bike. Ultimately this situation shows the maximum force generated on the front wheel that will need to be supported by our carbon fiber shell. The red circles with an "x" marked in them represent the three different centers of gravity corresponding to the rider, the bicycle and the RBS. They are labeled 1, 2, and 3 respectively. The resultant center of gravity for the rider, bicycle and RBS is shown as the green circle with an "x" and is labeled cg. The positions of all four centers of gravity are summarized in table 6 below. The height of the center of gravity for the rider (y2) was determined based on the fact that, "a person's center of mass is slightly below his/her belly button, which is nearly the geometric center of a person" (Stephanie Gambino, http://hypertextbook.com/facts/2006/centerofmass.shtml).

Figure 9: Free Body Diagram of Bicycle During Braking

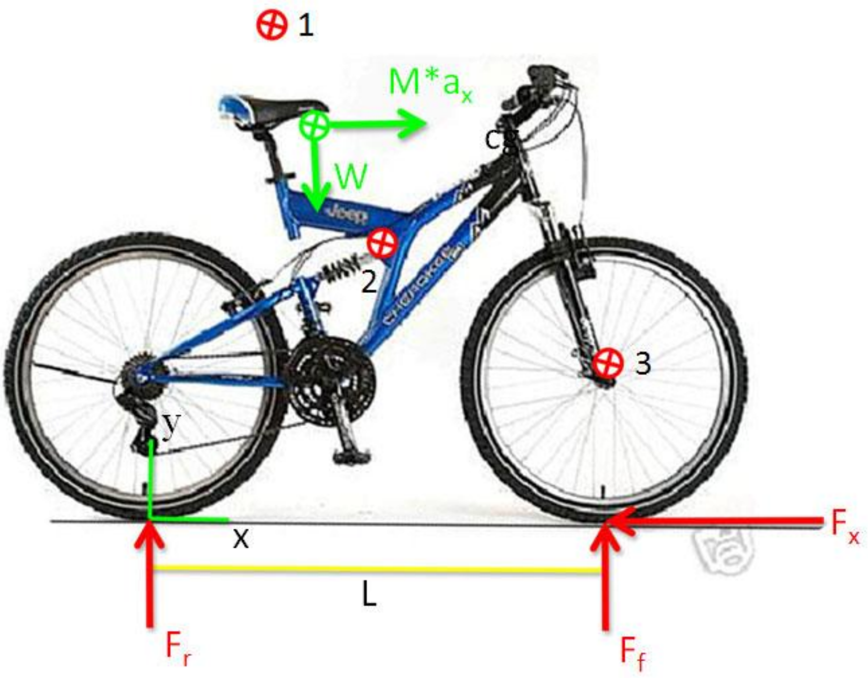


Table 6: X-Y Coordinates of the various Centers of Gravity

Center of Gravity	X-coordinate	Y-coordinate	Mass
1	x1 = 0.3048m	y1 = 1.1684m	m1 = 113.4kg
2	x2 = 0.508m	y2 = 0.6858m	m2 = 9.072kg
3	x3 = 1.016m	y3 = 0.3429m	m3 = 13.608kg
cg	xcg = 0.389m	ycg = 1.054m	mcg = 136.08kg

The position of the overall center of gravity (cg) was calculated using the following equations.

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

We summed the moment acting about the point of contact at the rear tire to solve for the maximum front axle load (F_f). We also used D'Alembert's Principle to calculate the inertial force due to the maximum deceleration of the bicycle (2.85m/s^2) provided by the hydraulic pump. The final result is that the front axle will see a maximum force of 205 lbs during braking from an initial velocity of 20mph.

$$\Sigma M = 0 = M a_x y_{cg} + x_{cg} W - F_f L$$

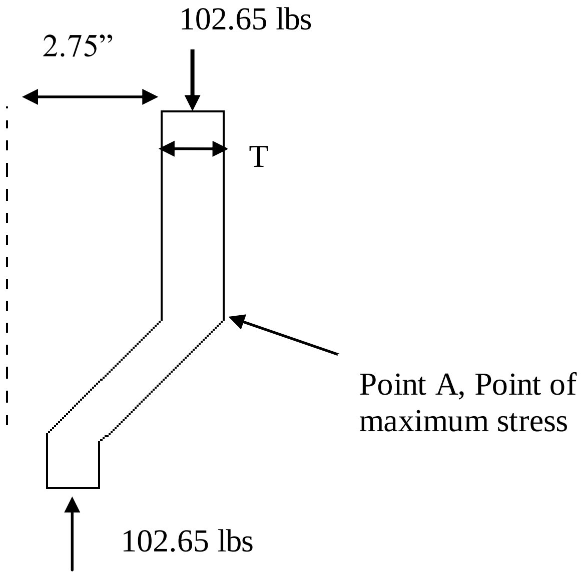
$$\rightarrow F_f = \frac{M a_x y_{cg} + x_{cg} W}{L}$$

$$F_f = \frac{136.08kg * 2.85m/s^2 * 1.054m + 0.389m * 136.08kg * 9.806m/s^2}{1.016m}$$

$$F_f = 913.241N = 205.3lbs$$

Normal Stress Analysis

Figure 10: Right Side Sectional View of bicycle shell



We can perform a stress analysis to find out the maximum normal stress that this material must sustain. Accordingly we need to pick a material with a yield strength higher than this maximum stress. Point A as shown in Figure 10 above experiences the maximum stress.

$$\sigma_{Max} = \left(\frac{Mc}{I} + \frac{F}{A}\right) \times n$$

Where M is the moment, I is the moment of inertia, F is the normal force, A is the area of the cross section, and n is the safety factor, which we set to 1.5.

$$\sigma_{Max} = \left(\frac{102.65 \times \left(2.75 + \frac{t}{2}\right)}{\frac{1}{12} \times 1 \times t^3} + \frac{102.65}{t \times 1}\right) \times 1.5$$

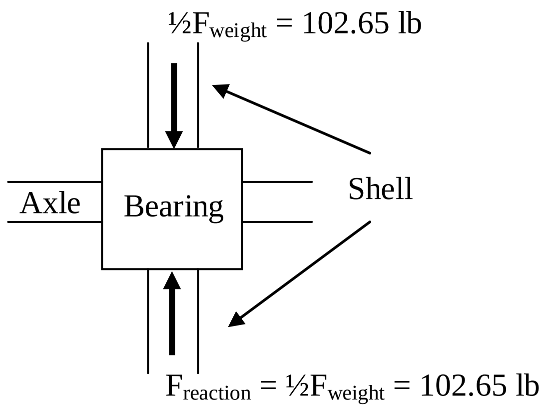
Carbon fiber yield strength varies between 82 ksi and 152 ksi. Using this range of values for the yield strength, we can calculate how thick our shell should be so that it can withstand the normal stress.

We need carbon fiber that's between **0.329 inches and 0.406 inches thick**.

Bearings Analysis

Each shell requires a thrust bearing at its center to ensure that the shells rotate around the axle with as little friction as possible. The two bearings need to support half of the total weight (150 lb) of the bicycle, rider, and all additional components; therefore, each bearing must support 102.65 lb.

Figure 11: **Diagram of forces on the shell bearing**



We can conduct a bearing life cycle analysis using the following equation:

$$C_{10} = F_D \left(\frac{L_D n_D 60}{L_{10}} \right)^{1/a},$$

where C_{10} is the catalog rating of the bearing in lbf, F_D is the desired radial load in lbf, L_D is the desired life in hours, n_D is the desired speed in rev/min, L_{10} is the rating life in revolutions, and a is constant that depends on bearing type ($a = 3$ for ball bearings).

To determine the catalog rating of the bearing, we estimated a 102.65 lb radial load, 5000 hour life, 500 rev/min, and $90\text{x}10^6$ revolution life rating, which is the rating Timken uses for their bearings [7].

$$C_{10} = F_D \left(\frac{L_D n_D 60}{L_{10}} \right)^{1/a} = 102.65 \times \left(\frac{5000 \times 500 \times 60}{90 \times 10^6} \right)^{1/3} = 121.7 lbf$$

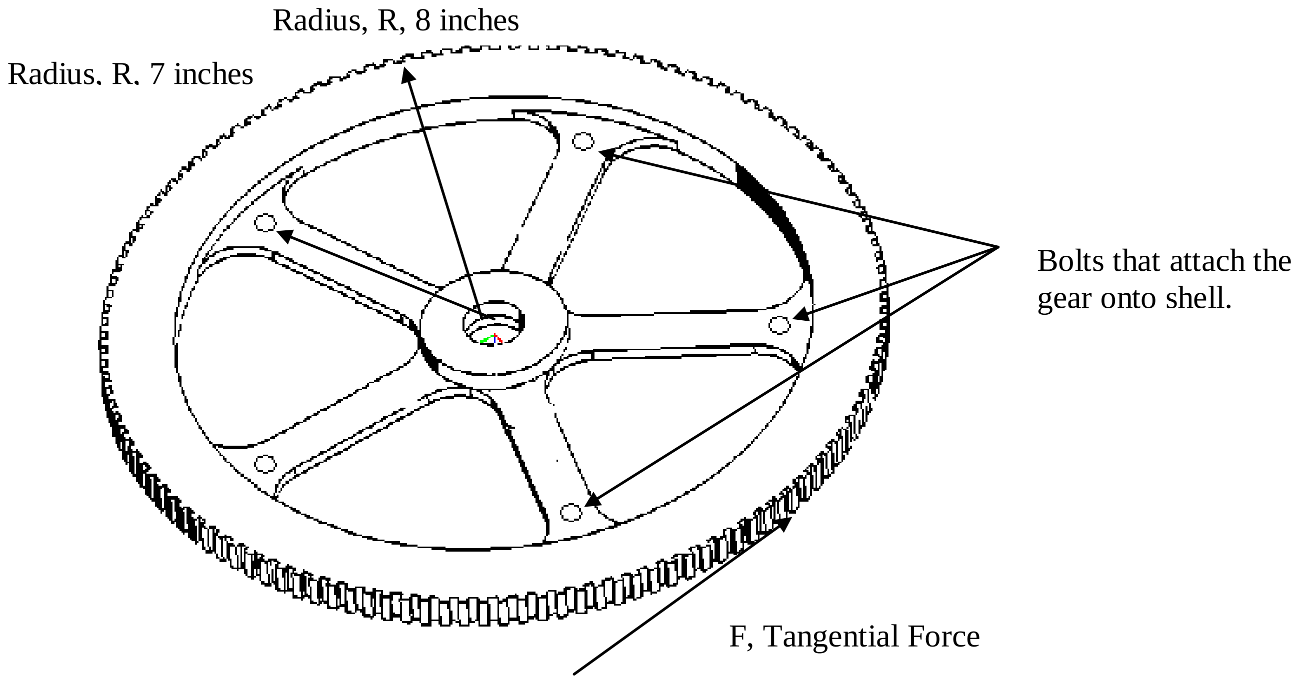
Therefore we have to pick bearings that are rated to 121.7 lbf for the shell.

Shear stress analysis on the bolts

The radial force experienced by the gear is equal to 117 lbf during launch and 89 lbf during braking. This data was calculated by Team 15 from Winter 2007 tests. Since we need to find the maximal value of shear, for the purposes of calculations we will use the 117lb force.

The torque experience by the gear is equal to $\tau = F \times R$

Figure 12: **Diagram of gear that depicts the exact placement/location of bolts**.



The torque experience by the gear is equal to the torque experienced by the shell. The torque on the gear is equal to $\tau = 117lb \times 8in = 936lbin$. We will be placing the bolts as far out as possible because we would like to decrease the force experienced by the bolts. This would decrease the shear that each of the bolts would cause on the material.

Assuming we place the bolts at a distance of 7 inches from the center we can find the force experienced by the bolt. The force experienced by the bolt will be

$$F = \frac{936}{7} = 133.714lbs$$

Figure 13: Free body diagram of bolt

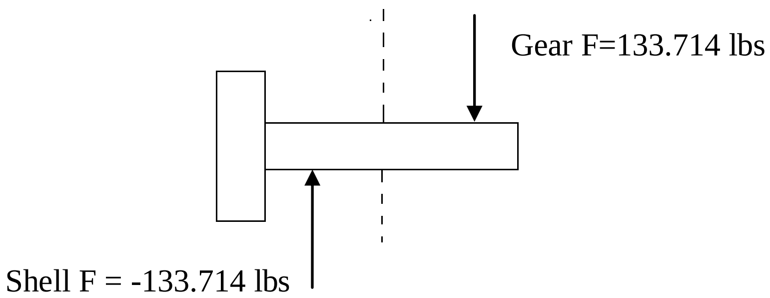
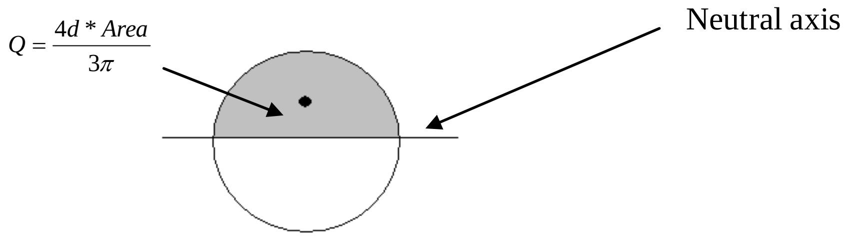


Figure 14: Cross Section of Bolt Depicting Q



The forces on the bolts must balance each other out, and hence the force experienced by the shell is the same value of 133.714 lbs. The shear on the material/shell is equal to

$$\tau = \frac{VQ}{IT} = \frac{133.714 \times 4 * d \times \pi \times d^2}{\frac{\pi \times d^4 \times d \times 3 * \pi \times 2x8}{64}} = 3.632ksi$$

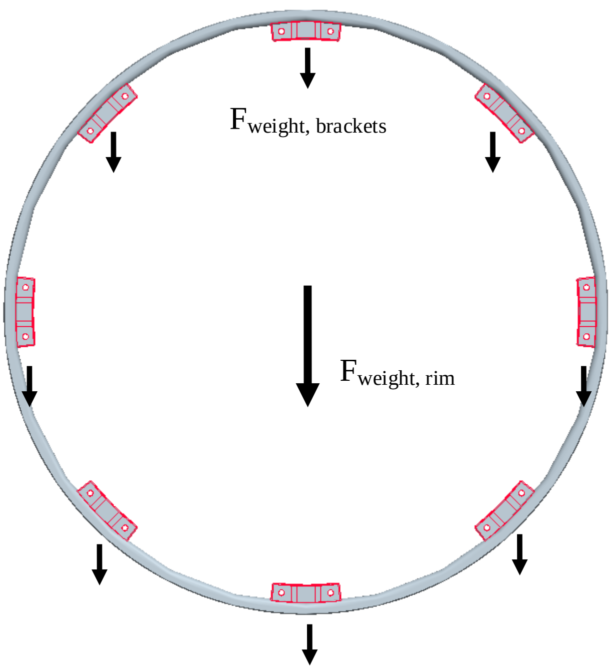
Since this force is distributed over 5 bolts, the force experienced by each bolt is 726.4 psi. Let's assume a safety factor of 2.5.

We need bolts which can withstand a shear of 1.816 ksi.

Engineering Analysis of the Rim

When analyzing the forces on the rim that will be attached to the shell housing, we must take into account two cases: the static case, where the bicycle is either in place or moving at a constant velocity; and the dynamic case, where the bicycle is accelerated by the gear.

Figure 15: Rim with brackets assembled



Each bracket weighs 1.5 oz. but these parts can be lightened even further upon final shell completion. The rim weighs 2 lbs 1 oz.; with eight brackets, the total rim assembly weights 2 lbs 13 oz.

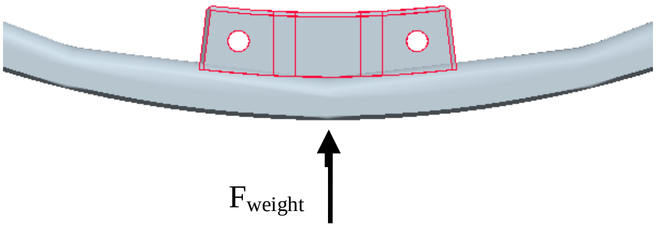
Figure 16: Bracket in detail

The area of contact that each bolt presses against due to the various forces is as follows

$$Area_{contact} = \tfrac{1}{2} \times \pi \times diameter_{bolt} \times number_{bolts} \times width_{bracket}$$

In the static case, the only force we have to account for is the reaction force of the weight of the rider, RBS, shell, rim, and brackets. The total weight force presses the rim into the ground, causing an equal and opposite force on the rim and brackets.

Figure 17: Forces on the brackets in the static case



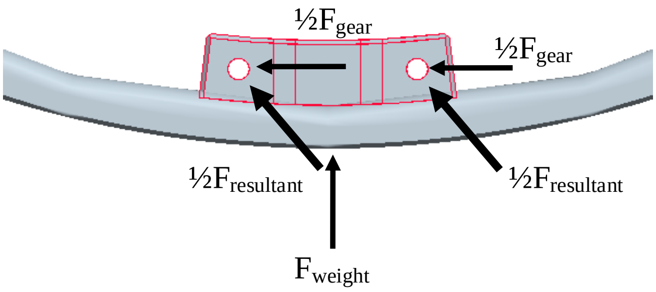
The average shear stress is as follows

$$\tau_{average} = \frac{F_{weight}}{Area_{contact}} = \frac{205.3lb}{\pi \times \tfrac{1}{4} in \times \tfrac{3}{8} in} = 697.0 psi$$

The shear stress value of 697.0 psi is much less than the shear strength of 6061-T651 aluminum of 30 ksi so the brackets should not fail when the bicycle is at rest or at constant velocity. In this case, there are no significant forces on the bolt that joins the bracket to the rim.

In the dynamic case, we have to account for the torque transmitted from the gear to the rim brackets in addition to the weight reaction force. As the gear accelerates, it transmits a force of 117 lb to the rim, which is 14.625 lb per bracket with eight brackets. The figure below illustrates the dynamic case where one bracket is under the maximum force it will see over of a complete revolution. When the bracket is at the very bottom position, as seen in Figure 18, it will experience the greatest component of the weight force, thus we have chose to examine only this case in detail. The brackets that are not in the bottom position will only experience a shear force due to the accelerating gear.

Figure 18: Forces on the brackets in the dynamic case



The resultant force of the forces due to the gear and the weight is as follows

$$F_{resultant} = \sqrt{\left(\frac{F_{gear}}{N_{brackets}}\right)^2 + F_{weight}{}^2} = \sqrt{\left(\frac{117lb}{8}\right)^2 + (205.3lb)^2} = 205.8lb$$

The average shear stress is as follows

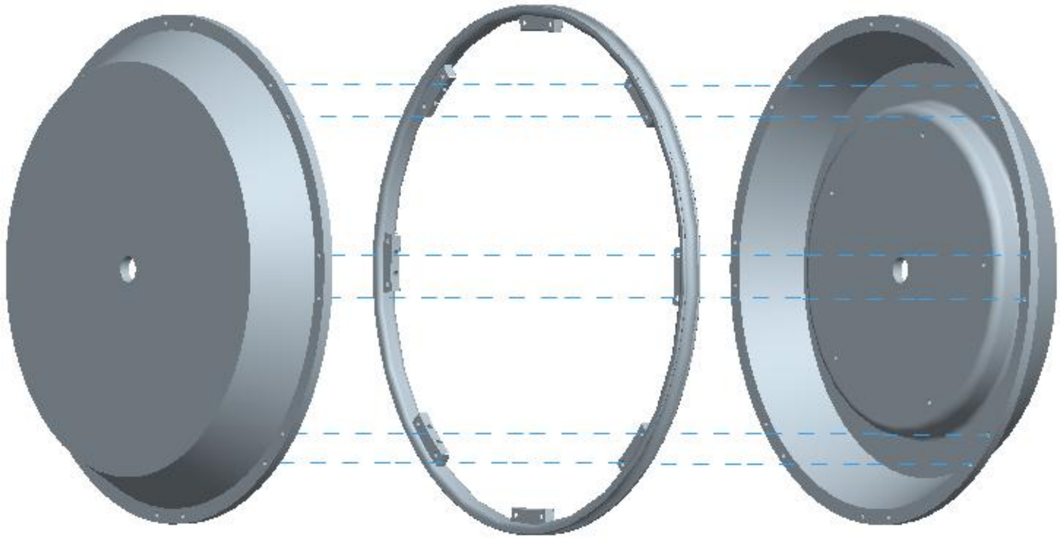
$$\tau_{average} = \frac{F_{resultant}}{Area_{contact}} = \frac{205.8lb}{\pi \times \frac{1}{4}in \times \frac{3}{8}in} = 698.8\,psi$$

Again, the shear stress value of 698.8 psi is much less than the shear strength of 6061-T651 aluminum of 30 ksi so the brackets should not fail when the bicycle is accelerated. In this case, the bolts that join the brackets to the rim feel a combined force of 117 lb, which is 14.625 lb per bracket. Applying the shear analysis of the bolts that join the gear and shell to the bolts the join the rim and brackets gives the following shear stress per bolt:

$$\tau = \frac{VQ}{IT} = \frac{14.625 \times 4 * d \times \pi \times d^2}{\frac{\pi \times d^4 \times d \times 3 * \pi \times 2x8 \times 2bolts}{64}} = 198.625\,psi$$

The shear stress of 198.625 psi per bolt is well below the ultimate shear strength of steel bolts, which falls between 14,228.82 – 83,665 psi depending on what grade of steel is used. Therefore, we expect the bolts to hold the brackets to the rim.

Figure 19: Exploded view of rim/shell assembly



Design for Manufacturing and Assembly

We took many measures to ensure simple manufacturability and assembly while maintaining reliability and a low cost.

RBS

To simplify manufacturing of the RBS system we used bolts to attach the RBS components to the superbracket and a simple angle bracket for mounting the high pressure accumulator to the superbracket. In addition, we planned on machining the RBS system to make it as thin as possible.

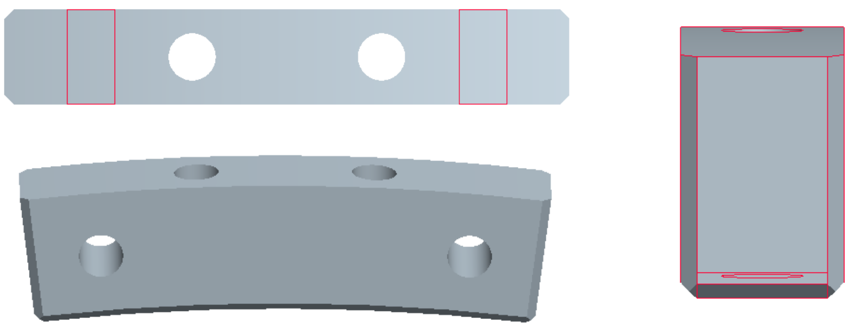
To simplify the component reassembly we determined the necessary clearance between the motor, the pump, the motor bevel gear, the pump bevel gear, the low pressure reservoir, the high pressure accumulator and the high and low pressure hoses. We also determined the required lengths and allowed bending angles for the high pressure hoses.

Shell and Rim

To simplify the manufacturing of the shell we planned on cutting out one mold for both shell halves. We would manufacture two different dies, which incorporate the different features of each shell, and cut them so that they would fit into the center of the main mold. This would reduce time and material costs as well as the number of manufacturing tools. Following completion of the shell mold, there are many areas that can be removed to reduce weight and enhance aesthetic appeal while maintaining structural strength.

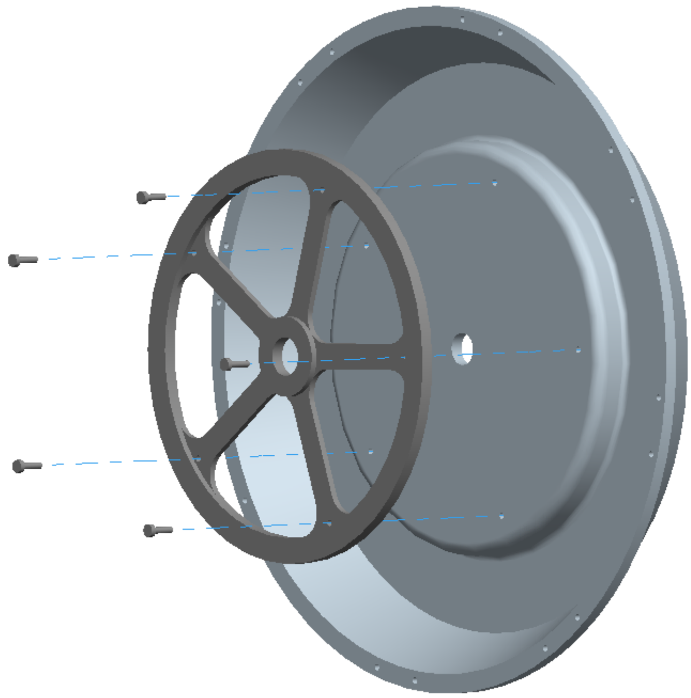
We have procured a bicycle rim that only requires that we drill holes through the center of its frame. To streamline that process all sixteen holes are designed to be the same size at 3/8 in, which are larger than the ¼ in. bolts so that the brackets will selfalign. These holes will tell each bracket where to be bolted, and the brackets have been designed so that there is only one way to attach to the rim. The brackets are all identical, and each bracket is symmetrical with obvious alignment and constraining features as seen in Figure 20 below to simplify the design for handling and insertion. This will simplify both manufacturing and assembly of the brackets. The brackets require two ¼-20 in. threaded holes to constrain the bracket to the rim rather conforming to the shape of the rim, which simplifies the manufacturing. This enhances the design for assembly by reducing the number of parts, reducing the number of fasteners, preventing over-constraining, and simplifying insertion. Due to time constraints and complexity, we did not manufacture the curved edges onto the brackets.

Figure 20: Bracket symmetry from top (top left), side (bottom left), and front (right). Alignment and constraining features include the top and side grooves clearly seen from the front view (right).



The shell-to-rim and shell-to-gear assemblies require only ¼ inch bolts, nuts, and washers, which will streamline the final assembly stage by reducing part variety. The entire prototype has been designed to permit assembly in open space, ensure tool access, and simplify part insertion and joining; specifically, the bolts that join the shell and gear will be inserted from the inside and tightened on the outside as seen in Figure 21. The further simplify part insertion we will chamfer all bolt holes.

Figure 21: Shell-to-gear assembly designed to simplify part insertion



Design for Assembly System

1) Minimize part counts – grouped holes for assembling shell to bracket in pairs to reduce the number of brackets
2) Permit assembly in open spaces – streamlined assembly of gear to shell
3) Standardize to reduce part variety – use only ¼ inch bolts, all brackets are identical

Design for Part Handling

1) Maximize part symmetry – brackets are symmetrical
2) Add features to facilitate orientation – brackets have aligning features

Design for Part Insertion

1) Add features for easy insertion – chamfered all holes
2) Add alignment features – brackets have curved aligning features
3) One dimensional assembly – shell assembled in one axis

Design for Joining

1) Eliminate fasteners – bolts go through both shells
2) Allow access of tools – bolts tightened on outside of assembly
3) Avoid over-constraining – no part has too many constraining features

Design for Environment: Strategy

We used five main strategies to make our design more environment friendly.

Optimize material use:

1) The shell that we designed for the front wheel would be made of carbon fiber. Carbon fiber is light and durable and does not actively pollute the environment. The additives that we are going to use to further coat the carbon fiber are also free of hazardous materials like mercury and lead.
2) We performed a stress analysis to calculate how thick our shell should be in order to withstand the weight of the bike rider. This calculation helps us use the right amount of material, and optimizes material usage.

Optimize production techniques:

1) We will be using environment friendly techniques for manufacturing the shell. It would entail the use of different machines like the mill, drill, and the band saw. These devices do not contaminate the surrounding, and do not let out poisonous gases.
2) Our wastes would be minimal because we purchased and used materials according to the model/calculation that we setup.

Reduced Impact during use:

1) Our project is to re-arrange the components of the RBS in a hydraulic bike. The RBS bike was created to reduce pollution to the environment, and use the energy obtained during braking in a more efficient manner. Our bike – the final product will be extremely environment friendly since it would work on manpower and hydraulics.
2) We are using very few consumables in our design, and most parts of the bike are permanent.

Optimize end of life systems:

1) The material that we will be using for the manufacture of the shell could be recycled. This would save material, and reduce wastage. Carbon fiber re-enforced plastics almost have an infinite life. The carbon fiber used for our bike could be shredded and used for other purposes e.g. in laptops to make them lighter and more durable.

Physical Optimization

1) The final bike that we produce will have a shell made of carbon fiber. Carbon fiber is extremely light and robust and will increase functionality/reliability of the entire system.
2) We will be re-arranging the internal components of the RBS in a more efficient/ergonomic manner which will make it a lot easier to repair/maintain in the future.

Figure 22: Durable and Light Carbon Fiber

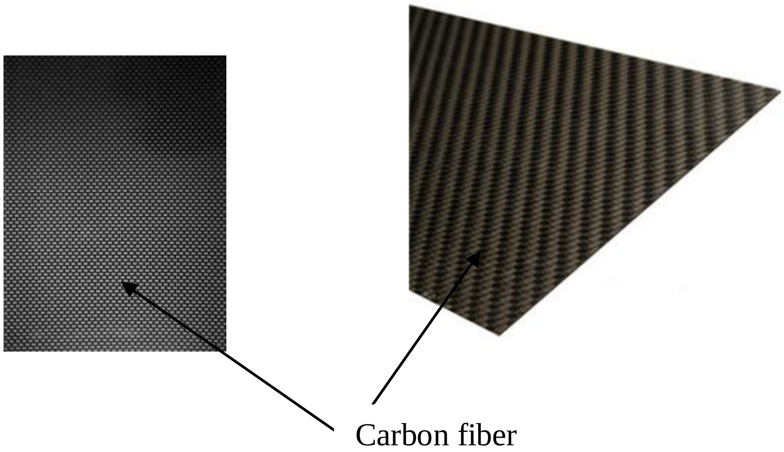


Figure 23: Rearrangement of RBS Components in an Efficient Manner

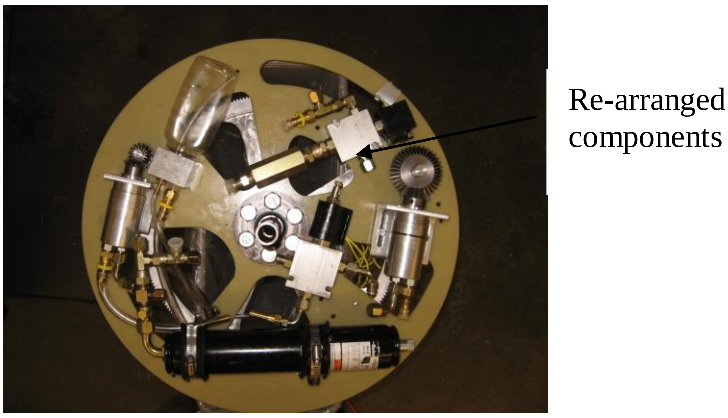


Figure 24: FMEA Chart for Shell

Product Name: Shell		Devel. Team: Team 09	Page No. 1 of 1
______	System		FMEA Number: 1
______	Subsystem		Date: 11/6/07
X	Component		

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Cause(s) / Mechanism(s) of Failure	Occurrence (O)	Current Design Controls / Tests	Detection (D)	Recommended Action	RPN	New S	New O	New D	New RPN
Shell: Protect RBS from weather, side impact, dust / contami-nates	Buckling due to weight of rider	Injury to rider, damage to RBS components	10	Insufficient shell thickness made during manufacturing	1	Stress and failure analysis during design, measure thickness using calipers after manufacturing	1	Recommend next team uses highest yield strength availible for carbon fiber	10	10	1	1	10
				Improper orientation of fibers	1	Include correct orientation in design outline, visual inspection	4	None	40	10	1	4	40
Shield user from noise or oil in case of pressure leak	Misalignment of center hole	Shell will not be centered with respect to centroid causing whell to hop	5	Improper alignment of drill axis during manufacturing	3	Use center finder during manufacture of shell mold	2	Mark drill axis onto carbon fiber shell while it is still in the mold and still in the milling machine	30	5	1	2	10
Support weight of RBS, approx. half the weight of the rider	UV deterioration	Shell color will fade	3	Storred outdoors, absense of laminant	8	Store indoors, visual inspection	4	Apply a UV protective laminant	96	3	3	4	36

Figure 25: FMEA Chart for Rim

Product Name: __Rim__			Devel. Team: __Team 09				Page No. _1_ of _1_						
____ System							FMEA Number: __2__						
____ Subsystem							Date: _11/6/07_						
_X_ Component													
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes / Mechanism(s) of Failure	Occurrence (O)	Current Design Controls / Tests	Detection (D)	Recommended Action	RPN	New S	New O	New D	New RPN
Rim: Support weight of rider	Yielding due to weight of rider	Injury to rider, damage to shell, damage to RBS components	10	The material used had an insufficient yield strength, or the safety factor applied was not high enough	2	Perform yielding test on material, Stress and failure analysis during design	1	Use a higher safety factor, use a material with higher yield strength	20	10	1	1	10
Hold two halves of the shell together	Fracture		8	Due to cracks and high stresses at critical points	1	Perform stress and failure analysis	1	Use a higher safety factor, use a material with higher fracture toughness	8	8	1	1	8
Hold the tire in place	Buckling		10	Due to high forces	1	Perform stress and failure analysis	1	Use a higher safety factor, use a more durable material	10	10	1	1	10

Figure 26: FMEA Chart for High Pressure Hose

Product Name: __High Pressure Hose			Devel. Team: __Team 09				Page No. _1_ of _1_						
____ System							FMEA Number: __3__						
____ Subsystem							Date: _11/6/07_						
_X_ Component													
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes / Mechanism(s) of Failure	Occurrence (O)	Current Design Controls / Tests	Detection (D)	Recommended Action	RPN	New S	New O	New D	New RPN
High Pressure Hose: Transmit working fluid under high pressure throughout the RBS	Fast fracture	damage to RBS components, makes the RBS system unusable	10	Due to extremely high pressures at critical points	2	Perform stress and failure analysis including the allowed bending angle	1	Use a hose with higher pressure rating	20	10	1	1	10
	Leaking		8	Due to cracks and high stresses at critical points	2	Perform stress and failure analysis including the allowed bending angle	2	Use a hose with higher pressure rating, tighten the connecting fittings	32	8	1	2	16

9. FINAL DESIGN

The final design of our project is shown in the exploded view assembly in Figure 27, (p.31). The dimensioned engineering drawings of the shell are shown in Figures 5 and 6 (p.13,14). The rim is a standard 27" x 1" bicycle wheel. The 27" inch diameter rating means that the rim uses a 27" diameter tire. The true dimensions of the rim are shown in the engineering drawings, Figure 28 (p.31). The engineering drawings of the brackets that attach the shell to the rim are shown in Figure 29 (p.32). The new RBS configuration is shown in Figure 30 (p.33). The minimum bend radius for the selected high pressure hoses is 2.5''. The new lengths for the high pressure hoses and required fittings are shown in Table 7 (p.32). The complete listing of purchased and donated materials/parts is listed in our Bill of Materials (BOM) Figure 31 (p.33). Based on our Engineering Analysis previously discussed in section 8, we hypothesize that we will be able to meet all of our engineering specifications. The total cost from our BOM is

$457.77. This exceeds our allotted budget of $400. However, the hydraulic hand pump will be used by multiple teams working on other ME450 projects. Therefore this purchase will not be deducted from our budget. If we subtract this charge ($279.52 + $27.25 shipping) from our total, we see that our team has incurred a total project cost of $457.77 – $306.50 = $151.27.

It is important to note that our final design cannot be fully prototyped. Although the shell was designed by our team, we will not manufacture the shell for the following reasons:

1. Both the foam board required for the shell mold and the carbon fiber required to make the shell are too expensive and out of our budget.
2. Our sponsor requested that we not make the shell in order to concentrate on finalizing the RBS dimensions.

Figure 27: Exploded View of Final Design

Figure 28: Engineering Drawings of Bicycle Rim

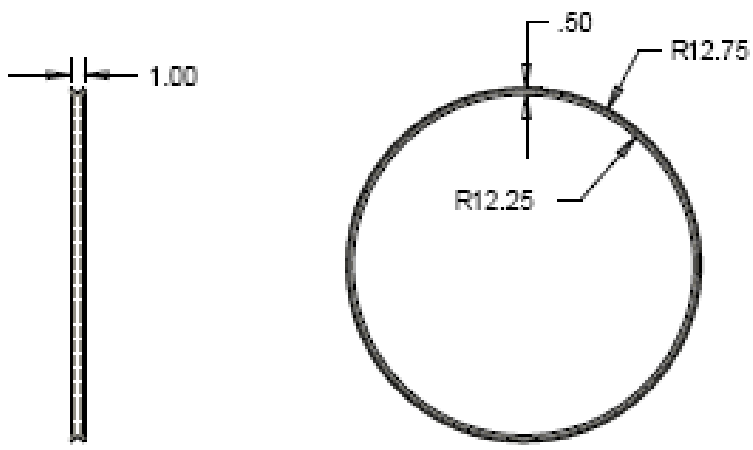


Figure 29: Engineering Drawings of Bracket that Attaches the Rim to the Shell

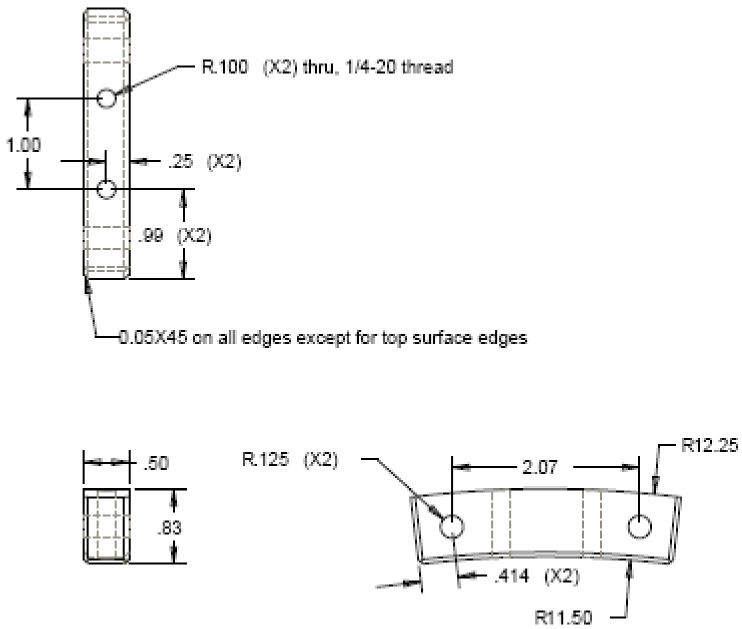


Figure 30: New RBS Configuration

Table 7: Required High Pressure Hose Lengths and Required Fittings

Location	Marker Color	Length (in)	Tolerance (in)	New Fitting Required
Motor-high to lower 3 way valve		9	±0.25	N/A
Accumulator high to lower 3 way valve		11	±0.5	Male to female JIC6 6502 MJ-FJX 45
Upper 3 way valve to accumulator high side		4	±0.125	N/A
Pump high side to upper 3 way valve		20	±0.75	Male to female JIC6 6500 MJ-FJX 90

Figure 31: Chart that depicts the Bill of Materials

Quantity	Part Description	Purchased From	Part Number	Price (each)
1	Hydraulic hand pump	McMaster-CARR (630) 600-3600	42985K73	$279.52
1	Hydraulic filter	Environmental Protection Agency (734) 214-4333	Parker 4Z-F4L-5-SS	Donated $0.00
2	High pressure hose	Environmental Protection Agency (734) 214-4333	RYCO Diehard T26D 3/8 inch Max WP 350 Bar/5100 Psi MSHA IC-227/0 FRAS & Abrasion Resistant Meets or Exceeds SAE100R2AT/EN853 2SN	Donated $0.00
4	High pressure hose	Ann Arbor Hydraulics (734) 973-2585	NPP-Jones A150 Hydralite II 3/8 inch-6 (9.5mm) SAE100R16 W.P. 4500 PSI Flame Resistant, US MSHA No. IC-2G-31 C/2	Not ordered yet
1	One way valve	Environmental Protection Agency (734) 214-4333	Parker C4CSS - 10MT	Donated $0.00
1	Pressure gauge	Environmental Protection Agency (734) 214-4333	25.310.10000 PSI McMaster 1/4" Back CONN Max IND Pointer	Donated $0.00
1	Low pressure tubing	The Home Depot (734) 477-5172		$0.37
1	Bicycle Rim	Campus Student Bike Shop (734) 327-6949	Unknown	$31.75
1	JIC Swivel Elbow 90 deg	Tompkins Industries (800) 255-1008	6500-06-06 MJ-FJX 90	$3.33
1	JIC Swivel Elbow 45 deg	Tompkins Industries (800) 255-1008	6502-06-06 MJ-FJX 45	$3.96
40	Fitting Caps	Environmental Protection Agency (734) 214-4333	Unknown	Donated $0.00
4	Blue Foam Board	The Home Depot (734) 477-5172	Dow Styrofoam 1x48x96 32 SQ. FT. UL 22 0103 01	$41.31
3	Yellow Foam Board	The Home Depot (734) 477-5172	Unknown	$45.73
1	Box of Nitrile Gloves	Environmental Protection Agency (734) 214-4333	N1022613	Donated $0.00
1	Box of All Purpose Wipes	Environmental Protection Agency (734) 214-4333	Pig - 75 all purpose wipes	Donated $0.00

Shipping costs:	$33.80
Total expenditures:	$457.77

10. MANUFACTURING PLAN

We plan to manufacture and assemble all parts in house with the assistance of Bob Coury and Marv Cressey.

RBS

To simplify manufacturing of the RBS system we used bolts to attach the RBS components to the superbracket and a simple angle bracket for mounting the high pressure accumulator to the superbracket. We also plan to machine the RBS to make it as compact and as lean as possible. The slender RBS would not only make the design more ergonomic and efficient but it would also help in reducing the thickness of the entire system.

To simplify the component reassembly we determined the necessary clearance between the motor, the pump, the motor bevel gear, the pump bevel gear, the low pressure reservoir, the high pressure accumulator and the high and low pressure hoses. We also determined the required lengths and allowed bending angles for the high pressure hoses.
We purchased four high pressure hoses. The first hose will connect the motor high side to the lower three way valve, the second will connect the accumulator high side

to the lower three way valve. The third hose will connect the accumulator high side to the upper three way valve and the fourth one will connect the pump high side to the upper three way valve.
We will also be purchasing two fittings to connect the upper three way valve to the high pressure hose leading to the accumulator. One is a 45 degree male to female JIC 6 fitting while the other one is 90 degree male to female fitting.

We will use the variable displacement hydraulic pump to charge the accumulator and check the system functionality, leaks, and the overall performance.

Shell

After much analysis, we have decided not to manufacture the shell until the reconfiguration of the RBS is complete. However, we have put a lot of thought into the manufacturing plan for the shell and have a basic outline for how we would have made it.

We would have molded the shell from a 36 in. x 36 in. x 5 in. composite called foamboard of a recommended density of at least 40 lb/ft^2. We would then mill the foamboard into a mold for the shell using a rotating vice. To save material and time, we would use the same mold for both shells by manufacturing two different dies that would fit into the completed mold with a keyed backing. Each die would take the shape of its respective shell half and include a hole in the center to the ensure concentricity of the shell. The gear-side shell will require an aluminum plate to be manufactured within the shell to reduce the stresses on the shell material due to the forces from the gear and the bearing. The thin, circular aluminum plate will have a center hole to a maintain concentricity with the bicycle axle and serve as a place to press fit the bearing. We would also drill the five holes for the bolts that join the gear to the shell to pass through. The RBS-side shell will require a small, circular aluminum ring to be manufactured within the shell to reduce the stresses on the shell material at the bearing.

The shells will be made of carbon fiber, which requires that a lubricant be applied to the mold before laying the carbon fiber and epoxy. To make the shell that covers the RBS, we would only use about 3 to 5 layers of carbon fiber to reduce weight. Within the layers of this half, we would place and properly align the small aluminum ring, so that when the carbon fiber set the ring would be fixed at the shell’s center. To make the shell that is attached to the gear, we would use about 3 to 5 layers of carbon fiber to ensure strength. Within the layers of this half, we would place and properly align the aluminum plate, so that when the carbon fiber set the plate would be fixed in shell’s center. As we are not making the shell, we did not look into the time it would take for the carbon fiber shell to set. Once the shell halves have set, we would drill the sixteen holes through the circumference of the outside flange. We would then press fit the bearings into the center of the aluminum plate and ring.

Rim and Brackets

We purchased a rim rated at 27 inches with tires that has an inner diameter of 24.5 inches. We will drill sixteen 3/8 in. holes, eights pairs, through the center of the frame spaced evenly out over the entire circumference with 45 degrees between each set of holes. The brackets will be bolted to the rim at these holes.

The eight brackets will be manufactured from 6061-T651 aluminum using a mill and a drill press. The first steps will be to mill the block of aluminum down to the basic outer dimensions and then to ensure the accuracy of the curved edges. Next we will add chamfers to the edges that will be exposed in the final design. Then we will drill the holes through the curved top, add a chamfer, and thread it with a ¼-20 in. tap. Then we will have to decide whether or not to drill the holes through the flange that will join the shells together with the rim assembly. Since we are not manufacturing the shell, we do not want to constrain the shell design to bracket design. We will then be able to assemble the brackets to the rim with ¼ inch bolts.

Upon completion of the manufacturing of the RBS, shell, rim, and brackets, we would bolt the gear-side shell to the gear of the RBS with the bolts inserted from the inside so that they can be tightened from the outside. Then to complete the entire prototype, we would assemble the rim/bracket assembly and RBS-side of the shell to the gear-side shell.

Complete dimensioned drawings are include in Appendix

11. TESTING PLAN

We tested our prototype to determine whether or not the engineering specifications listed in Table 2 (p.6) were met. Not all of our engineering specifications were able to be measured directly from the prototype. Instead, these specifications were calculated using the requisite initial conditions.

Hub width, Hub diameter, Maximum Braking Torque

The hub width and diameter were measured to be 5.8in and 25in respectively. The maximum sustained braking torque was calculated to be 132.84 N-m as shown in the calculation of the longitudinal load transfer on (p.17). This value barely exceeds the allowed braking torque of 130 N-m by 2.84 N-m, which is basically negligible.

Top Operating Speed

The top operating speed was addressed in our testing procedure because all of our analysis was calculated assuming an initial bicycle velocity of 20mph.

Efficiency

There is no way to measure or accurately predict the efficiency that our prototype is capable of achieving as the efficiency depends on the ratio of the initial breaking velocity and the final regenerated velocity squared. We do not have enough information to calculate the theoretical final regenerated velocity.

Maximum Sustained Launching Torque

The maximum sustained launching torque was calculated to be 105.98 N-m. This value exceeds the allotted value of 90N-m, but our value is somewhat exaggerated as it does not take into account energy losses due to pressure drop from the plumbing, friction in the gearing, and friction in the bearings. The actual sustained launching will be less than 105.98 N-m. The calculation of the maximum launching torque is shown in the equations below.

Table 2 (Restated): Engineering Specifications

Description	**Parameters**
Hub Width	< 6”
Hub Diameter	< 29”
Maximum Sustained Braking Torque	130 Nm
Top Operating Speed	20mph
Approximate efficiency	>70%
Maximum sustained launching torque	90 Nm
Maximum system working pressure	5000 psi
Maximum weight of hydraulic system	< 22 lbs
Motor/Pump Displacement	1.5 cc
Maximum Volume of fluid	1 L
Hydraulic fluid filtration	Rated for 4500 Psi max pressure
Accumulator Pressure After Braking	< 3000 Psi
Shell Weight	< 15 lbs

Table 8: Shell Parameters

	Low density Carbon Fiber	High Density Carbon Fiber
Density (lb/in)	0.05419	0.0578
Thickness (in)	0.329	0.406
Gear Side Weight (lb)	9.50	12.55
RBS-side weight (lb)	8.37	11.02
Total Shell Weight (lb)	17.87	23.57

Data From Point C in the Launching Cycle of Figure 8:

$$14{:}1 \rightarrow 7.57Nm * 14 = 105.98Nm = \tau$$

$$F_x = \frac{\tau}{r} = \frac{105.98Nm}{0.3429m} = 309.07N$$

$$a_{xi} = \frac{F_x}{m} = \frac{309.07N}{136kg} = 2.27m/s^2$$

$$\bar{a}_x = \frac{2.27 + 0}{2} = 1.135m/s^2$$

r = tire radius, τ = braking torque, a_{xi} = initial acceleration,
F_x = braking force, m = mass, $\bar{a}_x$ = average acceleration

Maximum System Working Pressure

Our high pressure hoses were rated at approximately 4100 psi. We ran the system below 5000 psi, to make sure that the system was secure and safe and the hoses did not crack. The working system pressure was around 2000 psi, which was a lot lesser than the maximum system working pressure.

Maximum Weight of Hydraulic System

We replaced some components and redid the plumbing of the entire system. After making changes and also after adding gear keys, we found that the weight of the assembly was approximately 20 lbs. The weight of the rim that we manufactured with the 'arch' pieces was approximately 2.8 lbs. The weight of the hydraulic system was less than 22lbs.

Maximum Pump Displacement

We did not change the pump or the motor. We used the same pump and the motor that the previous team used, and so the capacity was 1.5 cc.

Maximum Volume of Fluid

We emptied all the hydraulic fluid from the system. After completely draining the entire system, we added new hydraulic fluid. We added approximately 900 ml of fluid into the system. This is less than the maximum fluid of 1 L.

Hydraulic Fluid Filtration, Accumulator Pressure after Braking.

We filtered the fluid, and this filter could withstand fluid at a pressure of 4500 psi. We used a variable displacement hand up to pump the system pressure up to approximately 2000 psi. This was a lot lesser than 3000 psi.

Shell Weight

Exact dimensions of our shell can be seen in Table 8 (p.35). The initial CAD model of our shell gives us an approximate volume. Using the volume with density of carbon fiber, we were able to obtain a fairly accurate weight of the shell. We estimate a shell weight of 20.72 ± 2.85 lbs. We originally predicted a shell weight of 15 lbs prior to engineering analysis of the longitudinal loading due to braking. This extra load transfer requires a thicker shell for further structural support, increasing the shell's weight.

12. DISCUSSION FOR FUTURE IMPROVEMENTS

Further possible improvements to our RBS prototype are summarized below. We find the improvement tasks challenging enough to be considered as a separate ME450 project for one of the future terms.

Fixing the Current System

During a demonstration at the design expo in Lansing, Michigan, the lower three-way valve stopped functioning. Even though we applied the requisite 12V to the lower three-way valve terminals, the solenoid did not actuate. The most probable reason for this occurrence is that the solenoid coil was burned and needs to be replaced. However, we are not completely sure about what is causing the problem and further analysis has to be performed.

We noticed that the motor shaft key slot is heavily scratched from improper tightening of the set screw and we were unable to insert a gear key into the slot. This is not a problem when there is no load on the main gear. However, when the RBS is incorporated into a bicycle and the main gear has to accelerate the bike and rider, the inertia will be much greater and the motor shaft may spin relative to the bevel gear. This is due to the lack of the gear key to guarantee that the torque is transferred between the motor and bevel gear. The motor shaft key slot was heavily scratched by one of the past teams working on the RBS system when they directed the motor bevel gear set screw towards the motor shaft key slot. We suggest that filing of the motor shaft should be done to improve the key slot shape. Furthermore, the upper three-way valve wiring needs to be done.

Upgrading the Current System

Our current design has a lot of torque delivered from the motor to the main gear. We calculated the torque on the main gear to be approximately 100N-m. This is a very good performance. However, during our testing we noticed that the main gear does not always spin as smoothly as the other gears. There is a little bit of play in the main gear such that the bearing does not always provide the optimal performance. This primarily occurs when the RBS is tilted at an angle and the torques on the bearings are exaggerated. We did not have enough time to investigate the possibility of better securing the main gear to the axle. We believe improving this would enhance the efficiency of the RBS.

The manufacturing of the shell needs to be performed. We have already designed the shape of the shell including the required thickness based on failure analysis. The material of the shell should be carbon fiber. Research needs to be conducted as to how the shell may be manufactured. We suggest that the next team should mill a mold using high density foam board, however the foam board can be quite expensive. Furthermore, the shell needs to be attached to the current RBS system. We have designed and manufactured a rim and brackets system that can be used to hold the two halves of the shell together. Furthermore, one half of the shell needs to be attached to the RBS system main gear.

Once the shell is manufactured and properly connected to the rim the entire RBS system needs to be attached to the bicycle fork. However, we expect the shell width do be greater than a typical bicycle fork width and hence it is expected that design and manufacturing of a new fork should be performed.

Once the RBS system is attached to the bicycle fork electronic switches need to be added to the bicycle in order to control the actuation of the two 3-way valves during braking and acceleration. The user interface for the rider should be attractive and practical with ergonomic design in mind.

13. CONCLUSION

Our goals are to design a more compact, working RBS as well as a lightweight shell to protect and hide the RBS once attached to the bicycle. In order to complete the former, we have investigated alternate configurations to reorganize the current setup. To achieve the latter, we have brainstormed design ideas and manufacturing solutions that best meet the customer requirements. However, assembling a working RBS prototype must precede the completion of a shell. The reconfiguration of RBS components requires new pipe fittings, and hoses to be purchased in addition to re machining the super bracket. We have analyzed previous hub designs and compared the relative importance of weight and manufacturability to determine the best hub design. Should we complete the redesign of the RBS and the assembly of the hub in time, we will attach the working prototype to a bicycle chassis.

14. ACKNOWLEDGEMENTS

We would like to thank the EPA (Environment Protection Agency) and Mr David Swain for his time and advice on the project. Mr Swain provided us with low pressure hoses, plastic sheets, side brackets and mineral oil. He specified the client requirements, and served as our project coordinator. We had several meetings with him to understand the ultimate goal of the project.

We would also like to thank Bob Coury for his time and guidance. Bob helped us during the manufacturing of the rim. He provided us with the most optimal technique of manufacturing the brackets.

Harish Narayanan, a post-doctoral candidate also contributed with his advice. We really appreciate his time and inputs with respect to the shear/normal stress analysis.

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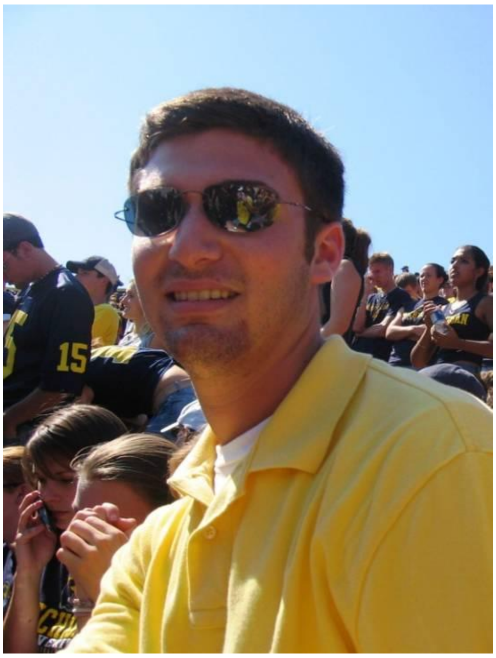
16. BIOS

My name's **Rohan Khubchandani** and I am an international student from South Bombay (Now Mumbai), India. I am really interested in airplanes/cars and have always wanted to know the methodology that is involved in making them. I also enjoy mathematics and found that the best way of integrating both my interests, would be a major in mechanical engineering. I play a lot of table-tennis and have played at the state-level in India. I have also represented the University of Michigan for table-tennis, at the NCTTA college nationals. After I graduate from University of Michigan, I hope to get a job and work for a consulting firm for a couple of years, before I pursue graduate school in engineering/business. I am also interested in world affairs/model United Nations conferences and have served as committee staff for the University of Michigan Model United Nations. I really enjoy listening to music and in my spare time I play the keyboard.

My name is **Milan Paunovic** and I am a student from Belgrade, Serbia(Ex-Yugoslavia). I have always had an interest for vehicles, especially cars and airplanes. Furthermore, I find the scientific fields of math and physics very appealing and a hence I developed a strong interest for mechanical engineering. My future plan is to hopefully get a job with a major engineering/financial company. I am also considering to pursue the Masters Program in Mechanical Engineering specializing in Internal Combustion Engines. At the University of Michigan I am a member of the Serbian Student Association and take part in organizing various social and cultural events. I enjoy both watching and playing sports especially soccer, tennis and basketball. My favorite soccer team is Red Star Belgrade. I enjoy reading books and listening to music. I also like spending time with my brother, my family and with my good friends.



My name is **Adam Lovit**, and I am from Columbia, SC. I have always known I would be an engineer because I am always wondering how things work and how they would work better. I really enjoy my engineering design and manufacturing classes because I get to utilize my creativity in design, and I like building things from scratch. I like to watch and play all types of sports, especially basketball, football, and tennis, in which I earned a state championship at the varsity level in high school. I have loved my time at Michigan, but I cannot wait to graduate so I can concentrate on my career and eventually start a family. I plan on working for an engineering or engineering consulting firm for 3-5 years before going back to school to get a Masters in Business Administration, concentrating in entrepreneurship and new product development. I would love to own my business some day so I could have the freedom to make my own hours because I really enjoy traveling.

My name is **Matthew Brewer**. I was born and raised in Albuquerque, NM. Ever since I was a small child, my parents knew I would one day become an engineer because every time they would buy me a new toy, few hours later it would be lying in pieces on the floor as I had taken it apart to see how it worked. They soon learned to stop buying me nice toys. I find engineering classes that involve physics to be the most interesting. I love mechanical devices, especially vehicles. I do all the repairs/maintenance on my car myself. I am also infatuated with watercrafts. I currently participate in the University of Michigan Sailing Club and I have water skied for 10 years. After graduating in May 08 I will attend graduate school here at the University of Michigan where I will pursue a masters in mechanical engineering.

17. APPENDICIES

Figure 32: Gantt Chart