ILLINOIS INSTITUTE OF TECHNOLOGY
PARKER HANNIFIN CHAINLESS CHALLENGE

A DESIGN REPORT FOR THE ILLINOIS INSTITUTE OF TECHNOLOGY HAWK HYDRAULIC VEHICLE, 2014 – 2015

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1.0 ABSTRACT

Efficiency is why cycling is one of the most widely used methods of human transportation. While fluid power is mankind's way of manipulating forces to move great loads. It is combining these two design disciplines that presents one of engineering's greatest challenges. The Parker Chainless challenge asks the question, how do we make this thing efficient? The method to this year's chainless bike is simple; design a bike using our knowledge gained from previous years in order to make the most efficient fluid driven bike possible. This means we minimized the amount of hydraulic circuitry, making the bicycle pedal and feel as close to a standard bike as we can. This year's chainless challenge team was able to produce a two-wheeled design that adapts to a standard bike frame, utilizes a standard bicycle pedal drive mode, but also features an integrated energy auxiliary system. This is how we did it.

2.0 PROBLEM STATEMENT

Build and design a human powered vehicle that employs a fluid means of power transmission. For additional points the vehicle should include an energy recovery system or renewable energy source. And be able to race the bike in three different competition events: A sprint race, efficiency challenge, and a time trial.

3.0 PROJECT PLAN /OBJECTIVES

Going with a new circuit this year the team entered a vehicle with a completely original cylinder system and pneumatic stored energy circuit which took months to design and validate. Our shortcoming last year was a mechanical failure of our over-drive hub which was redesigned this year from the ground up. The design for this year's competition began where last year left off but with our intent to fully integrate the circuit. The plan this year was to make the bike more efficient and especially robust.

Objective 1: Increase the efficiency of the hydraulic system

Since the vehicle is to be completely human powered, all sources of resistance need to be minimized. This would be achieved by decreasing pressure loss and minimizing fluid flow. The circuit would also use only the power generated by the rider to complete this task. Using two sets of paired cylinders, cycling fluid back and forth between each other in order to transmit power from the pedals to the rear crankshaft. A small portion of this power will be released to the regenerative circuit to be stored for later use. As the front cylinder extends, the corresponding rear cylinder retracts at an equal rate. Once the front cylinder extends to the end of its effective stroke, it retracts as the rear cylinder extends. At the top of this effective stroke a small portion of the fluid pressure is diverted to the pressurized accumulator. The second set of cylinders follow the same motion as the first set of cylinders, but do so with a 90 degree lag in the pedal stroke. This is to ensure the rear wheel rotates; unlike a locomotive (similar to our design) where the wheel of the train is carried over by the rotational force of it spinning, we needed to ensure that some portion of the pedal was always pushing or pulling the cranks. This avoids the cranks being stuck in their top dead center position and allows us to transmit our rotational pedal stroke to the rear wheel.

Objective 2: Creating an energy storage system with a high energy density

The option to store energy onboard the vehicle presented a unique challenge and opportunity for the Hawk EHV team. Integrating our regenerative circuit into the primary drive circuit allowed us to use the regen system to drive the bike while collecting only fluid power to do so. This eliminates the need to mechanically divert energy from the bike elsewhere and focus on making the bike more efficient. The motor used is a Parker F11-005-HU-CV-K, which is a motor that can handle the pressure we develop. This allows us to use a smaller fluid valve block coupled with a flow control valve. This motor is also able to be used as a pump, which enables regenerative braking.

Objective 3: Alternative power transfer

There are several ways to transmit power without the use of chains. The need for tight packaging and dual power input are enough of a reason to avoid using chains, but the point penalty also provides a considerable incentive.

Objective 4: Create a natural riding experience

Riding a bike is second nature for most people and is second only to walking as far as human powered transportation is concerned. A natural experience is defined by predictable pedal resistance that directly correlates to torque at the drive wheel. Braking, maneuvering, and the ergonomics of a bicycle are all part of the natural riding experience as well.

Objective 5: Create a system that can be adapted to any standard bicycle

The modern bicycle comes in many shapes and sizes, most of which can benefit from an additional power source. We also strove to reduce manufacturing costs and increase its versatility by making it fit on most standard bicycles.

4.0 DESIGN ANAYLISIS

I. The 2014 Hawk EHV

The hydraulic circuit implemented on the 2014 Hawk EHV actually consisted of two separate systems with two different functions. A power circuit, consisting of two cylinder-pairs offset on either side of a bicycle and connected via crank shafts and cam levers to the mechanical system of the bicycle, provided the "chainless" propulsion of the vehicle. This system can be described as a fluid-displacement circuit where there is minimal pressure generated, and fluid is directly moved from one cylinder to the other by extending or retracting one of the system's rods. Figure 1 shows this system.

The second hydraulic circuit on the vehicle sought to harness the power of the spinning wheel to charge an accumulator, which in turn could be dispensed through a hydraulic motor and recovered by the wheels as torque. A friction drive wheel attached to the shaft of the hydraulic motor transfers torque directly to the rear bicycle tire in a similar manner to electric bicycle assist motors commonly used by cycling enthusiasts. This system never functioned correctly, and due to mechanical failures of the bicycle at the competition, was never thoroughly tested. However, the concept showed promise in limited testing before the vehicle was deployed, and a variation of it will be used for the 2015 vehicle.

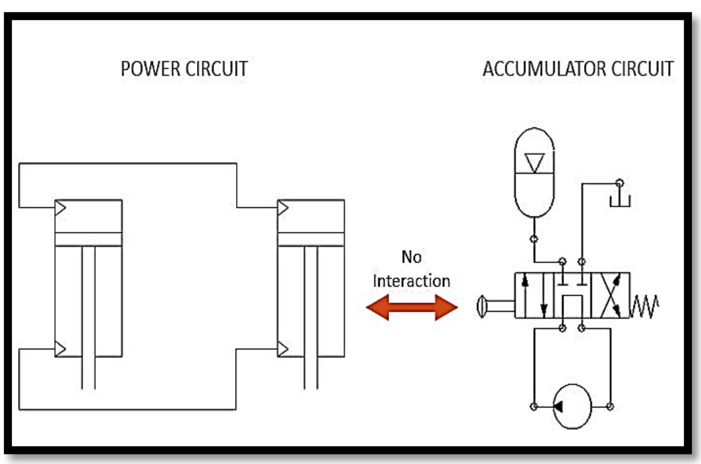


FIGURE 1: 2014 HAWK EHV HYDRAULIC CIRCUIT

II. The 2015 Hawk HV Hydraulic Design

Some hardware limitations prevented the original hydraulic circuit design from being implemented but for the sake of clarity of design intent this report will still detail the preliminary design work that was completed. A following section will explain the difficulties experienced during assembly and testing of the circuit and what changes were made in that process.

A. The Original Design

The 2015 circuit seeks to build on the successful elements of the previous generation's designs while incorporating a more advanced hydraulic design. The original design of the entire circuit can be seen in Figure 2. The primary concept of this year's system is to turn the fluid-displacement circuit into a fluid-power circuit by generating pressure with each pedal by the operator. This pressure is then fed through a shuttle valve to an accumulator circuit, where it can be stored. This circuit was intended to use a differential in volume between the two cylinders to allow the pedal cylinder to act as a pump by diverting a small amount of fluid with each

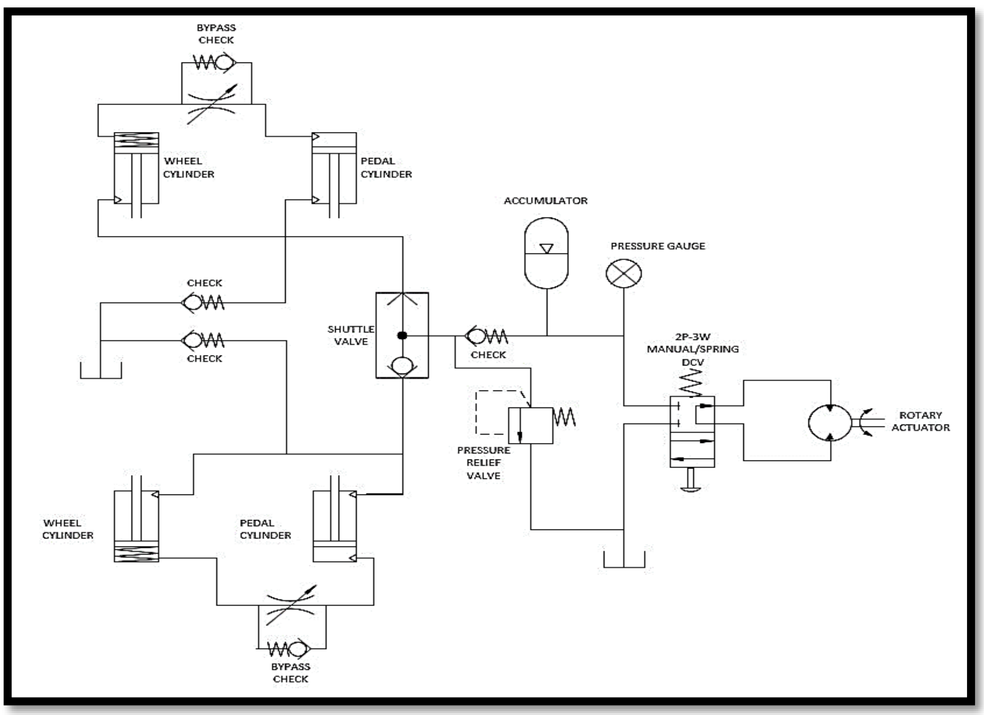


FIGURE 2: SHUTTLE-VALVE CONNECTED ACCUMULATOR CIRCUIT

B. Pressure Generation in the Circuit

Pressurized fluid is created in the circuit through the use of a variable orifice. This flow restriction creates a pressure differential as given by the full form of the orifice equation, shown in Equation 1. Varying the orifice coefficient alters the pressure differential through the square of the flow through it. This can be related to the velocity of the cylinder extension by Equation 2. In turn, the maximum pressure that can be generated can be related to the force applied to the pedals by Equation 3.

$$P_2 = \left(\frac{Q_P}{k}\right)^2 + P_1 \tag{1}$$

$$V = \frac{k}{A}\sqrt{\Delta P} \tag{2}$$

$$F_{EXT} = \frac{F_{MAX}A_R}{A_C} = \frac{0.589F_{MAX}}{0.785} = 0.75F_{MAX} \tag{3}$$

P_1 is the pressure downstream of the orifice, P_2 is the pressure upstream of the orifice, V is the velocity, k is the orifice coefficient, A is the area of the orifice opening, F_{EXT} is the force exerted by a rider, A_R is the cylinder rod area, A_c is the cylinder cap area, and F_{MAX} is the maximum output force on the bicycle wheel. Using these equation sets, we can estimate the ability of the system to generate pressure under a variety of force loading conditions. These equations provide only a brief estimate of the performance, however, and a more accurate means of looking at the circuit is to use MatLab's SimHydraulic package, which is described in greater detail below.

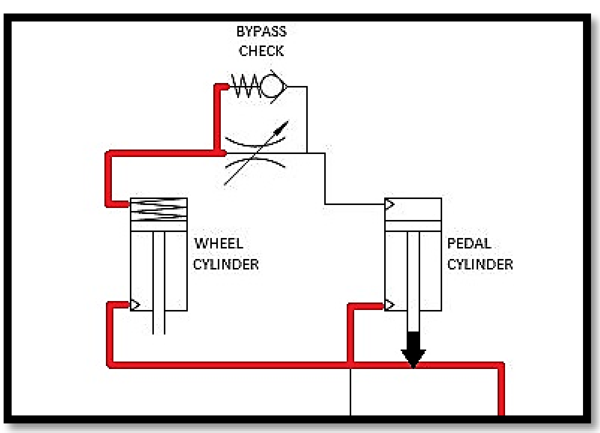


FIGURE 3: PRESSURE GENERATION IN ONE CYLINDER PAIR DURING A POWER STROKE

Pressure is generated in the circuit as shown in Figure 3. As can be seen, high pressure exists on the cap end of the wheel cylinder and the rod end of the pedal cylinder during the "power stroke," which is the extension stroke of the pedal cylinder, corresponding to a rider pushing their foot downwards. A bypass check valve allows open flow during the non-power stroke, removing the resistance caused by the flow control when the operator is not pushing on the pedal.

C. Interconnectivity and Accumulator Charging

The main difference in the function of the hydraulic circuit and the previous years' designs is that the two cylinder-pairs are interconnected via a shuttle valve. In the past, the left and right side cylinder pairs operated independently. In this system, they alternatively provide pressure to the accumulator charging circuit through the shuttle valve, as in Figure 4. High pressure (red) forces the ball in the shuttle valve to block flow from the cylinder pair not undergoing a power stroke (blue). Pressurized fluid from the cylinder pair undergoing a power stroke passes through the shuttle valve and into the accumulator charging circuit, which is protected by a pressure relief valve.

Because the cylinder's operation is offset by ninety degrees, the interconnected circuit will charge the accumulator during 75% of one full-pedal cycle. The gray highlighted areas of Figure 5 demonstrate the time during the cycle during which the accumulator is charged. Connecting the two circuits allows a rider to charge the accumulator 25% faster than if connected to only a single side.

Additionally, using both circuits to generate pressure provides a more even riding experience for operators, which is an important design feature for all

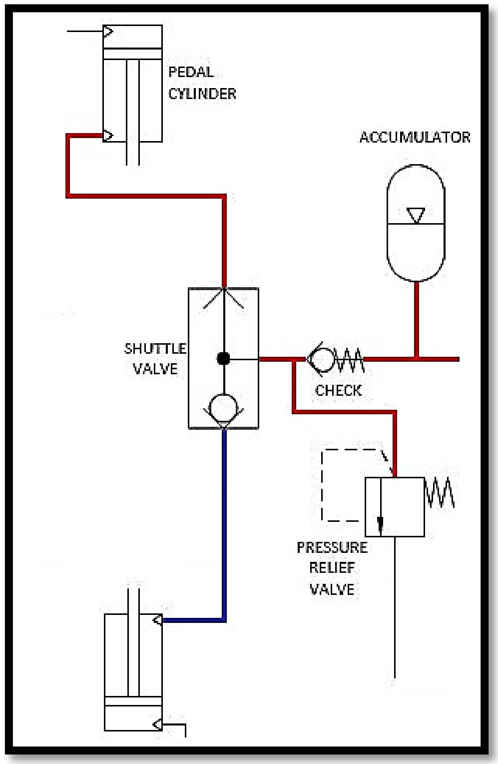


FIGURE 4: ALTERNATING ACCUMULATOR CHARGING THROUGH A SHUTTLE VALVE

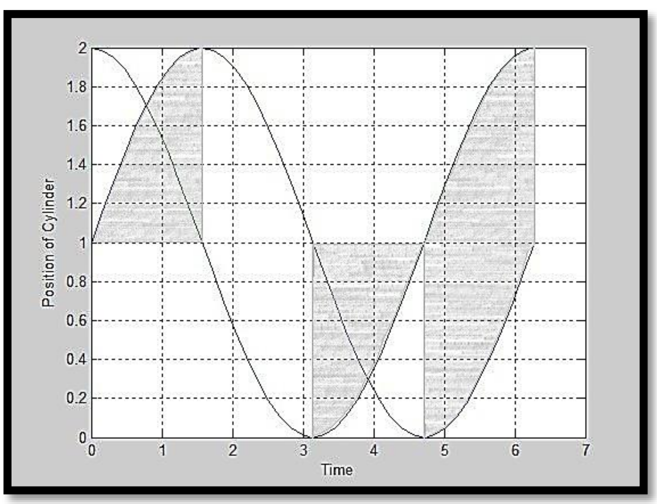


FIGURE 5: CHARGING OF THE ACCUMULATOR IN A 90- DEGREE OFFSET PEDAL ORIENTATION

Hawk EHVs. While the presence of pressure will make this vehicle slightly more difficult to operate, it will remain a balanced operation, as resistance on both sides will be essentially equal. This maintains the important parameter that the vehicle must behave similar to typical bicycles.

D. Accumulator Discharge and the "Boost" Cycle

The primary means of recovering the stored energy is through a hydraulic motor. A friction drive wheel attached to the output shaft of the motor is placed in contact with the rear tire of the bicycle. When pressurized fluid flows through the motor, the friction wheel provides a force onto the rear tire, driving it forward and assisting in the propulsion of the vehicle.

The mechanics of this discharge circuit are presented visually in Figure 6. A manual directional control valve is actuated, shifting the spool from a float center to a bi-directional center and opening the motor ports to the accumulator circuit. A float center on the valve allows the motor to rotate freely while not being used to provide power, allowing the friction drive wheel to remain in contact with the vehicle's rear tire at all times. When the valve is shifted, high pressure fluid (red) flows from the accumulator through the motor. The pressure drop across the motor is converted to mechanical energy, which is recovered by the vehicle in the form of torque on the motor shaft. Low pressure fluid (blue) then exits the motor back to the bicycle's hydraulic reservoir.

The resulting expulsion will not provide a significant amount of torque (not enough to power the entire vehicle), but it would provide a small boost of speed, which could help a rider up a steep slope, or over particularly rough terrain.

Fluid is released from the accumulator, and passes through a hydraulic motor, where the output torque is a function of the motor's volumetric displacement *D*, and the pressure differential *ΔP*, as given by:

$$T = \frac{D\Delta P}{2\pi} \qquad (4)$$

Because the pressure differential will be relatively small, the torque output during a boost cycle will be correspondingly small. Larger pressure differentials during the efficiency test can be used with the same system to achieve greater torque, and as will be discussed later, can theoretically power the vehicle a considerable distance.

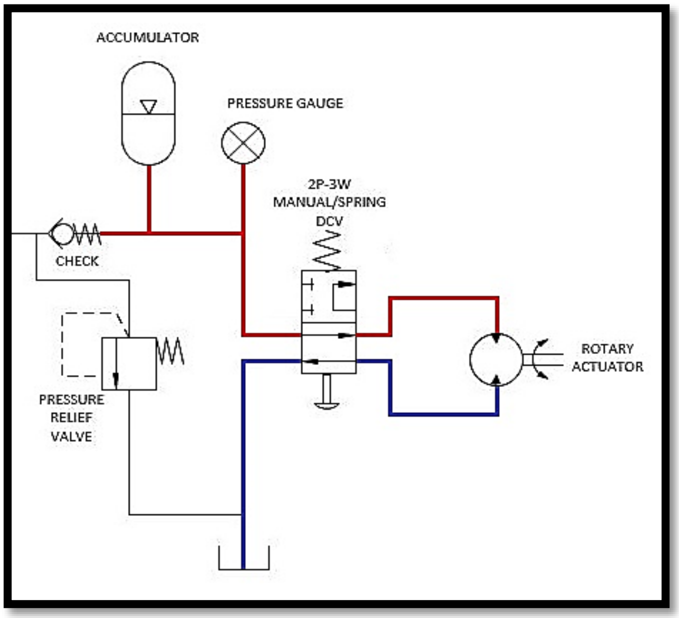


FIGURE 6: ACCUMULATOR DISCHARGE CIRCUIT

E. Determining Input/Output Conditions

Before having physical components to test, the primary means of analyzing this circuit were digital, using the SimHydraulic package for MatLab's Simulink environment. The full Simulink model is presented in the Appendix in Figure A.

Most hydraulic circuits are analyzed from the perspective of pressure and flow. Typically, a hydraulic pump is supplied with known energy, and the entire system is analyzed using the knowledge of the pressure and flow leaving that pump. Pressure and flow are known input conditions, and force, position, velocity and torque are output variables. However, the circuit on the Hawk EHV does not contain a pump in the traditional sense, and therefore cannot be analyzed using these techniques.

Because the hydraulic system responds directly to the actions of the rider, the modeling technique prescribes the cylinder position as the input variable, and analyzes the pressure, flow, and torque as the output variables. This modeling technique allows the system to be evaluated for a variety of riding styles.

The primary signal used to evaluate the circuit assumed a two-second cycle time for a full revolution of a pedal. Assuming an even riding mechanic, this signal was approximated by a sin wave, as given by:

$$v(t) = \left(\frac{12.57in}{sec}\right)\sin(\pi t) \quad (5)$$

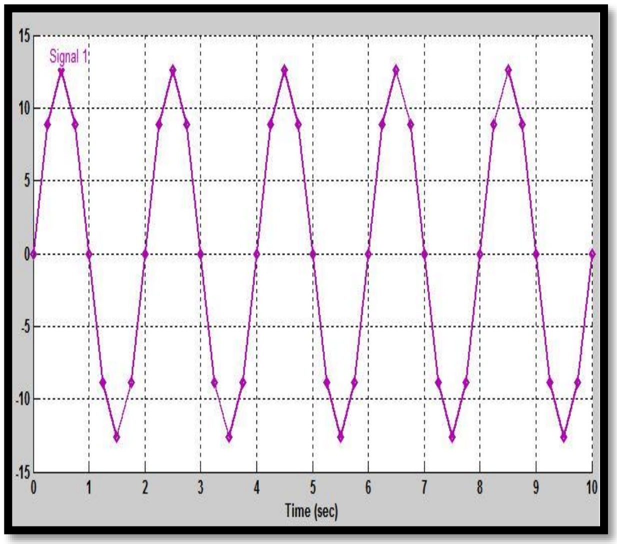


FIGURE 7: POSITION INPUT SIGNAL FOR DIGITAL MODEL OF FLUID CIRCUIT

This signal is visible in Figure 7. Most of the analysis in the digital model was accomplished using this input signal profile. However, any riding motion can be approximated as a series of sin or cosine waves and fed into the model, and the resulting system response can be analyzed. In this way, performance can be analyzed for riders of varying strength, speed, size, and tendency.

F. Modeling the Cylinder Pairs

The hydraulic cylinders are modeled independently as subsystems. Their physical characteristics are based off of the actual cylinder pairs, so the dimensions accurately represent reality. Frictional resistance is described using knowledge of their performance in the past. The subsystem is visible in the Appendix in Figure B.

Each subsystem was tested independently to ensure the response matches expectation. Each component's performance was verified independently, which allows greater confidence that the response observed from the full integrated circuit will correspond to reality. Figure 8 demonstrates the system response for both cylinder pairs acting in tandem with a 180° offset.

As can be seen from the plot in Figure 8, the cylinders behave as intended, with each cylinder offset from its pair, and with the two cylinder systems operating out of phase with respect to each other. Significant analysis was undertaken to ensure that different input signals resulted in the correct phase relationships; Figure 8 represents the response to the input signal in Equation 5.

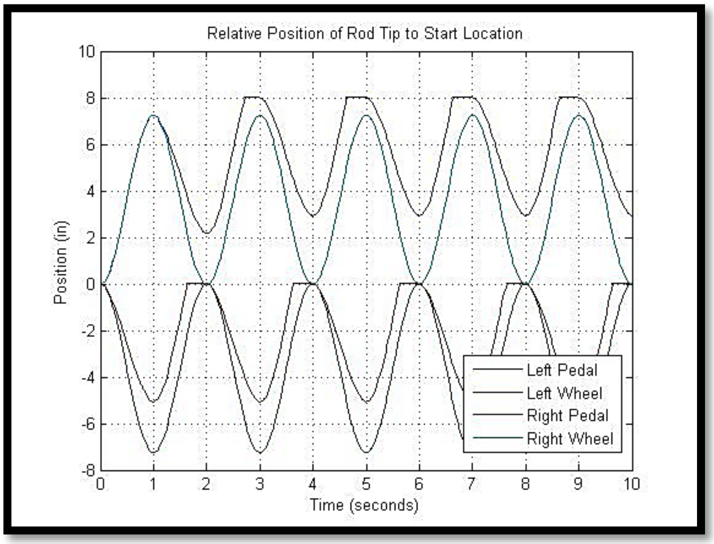


FIGURE 8: CYLINDER HEAD POSITION AS A FUNCTION OF TIME

Of particular note from the graph in Figure 8 is that the pedal cylinders extend further than the wheel cylinders. This occurs because of the previously described volume differential necessary to divert fluid to the accumulator to achieve energy storage. The wheel cylinder on the primary drive side has a seven inch maximum extension, whereas the pedal cylinder undergoes a full eight inch extension and retraction stroke. In reality, the exact position of these cylinders will need to be experimentally determined once the system is assembled.

G. Modeling the Shuttle Valve and Motor Circuits

Separate subsystems were created to model the shuttle valve and the hydraulic motor. The shuttle valve subsystem is visible in the Appendix in Figure C. It consists of a 3-way directional control valve that passes fluid from either of the cylinder pairs depending on the signal to the valve. A pressure differential is calculated between the two cylinder-pair sides, and the resulting number determines the shift direction for the shuttle valve. Positive values of pressure differential shift the valve to the right cylinder-pair, while negative values shift it to the left cylinder-pair.
The motor subsystem, which is visible in the Appendix in Figure D, consists of a hydraulic motor block and a control valve that determines when the motor is actuated. The signal fed to the control valve is arbitrary; it represents the rider engaging the lever on the valve and discharging the stored fluid. Much like the input signal, this parameter can be varied to model different use of the accumulator charging circuit. Figure 9 shows the input signal most often fed to the system during the analysis in this paper. One axis shows the simple step sent to the control valve, and the other figure shows the corresponding motor signal.

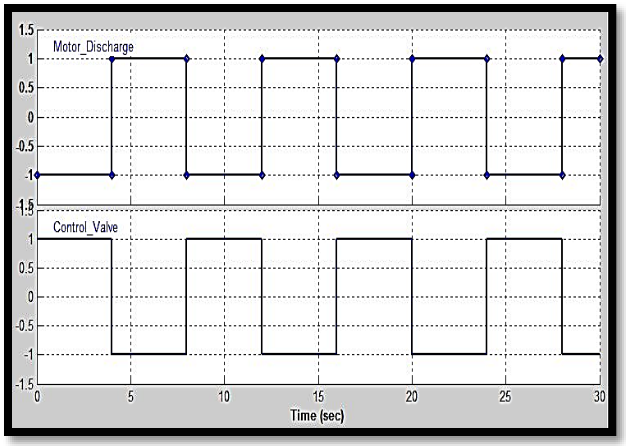


FIGURE 9: MOTOR AND MOTOR CONTROL VALVE SIGNALS

H. Model Limitations

As with any system, this model is not perfect. There are several drawbacks to the performance results this model predicts. Specifically, three areas for concern exist in this model:

1. *Interaction of the Mechanical System*: The mechanical system is not modeled with this circuit. It is possible to achieve this in MatLab, but as of this time that task is not completed. The resistance to the hydraulic circuit's operation resulting from mechanical linkages are not represented in this circuit. In addition, the fact that the cylinders are mechanically linked is not represented in this circuit; this will result in a slight difference in position than observed in output curves such as the one in Figure 8.

2. *Frictional Resistances of Hydraulic Components*: While every attempt has been made to accurately portray the resistances of the components, in actuality these resistances are not linear, and cannot be represented simply by a number. Conservative values have been applied to each component, but until the system is physically tested there is not a way to confirm these assumptions.

3. *Frictional Resistances of Lines and Fittings*: Pressure drop as a result of friction in the hoses, tubes, and fittings is not modeled at all in this system. Depending on the speed of the fluid, the temperature, and a host of other factors, these losses can be significant. Care has been taken to reduce the length of hoses, as well as the number of fittings used as much as practical, but there will be some un-modeled losses in the final system. As with the hydraulic components, the effect of these losses are best determined upon experimentation when the circuit is assembled.

I. EXPECTED PERFORMANCE CHARACTERISTICS

Full system response is difficult to model when the input conditions are so varied. As a result, the expected system response is actually a range of possible values dependent on the input signal, pressures generated, and time between cycles. Additionally, performance in the system differs for typical riding conditions and for the efficiency test, when the system will be charged to a much higher pressure. A summary of the expected results is visible in Table 1.

For the "boost" cycle, pressures are low and output torque is relatively small. This is why the typical accumulator charging circuit is useful for small boosts of energy and not for full propulsion of the vehicle. The pressure achieved in the system is a direct result of the orifice setting; the amount of time the "boost" can assist the rider is a function of how much fluid is stored in the accumulator, which in turn is a function of the system pressure, the accumulator pre-charge pressure, and the accumulator volume.

Charging of the accumulator will happen cyclically; each stroke of the pedal cylinders will displace a small amount of fluid into the accumulator. The overall maximum pressure achieved in the system is set by the size of the orifice opening; however, this pressure will slowly build against the pressure in the accumulator, as in Figure 10. The peak pressures for the blue and green curves, representing the pressures in the pedal cylinders, are determined by the orifice opening. The red pressure, representing the pressure in the accumulator, is determined by the pressure relief valve setting (in Figure 10, this value is 100psi).

As can be seen in Figure 10, the discharge of the accumulator can last over 30 seconds; this value is determined by the volumetric displacement of the motor, which determines how fast the accumulated fluid can move through the motor circuit.

Torque performance from the motor is visible in Figure 11. After an initial peak torque, the circuit experiences an exponential decay.

Parameter	**Expected Values**
"Boost" Pressures	90-140psi
"Boost" Torque	7-13in-lbf
Efficiency Pressures	1500-2000psi
Efficiency Torque	75-80in-lbf
Efficiency Distance	50-200 feet

TABLE 1: EXPECTED PERFORMANCE CHARACTERISTICS

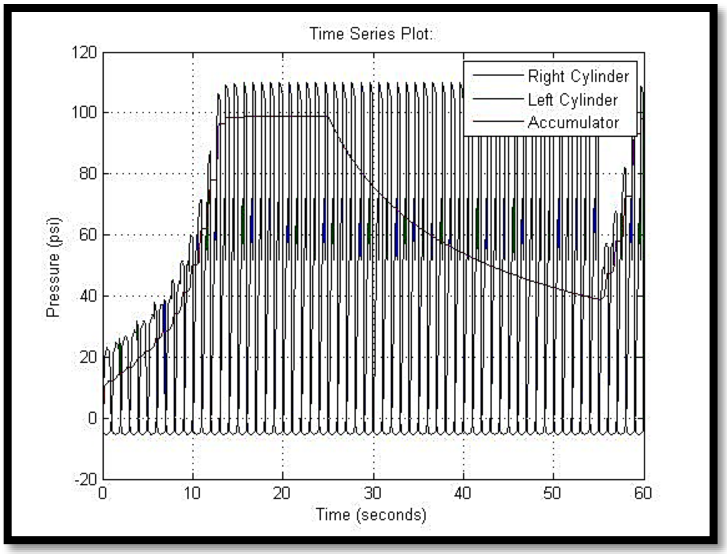


FIGURE 10: PRESSURE RESPONSE OF ENTIRE HYDRAULIC CIRCUIT

FIGURE 11: MOTOR TORQUE VS. TIME WITH 2.5CIR DISPLACEMENT AND 100PSI CHARGE

The range of torque that will be useful in assisting the vehicle will be determined through experimentation. It is likely that during some portion of the accumulator discharge, when the pressure differential is low enough, the effect on the vehicle speed and performance will be negligible. Therefore, it is unlikely that the "boost" cycle will be as long as the model in Figure 11 suggests.

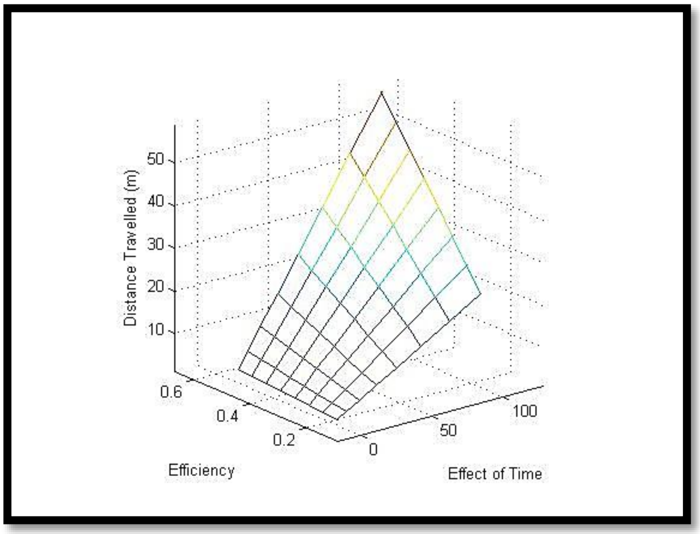


FIGURE 12: EFFECT OF EFFICIENCY AND DISCHARGE TIME ON DISTANCE TRAVELLED

The high pre-charge for the efficiency challenge results in significantly higher output torque on the motor shaft; this, in turn, will provide a greater force to the rear tire, and should be sufficient to accelerate the vehicle without the need to pedal. The distances visible in Table 1 represent the range of possible distances, depending on the assumptions for wheel friction, hydraulic friction, and efficiency by which the force is transferred from the friction drive to the rear tire of the vehicle. Additionally, the mass of the vehicle and rider combined will change depending on who operates the vehicle, and correspondingly the total weight of the vehicle-rider system.

To illustrate the effects of these varying parameters, see the surface in Figure 12. Variations in the effective discharge time and the overall efficiency of the process (a combination of different friction coefficients and losses) directly impact the resulting distance travelled. As illustrated, the distance is difficult to directly predict, as even simplifying the analysis to two variables results in a wide range of outputs.

J. COMPONENT SELECTION

Working with Parker engineers and salespeople, components were selected to construct the hydraulic circuit presented in this paper.

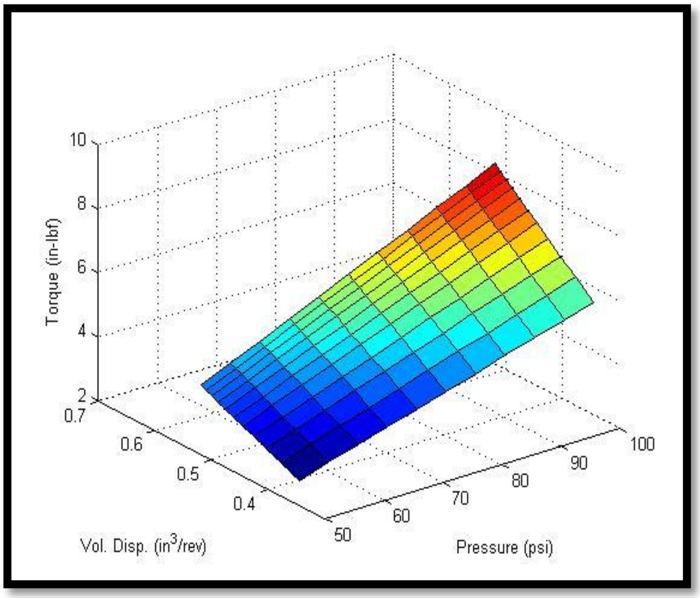


FIGURE 13: SIZING OF THE MOTOR USING PRESSURE, DISPLACEMENT, AND OUTPUT TORQUE

Component selection and sizing was done using the digital model to predict output performance based on each individual element's characteristics and settings. Iterative processes were used to determine some components, as different specifications were inserted into the model and response was evaluated until a suitable configuration was found.

Others were selected by matching values on performance surfaces generated in MatLab with the closest possible Parker product, as in Figure 13, which relates the pressure and volumetric displacement of a motor to its output torque.

III. Circuit Revision

Once assembly of the hydraulic circuit began, a number of design flaws came about that required some impromptu modulation of our circuit components which ultimately changed the end performance characteristics of the vehicle.

The front end of the circuit containing both pairs of cylinders up to the connection point of the shuttle valve was assembled first. There was great difficulty in getting the cylinders to move past one complete cycle. The suspected issue was having the down stroke of the pedal cylinder also being the circuit section to divert flow into the regenerative circuit. The pressure would build from the down stroke as expected, but the fluid will always take the path of least resistance, and with an unpressurized accumulator would divert into the regenerative circuit instead of working to drive the bike forward. The down stroke of the pedal would also move the fluid in the cap ends of the pedal cylinders and one would expect that to help drive the bike as well, but looking back on our assembly of the circuit it is likely that we had air trapped inside of the lines that prevented the wheel cylinder from actuating. The air inside would expand from the low pressures preventing any actuation of the wheel cylinder.

In an effort to remedy this situation, the lines of the cylinders' cap and rod ends were flipped as can be seen in Figure 14. With this new configuration, the down stroke of the pedals would pressurize the rod ends of the cylinder pairs making for a reliable wheel cylinder actuation since no fluid would be displaced with during that power stroke phase of a pedal. Even with a small amount of air in these lines, it would compress quickly and still allow for smooth riding operation, unlike the original circuit which would not be tolerant of any entrapped air. A flow valve was also added before the check valve of the regenerative circuit so that the rider could stop flow into the accumulator, effectively turning it into a simpler fluid-displacement circuit. As the pedaling of the bike behaves differently when able to charge the accumulator, having the functionality to turn off the regenerative system could be advantageous depending on the riding conditions.

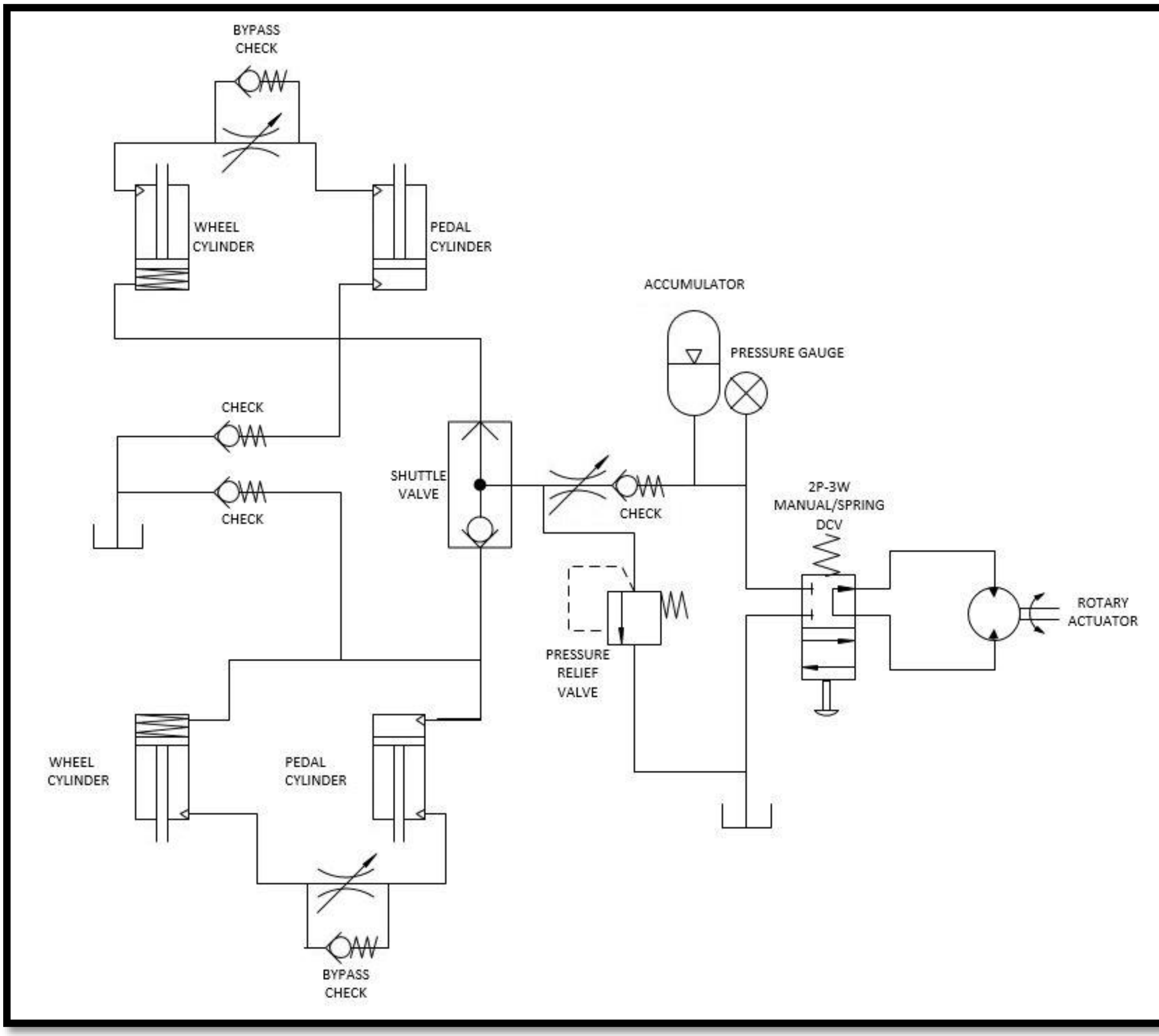


FIGURE 14: REVISED SHUTTLE-VALVE CONNECTED ACCUMULATOR CIRCUIT

This system is not without its own flaws. The bypass check circuit is no longer being used as was originally intended. Initially planned to allow for a difference in pressure generation, letting the rider determine how much pressure the regenerative circuit could build, the bypass check system now serves only as an option for the rider to increase pedaling resistance. Closing of the orifice in the flow valve would require a higher pedaling force to maintain the same flow rate, and thus riding speed. No longer used as a feature of the regenerative circuit, the bypass checks can now serve as a training tool for the rider to increase the resistance they experience on their power stroke.

The filling of the regenerative circuit now causes the need to pedal backwards at some points of the rotation cycle. Once a down stroke of a pedal is complete and if fluid was diverted past the check valve of the regenerative circuit, then the cap ends of the cylinders are void of some fluid and back pedaling allows for more to be drawn back in from the reservoir. This creates a highly irregular pedaling pattern, but can be turned off with the flow valve that follows the shuttle valve.

This circuit design also limits the pressure that the regenerative circuit can build. It is limited by the resistance that the wheel cylinders encounter on their retraction. Some factors that go into this include the weight of the rider, incline of the ground, and pedaling speed. The higher the force required to move the bike forward, the higher the pressure can build in the accumulator. For example, less pressure can be generated on level ground than compared to an uphill slope as the force required to move the bike forward is less and thus the wheel cylinder does not experience as high of a pressure on retraction. In testing of the circuit, pressures were built in the accumulator to roughly 1200 psi before leaks began propagating at hose connections.

III. The 2015 Hawk HV Mechanical Design

For the 2014 Parker chainless challenge our design failed due to the mechanical failure of the rear overdrive hub. For the 2015 competition we redesigned the mechanical interworking and attachments of the hub to the bike to avoid failure and increase the long term use of the hub.

Using a Sturmey Archer 8-Speed hub we originally affixed the drive mechanism of the hub and through a makeshift crank arm drove the axle of the hub via the cylinders. This purpose built hub was lightly modified in order to complete its task mechanically but this is why the hub failed. The axle was far too weak to transfer the force to the internal carrier gears. This year we used a completely new mounting system and an adapted axle and crank arms to design the hub.

The dropouts were custom made to attach the hub to the bike frame and secure the planetary gears in a fixed position. This allows us to keep the stationary aspects of the hub secure while we pedal the bike against them. This can be seen in Figure 15. The frame we used last year was modified and formed to fit the redesigned hub with its new width.

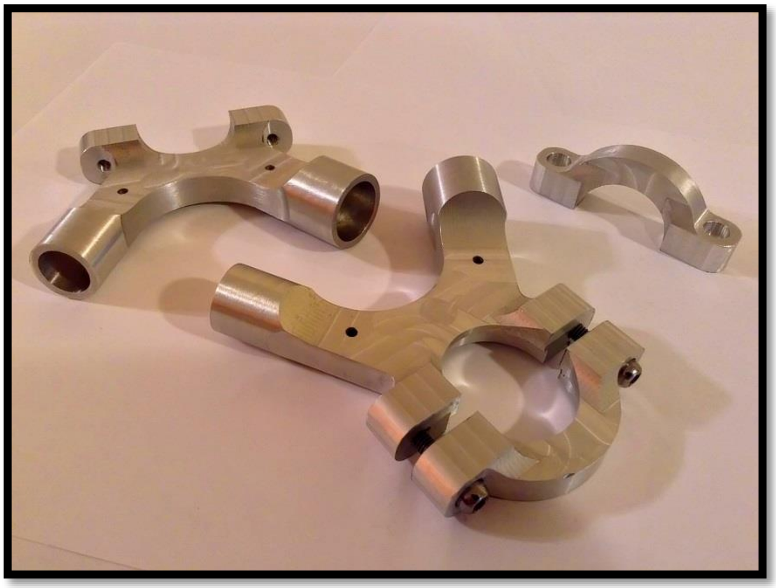


FIGURE 15: REAR DROPOUTS BEFORE BEING WELDED TO THE FRAME.

The original drive sided of the hub was where the original cog of the bike connected to the planetary gears. This used the original ball bearing retainer ring to accommodate a new bearing and tighten over the outside of the designed drive side cog. Using the preexisting holes in the drive gears in the new part allowed us to save cost by not having to redesign the complicated internal gears. The reused parts can be seen in Figure 16.

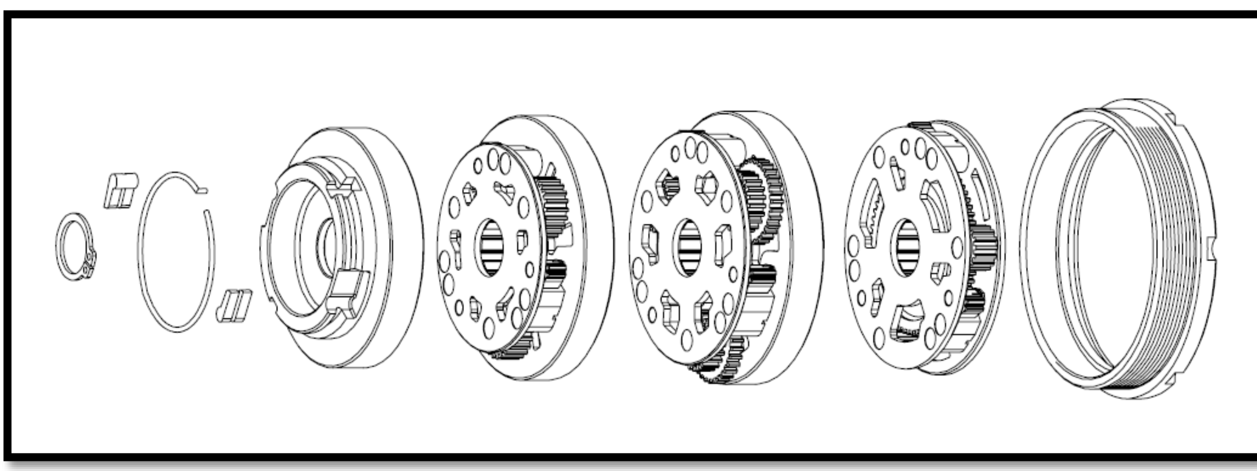


FIGURE 16: REUSED PARTS (PLANETARY/CARRIER GEARS & BALL RING RETAINER)

FIGURE 17: DRIVE SIDE COG

The original axle in the 8-speed hub utilized a system of paddles that incrementally engaged to drive (and let coast) specific combinations of planetary gears and carrier gears. These paddles were small and only had contact in the red locations. This can be seen in Figure. 17

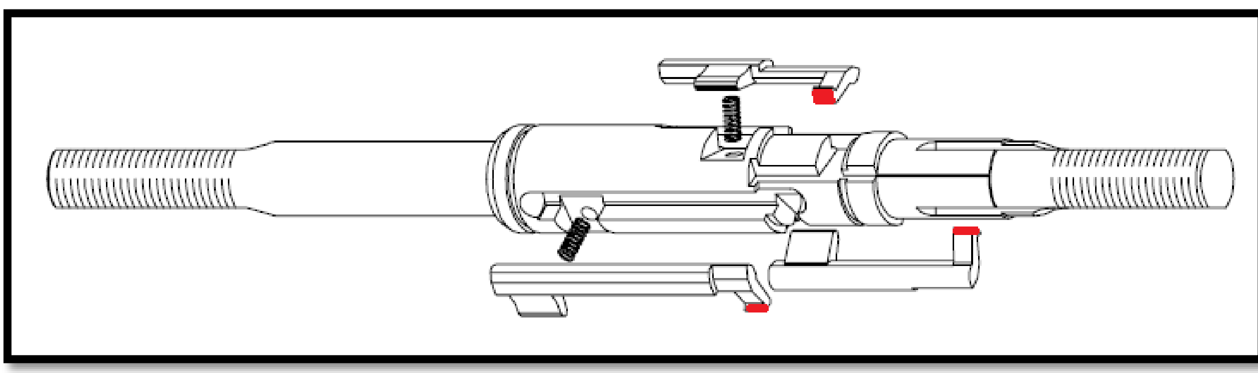


FIGURE 18: ORIGINAL STATIONARY GEARED AXLE

The new axle connects to all the internal gears rather than just one at a time. This helps distribute the load within the gears so we don't have to worry about stripping the axle. It also fits the square fit crank arms to the axle and fits perfectly in between the drive side and non-drive side cog with the help of retainer rings. This can be seen in Figure 18.

FIGURE 19. AXLE AND AXLE CRANK ARMS.

The hub body was repurposed but machined so we could accommodate the opposing non drive side cog. The hub body on the non-drive side was machined for a bearing that allows the axle to rotate on the hub body without hindering the gears and the dropouts. This can be seen in Figure 19.

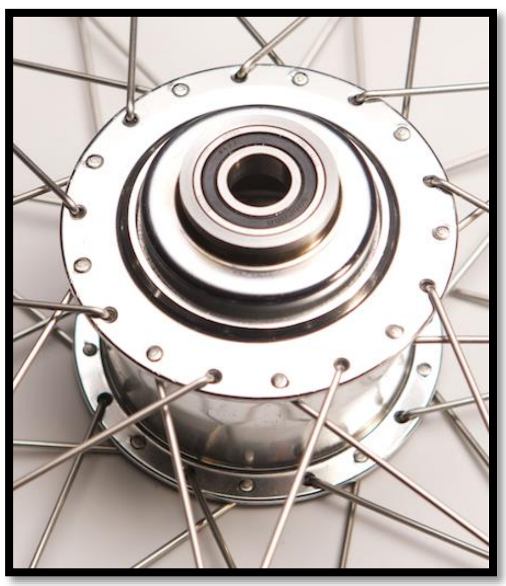


FIGURE 20 – HUB BODY (LACED)

The cylinders of the bike were custom made last year and reused this year along with the crank arms, which can be seen in Figure 21.

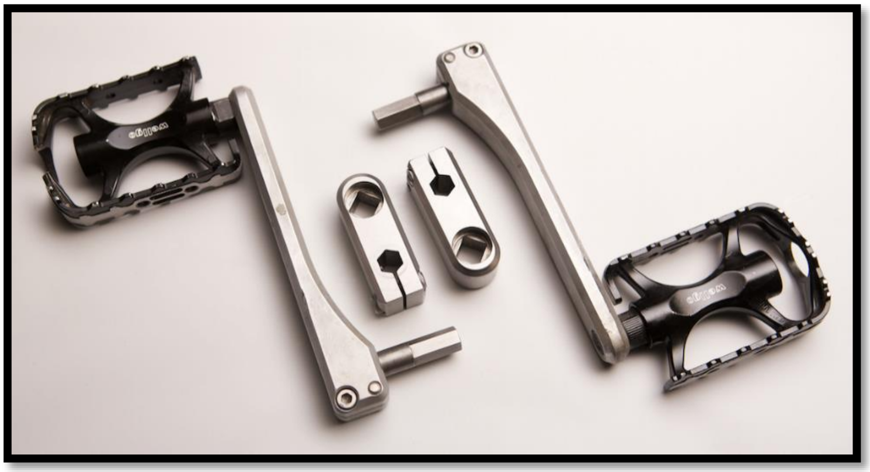


FIGURE 21: CRANK ARMS

The rear cranks however were moved to accommodate the extra fluid circuit. Building new mounts for the cranks so that we had semi adjustability. These mounts can be seen in the figure below

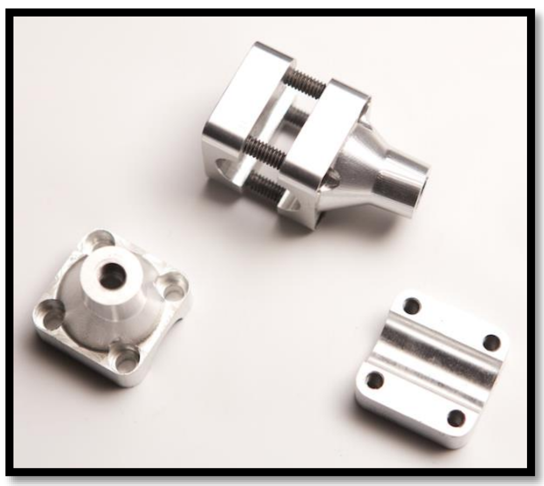


FIGURE 22: REAR CYLINDER MOUNTS

Many other small changes to the frame were made including, the removal of paint, welding small holes, upgrading the cockpit of the bike, and small mounts for other components of the hydraulic systems. Mounting of the motor and the directional control valve required light machining with a focus on the ability to adjust them slightly as their position depended on many other components of the bike. Hose management was key to package and direct the fluid over the bike so that we can pedal and steer the bike. These encompass the total mechanical designs to the bike.

The bicycle utilizes two sets of paired cylinders, cycling fluid back and forth between each other in order to transmit power from the pedals to the rear crankshaft. As the front cylinder extends, the corresponding rear cylinder retracts at an equal rate. Once the front cylinder extends to the end of its effective stroke, it retracts as the rear cylinder extends. The second set of cylinders follow the same motion as the first set of cylinders, but do so with a 90 degree phase shift in the pedal stroke, so that when one set of cylinders is at either end of its stroke, the second set of cylinders is at mid-stroke.

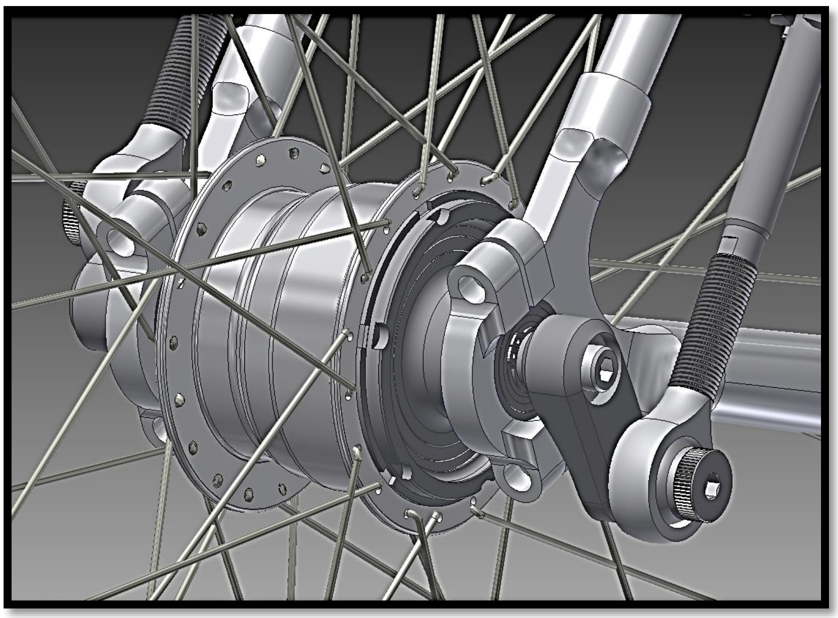


FIGURE 23: REAR OVERDRIVE HUB AND CRANKS

The set of cylinders used in this year's bicycle is very unique. The cylinder design is based off a Parker 3L cylinder series, but modified to decrease weight and friction. The head and cap of the cylinder are modified to accommodate SAE 8 oversized ports. The piston is a custom design that incorporates a bidirectional seal and wear band. The piston seal is a bronze-filled PTFE seal that we had special ordered from Parker's EPS division, and this is the first use of this seal in this bore size to our knowledge. This seal reduced cylinder friction significantly in our testing, and we didn't have any leakage issues. Furthermore, the head, cap, piston, and cylinder body are all machined from aluminum. This allows our cylinders to save over 50% in weight as compared to a standard 3L cylinder.

Hydraulic Stored Energy System:

Another part of the competition is to use a regenerative circuit. We use an integrated circuit to provide an assistive circuit. This is a departure from last year's design where we used a separated circuit. The stored energy density of hydraulics is much greater than that of pneumatics with the use of a hydraulic accumulator. This would allow us to store more energy and propel our bike further using recovered pedaling energy. This is similar to ovalized chainrings on existing bicycles, which use the stronger power stroke of the bike pedal sequence to force a greater gear ratio.

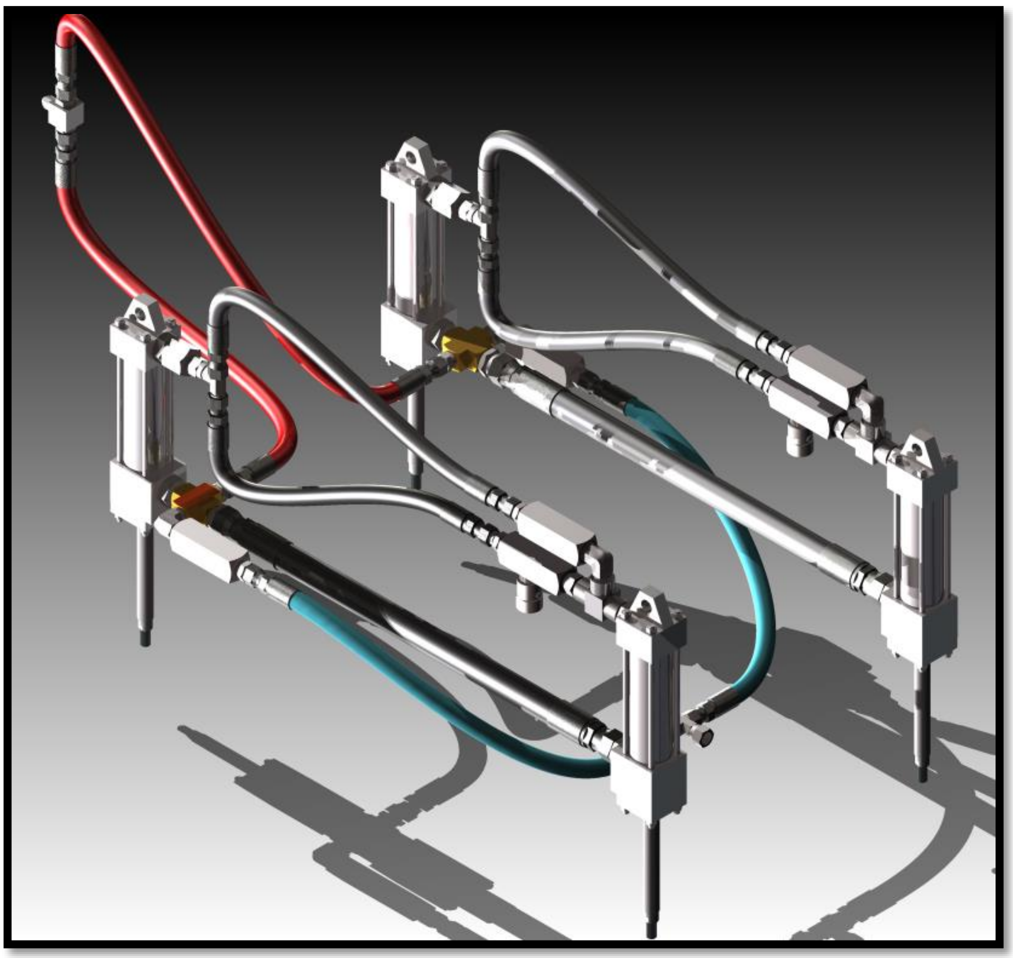


FIGURE 24: CYLINDER CIRCUIT (LOWER SECTION OF THE CIRCUIT)

Due to our inability to shift we needed an overdriven hub so our bike becomes feasible to ride at speed. Modifying a Sturmey Archer 8 speed hub we can achieve this much needed gear ratio.

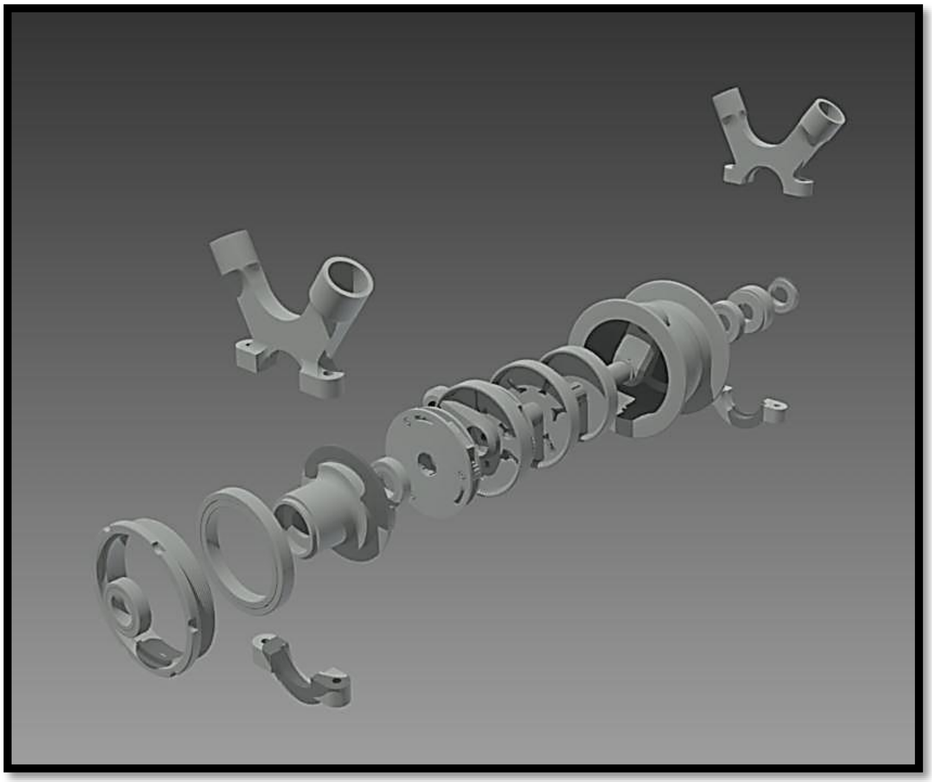


FIGURE 25: INTERNALS OF THE OVERDRIVE HUB

giving us a 5:1 overall ratio. Since we wanted to keep the bike as light as possible, we chose the smallest motor Parker-Hannifin offered, with an aluminum body. We also chose a one pint bladder style accumulator for the stored energy. Since the motor had a very small displacement, we could pair it with a small accumulator which could easily be filled fully during the ten-minute charging period. The final production model of the bike could be paired with any size accumulator. The small size that we chose however provided for an overall 'bicycle' feel to our design because of the light weight.

FIGURE 26: REGEN WHEEL MOUNDED MOTOR

To charge our stored energy circuit, we simply ride the bike normally and adjust the amount of pressure we accumulate using a control valve mounted on the top tube of bike. The integrated system provides us with an easy method of charging the accumulator. Since the accumulator is only one pint we are able to charge it to 2500 psi in a few minutes. We do not charge the accumulator to the maximum 3000 psi due to the pressure rating due to the limit of the hoses.

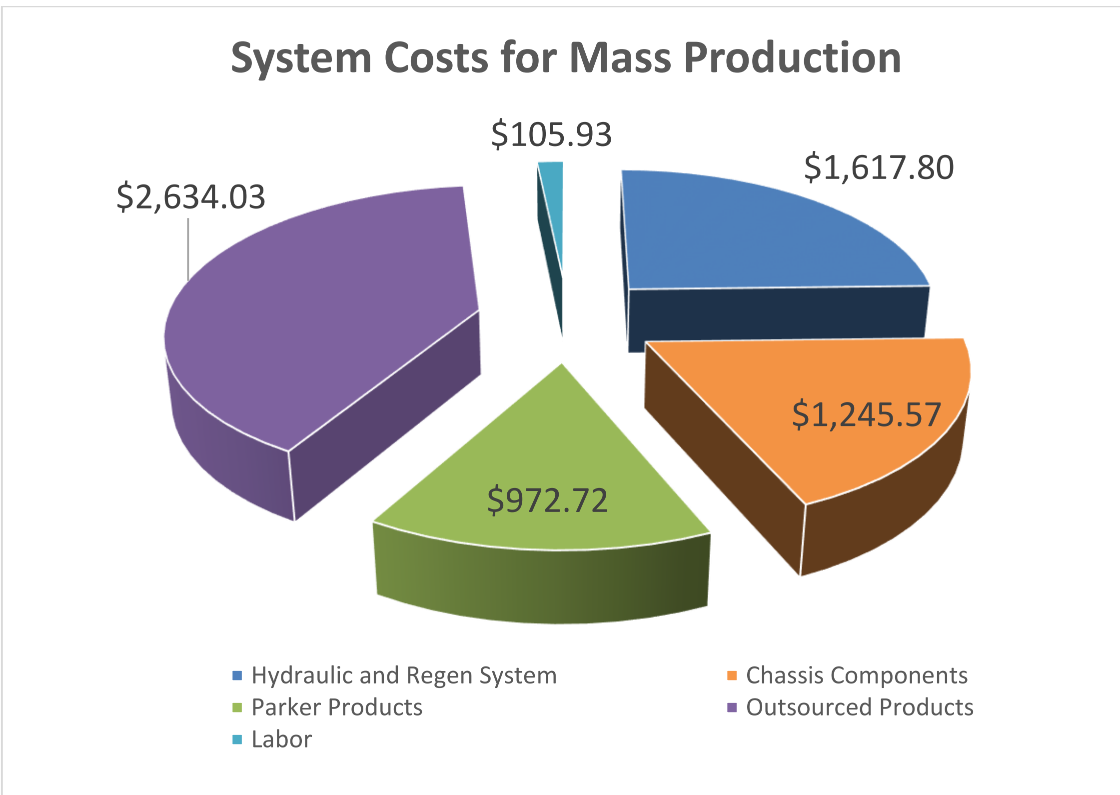
A small tensioning bar keeps the motor wheel in contact with the bicycle wheel, and since the wheel gets pulled laterally (similar to a wheel powered light) there is very little force required to keep the wheel in contact with the bike. A simple pressure release leaver mounted on the top tube of the bike allows the rider to operate the regenerative circuit all while remaining in a stable riding position. In order to discharge the accumulator the rider needs to push the toggle leaver forward so that the accumulator releases into the motor.

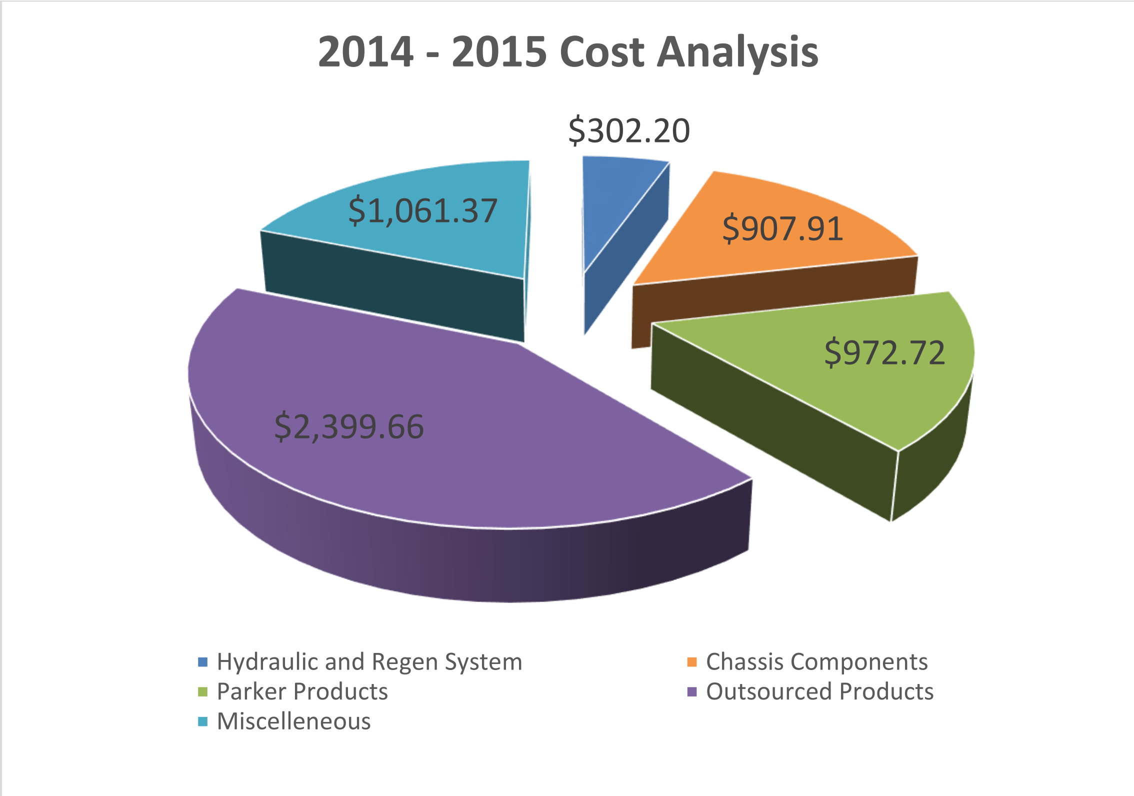
6.0 COMPONENT LIST

Item	Model #	Quantity
Metric Steel Ball Bearing, Double Sealed Bearing No. 6002 for 15mm Shaft Diameter	*	1
Metric Steel Ball Bearing, Double Sealed Bearing No. 6802 for 15mm Shaft Diameter	*	4
Ultra-Thin Multi-Load Steel Ball Bearing for 2" Shaft Diameter, 2-5/8" OD, 5/16" Width	*	1
Stainless Steel External Retaining Ring for 15mm Shaft Diameter, packs of 5	*	1
Premium Grinding Bit for Steel & Alloy Steel, .256" Diameter x .28" Head Length, 1/4" Shank	*	3
Very High-Strength 7050 Aluminum, 1/2" Thick, 6" Long x 6" Wide	*	1
Medium-Pressure Brass Threaded Pipe Fitting, 1/4 Pipe Size, Cross	50785K233	1
Medium Pressure Brass Hex Nipple, 1/4 Pipe Size	5485K22	8
Medium-Pressure Brass Threaded Pipe Fitting, 1/2 Female x 1/4 Male Pipe Size, Adapter	50785K614	2
Medium Pressure Brass Hex Nipple, 1/2 Pipe Size	5485K24	2
Medium Pressure Brass Hex Nipple, 3/4 x 1/2 Pipe Size, Hex Reducing Nipple	5485K34	2
Liquid-Filled Gauge, Plastic Case, 2-1/2" Dial, 1/4 Bottom, 300 PSI	3845K1	2
General Purpose Lever-Handle Blowgun without Hose, 150 PSI Maximum Inlet Pressure	*	1
General Purpose Lever-Handle Blowgun without Hose, 150 PSI Maximum Inlet Pressure	*	1
Multipurpose 6061 Aluminum, 2" Thick x 3" Width x 1' Length	*	4
DT Swiss Comp. 2.0/1.8 Spokes - Silver Silver, 274mm, Box/100 With Brass Nipple	*	1
DT Swiss Comp. 2.0/1.8 Spokes - Silver Silver, 266mm, Box/100 With Brass Nipple	*	2
Park Tool PFP-7 Professional Floor Pump	*	1
Park Tool MG-2 Nitrile Gloves (Medium)	*	1
VENZO Bicycle Bike Torque Wrench Allen Key Tool Socket Set Kit	*	1
Park PPL-1 Polylibe 1000 4.4 OZ.	4.4 oz	1
Shimano UN55 Bottom Bracket	68X107MM	1
Multipurpose O-Ring, Oil-Resistant Buna-N, 1.6mm Wide, 10.1mm ID	9262K143	1
Klean Kanteen Stainless-Steel Wide-Mouth Water Bottle with Loop-Top Cap - 27 fl. oz.	Stainless Steel	1
Rock N Roll Gold Lube	16oz	1
Park Tool Shop Hammer - HMR-4	*	1
Sturmey Archer HTR146 8-speed ball ring spanner, S80(W)	*	1
2 in. x 4 in. x 96 in. Premium Kiln-Dried Whitewood Stud	*	24
1/2 4 ft. x 8 ft. Orientated Strand Board	*	8
TRP ML930 Linear Pull Brake Levers ML930 LP Brake Levers BLK	*	1
Truvativ Stylo T30 Riserbar Blast Black, 700mm, 30mm Rise	700mm, 30mm	1
Lizard Skins Bearclaw Lock On Grips	White	1
Ultra Club Tonal Stripe Performance Polo	(2xS)(3xM)(1xL)	1
Chasing Fluid Power (Parker) - Hoses	*	1
Hydraulic Motor, Axial Piston, Fixed Displacement	F11-005-HU-CV-K	1
Hydraulic Valve, Cartridge Relief	RD102S30	1
Hydraulic Valve, Threaded Cartridge Body	B10-2-A4P	1
Triple-Lok® 37° Flare -4 JIC Tube to 1/4" NPT	4-4 FTX-S ZJ	14
Valve Block	SPD24S35	1
check valve	C400S	5
flow control valve	F400S	2
SAE -8 Nut	8 BTX-S	2
Tube End Reducer (-8 to -4)	8 4T RTX-S	2
SAE -4 Tube End Tee/ 2male 1 female	4 S6X-S	2
Directional FlowValve	D1VL008KN	1

7.0 COST ANALYSIS

Cost Summary	
Hydraulic and Regen System	$ 1,617.80
Chassis Components	$ 1,245.57
Parker Products	$ 972.72
Outsourced Products	$ 2,634.03
Labor	$ 105.93
Total Vehicle	$ 6,470.12





8.0 LESSONS LEARNED

We were able to address most of the shortcomings of our design compared to last year's bicycle. The system was redesigned to be much more robust as well as eliminating the need for a separated circuit. Even with the transition to a hydraulic stored energy system, the final weight came in at less than our previous bicycle due to the elimination of the rear bulkhead. In testing, we were able to complete multiple laps around campus in our hydraulic bicycle without any issues; proving the reliability of the rear hub. Although the competition is likely to be much tougher this year than last year, we are confident in our bike's abilities to conquer the competition in this year's events.

9.0 CONCLUSIONS

10.1 Industry Experience

The Parker-Hannifin Chainless Challenge provides students with a unique opportunity to interact with industry leading engineers, along with attempting to solve real world problems and improve upon the age old design of the common bicycle. In this competition, we learned how to set goals for our bicycle before starting the design. This became key for determining the importance of the challenges we had to overcome. We learned how to interact with one another, and utilize each other's strengths to engineer the best design that we could come up with. Learning the importance of a bill of materials, and how to conscientiously manage our funds and not frivolously spend money.

Interacting with school staff and professors to receive input on the problems we were facing allowed us to become experts at using online supply websites to purchase our materials and find the cheapest option. Working closely with machine shop specialists we developed an understanding on how to produce parts from raw materials. Most importantly, we learned how to see a project through from start to finish. These skills will all come in handy to us once we have graduated from school and work in the industry.

10.2 Outside of the Classroom Learning

This project involved many different engineering disciplines. We had to learn about hydraulic power and stored energy circuits and how to effectively utilize them. It provided us with an application based learning style, which allowed us to learn with our hands but also use the math and theory behind these power circuits to create a functioning product. This project also relied heavily on the solid modeling program, Autodesk's Inventor.

Each of the team members became well versed with this program to help design the bicycle. It allowed us to piece together the bike using custom parts we designed while providing us with part drawings which we could use to have them produced.

Overall, this competition taught us many new skills which we would not have learned from classroom instruction. It provided challenges which allowed us to push ourselves and develop methods for overcoming problems we encountered. We were able to apply much of what we learned in the classroom. This challenge took many of us out of our comfort zones and gave us a unique learning opportunity.