Murray State University
Parker 2016/2017 Chainless Challenge Project Report

A New Era

Murray State University
Electromechanical Engineering
Technology
Department IET IT 263
Technology Center

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1.0 ABSTRACT

Murray State University Students in the Spring 2017 Electromechanical Engineering Technology Senior Design class designed and built a chainless bike that is driven by hydraulic pressure. The bicycle was created in accordance with the 2016-2017 National Fluid Power Association's Fluid Power Vehicle Challenge's rules and regulations. The Murray State University Chainless Fluid Power Bike is a three-wheel recumbent bicycle that utilizes a rear internal gear hub, rear gear ratio, front gear ratio, and pump/motor volumetric displacement for a mechanical advantage.

Murray State University Electromechanical Engineering Technology students have competed in the Chainless Bike Challenge since its inception in 2006 when it was sponsored by Parker Hannifin Cooperation. The Murray State bicycles have evolved over the years, and the teams have accomplished better outcomes as the years progressed. In 2014 the Murray State team won first place overall with a completely custom recumbent bike that had a total weight of over 300 lbs. The bike had a motorcycle transmission for a gear box that was designed for input horsepower of 50 HP, and the transmission weighed 50lbs. Although the team won first overall, they scored very low on manufacturability as most of the components were customized and over engineered.

The Electromechanical Engineering Technology students decided to focus heavily on manufacturability and designed the bike to use mostly pre-manufactured components for the 2017 Fluid Power Vehicle Challenge. The students also decided to utilize the 2006 recumbent bike frame that was used for the university at the first Chainless Bike Challenge. Some of the most recent bike components were customized using Computer Numerically Controlled Machinery and 3-D Printers, but the components were minimal to the overall design.

The team decided to utilize the recumbent bicycle because of its low center to gravity and stability. One disadvantage of the recumbent bicycle is the large turning radius. The Murray State students created an improved turning system so that the recumbent bike will meet the requirements of the Fluid Power Vehicle Challenge races. The pedals for the bike are directly connected to a hydraulic pump that provides pressure to the system. There are two level actuated piston pumps that allows the students to provide the initial charge for the system. The bicycle utilizes the fluid power system by storing a charge in a bladder reservoir for on demand responses. The final control element for the bicycle is a hydraulic motor that is coupled to the back drive wheel by two gears. Although there is a significant amount of energy loss in the chainless bicycle, the bicycle is fully operational and does not include a chain or belt in its design.

2.0 THE PROBLEM STATEMENT

The Statement of Need (SON) for the Fluid Power Vehicle Challenge is to design and build a bicycle that is propelled by a fluid power system instead of a chain in order to meet the following objectives listed on the National Fluid Power Association's (NFPA) website (NFPA. Nd):

1. Stimulate education in practical hydraulics, pneumatics, and sustainable energy devices for motion control.
2. Provide students with experience in real world engineering under a strict timeline of designing, simulating, ordering, building, testing and demonstrating their designs.
3. Stimulate innovative thinking for designing and testing potential new technologies or concepts integrated into a vehicle platform.
4. Provide an industry recruitment opportunity for high potential engineering seniors by engaging directly with practitioners in the field.

The bike is one of the simplest and most efficient sustainable modes of transportation available. The US Census Bureau surveys the number of citizens that use a bicycle as their primary mode of transportation to work. The survey is called "Journey to Work" and is a part of its yearly American Community Survey. In 2013 the survey identified an increase in American citizens who commute to work on a bike from under .5% 5o just under 2.5% (McKenzie, 2014). A similar study conducted by the Bicycle Coalition of Greater Philadelphia identified an increase of bike usage in Philadelphia of 260% between the years 2005-2013 (Philadelphia, 2014). The studies prove that there has been an overwhelming increase in bicycle usage in recent history. The problem, simply stated, was to make a green powered vehicle using a bike without using a chain, hence the name of the competition, "Fluid Power Challenge". Specifically, the statement of needs dictates that the team needs to find a way of creating a bike that uses a hydraulic (or pneumatic) system at the maximum efficiency possible while incorporating features such as a regenerative braking that stores power otherwise lost to traditional friction braking.

One advantage of using fluid power to drive the fluid powered vehicle is the ability to store energy in the system. This is something that cannot be done by any traditional bike. With the ability to capture energy when demand is low, such as on a downhill slope, it is possible to build a reserve that can be used later when demand is higher, such as an uphill slope and thus smooth workload throughout the duration of the ride. In addition, the bicycle can be charged with piston pumps, that are connected parallel to the drive pump, so the bike can be pressurized when it is in a stationary position.

The second advantage to using the hydraulic drive system is the numerous design options. A chain driven bike is by no means limited to the typical design seen in mass produced bikes; however, the additional components required for a hydraulic bike give the designers an enormous opportunity to be creative and develop a bike that will be unique. By means of the hydraulic system, the team was able to create a bike that is extremely low center of gravity and stable at high speeds, which would be extremely difficult to achieve if a direct path for the chain to the rear wheel was needed. Moreover, utilizing a Shimano internal gear hub allowed the Murray State bike to achieve higher speeds.

Typically, hydraulic systems have high power densities. In theory, the HP to weight ratio is high which would result in less weight than many of the other options available. However, because the components of the Murray State bike are meant for industrial applications, this advantage will become one of the bikes' greatest disadvantages. In 2014 the Murray State University bike was over-engineered in many areas causing excessive weight. Through research and testing the team created a completely new bicycle for the 2017 NFPA Fluid Power Vehicle Challenge, utilizing the recumbent bike frame the university used in 2006. The result is a much lighter bike that is more efficient.

The main challenge of this competition was to create a hydraulic bike that is as close to the efficiency of a typical chain driven bike as possible. Three disadvantages: high weight, high complexity, and high cost are all derivatives of low efficiency. Low efficiency is the biggest disadvantage of using fluid power as a driving force for the bike. The industrial components the team used for the hydraulic system make the bike very complex and very heavy by comparison to a chain driven system. In the case of hydraulics, the higher complexity results in a less efficient system due to line losses and higher k-factors. Furthermore, weight is a key to the efficiency in a bike's design; however, industrial grade hydraulics further hinders efficiency due to their high weight.
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Next, the high complexity of the bike will mean that the cost of this bike will far exceed that of a typical bike. Additionally, high efficiency parts are much more expensive than their mass produced counterparts. The biggest challenge for the team was having the budget to replace the heaviest parts while maintaining performance.

Lastly, and most importantly, the design of the bike must be competitive in each of the three competitions. The beginning of the design and the end testing was all done to ensure that the bike was made to meet the statements of need.

3.0 PROJECT PLAN/OBJECTIVES

Design objectives were defined for each individual on the team based on their expertise and interest. Many of the task needed to complete the bike were already completed by previous teams. For example, the 2014 Murray State team built the test fixture to test components and gathered performance data on all components in stock at the university. The performance data was then used to determine the parts we should utilize on the bike. The Input System, Drive System, Storage System and Control System groups where all able to use the test fixture to test and improve their designs simultaneously (i.e. Concurrent Engineering).

The overall objectives were as follows:

- Identify components of the bike that could have a reduction in weight
- Test each key system component.
- Do an analysis of each key system components.
- Test all key system components together for full Drive Train performance.
- Component selection process.
- Begin procurement of components.
- Validate performance of components on delivery.
- Vehicle fabrication and assembly.
- Vehicle startup and test.
- System and vehicle optimization.

The team started their project with the problem that has already been outlined. Since weight reduction was a big concern it took priority in design choices. The other major change from previous years was the course which needed to be reanalyzed. Unfortunately, this was not done until late in the process due to the fact that there was a lengthy period of time when that information had not been released.

Next the team looked at the hydraulic parts that were available from the new supplier, Eaton, and ordered parts that may be an improvement over what was available from previous years. Much of the calculations that were done in previous years were not done this year. Instead the team did some calculations and left room for adjustment. While this was never explicitly "planned" it was to the team's advantage.

While the hydraulic circuit and mechanical gearing was certainly a concern, much of this had already been proven in previous years. As already stated the major concern was weight which drove the team to using a lightweight aluminum frame that hadn't been used since 2006. Many of the mounts either never worked or were missing all together. The team had planned to put a great deal of time into using a proven concept and adapting it to a lighter frame using lighter components. This would involve designing new places to put components and designing and machining new parts to mount them. After all parts have been designed/manufactured/assembled there was a test assembly made to determine viability and the accuracy of the team's calculations. Small alterations were made and a prototype was assembled.

4.0 DESIGN ANALYSIS

4.1 Analyze Course and Rider

4.1.1 Analyze the Available Power:

This analysis is that of available power to drive the bicycle. Input power will be in the form of human power transferred to the system via pedals. While the accumulator present within our system will be able to provide a burst of power, it is not sustainable for a length of time necessary to provide any meaningful transport and, therefore, is not included in the input power calculations.

Research, past experience, and testing at the local gym showed that the average person can provide one-half horsepower continuously when pedaling a bike. Since horsepower is a product of torque and angular velocity (RPM) (Eq. 2) it is possible that a rider could produce the same one-half horsepower under a wide ranges of circumstances. (Figure 2) provides some examples of how a human can input that power as a function of torque and angular velocity.

Previous teams determined that a rider can't maintain over 90 rpm; 60 rpm is optimal and anything below 25 rpm is too strenuous with torque exceeding 1260in-lb. An angular velocity of 60 rpm will result in 525 in-lb. of torque at .5 horsepower. 525 in-lb. of torque will result in the rider exerting 58.3 pounds on a 9-inch crank lever (Eq. 1). Our team tested these conclusions and concurred with the results.

In conclusion, the team determined that the bike needed to never require the rider to exceed 90 rpm or 1260 in-lb. in order to maintain one half horsepower of input. The next step is to calculate the required torque by examining the course.

Human Energy Input Characteristics

- 1260IN*LB @ 25RPM
- 525IN*LB @ 60RPM
- 315IN*LB @ 100RPM
- 210IN*LB @ 150RPM

Figure 1: Pedal Force Diagram

Equation 1: Pedal Force

$$\text{Force on the Pedals} = \frac{\text{Torque}}{\text{Crank Length}}$$

Equation 2: Horse Power

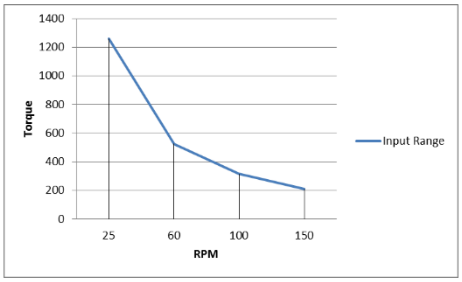


Figure 2: Human Input Graph

4.1.2 Analyze the Required Power:

The next variable needed was the maximum required torque. The number can be found using the maximum grade. To get this we used the path tool in google earth to generate an elevation chart. The maximum grade was 62.1% according to Google's tool, but this is inaccurate because the elevations were calculated before construction was complete on the test area. We instead took a grade of 3% as our maximum. (Table 1)

Equation 3: Percent Grade Definition

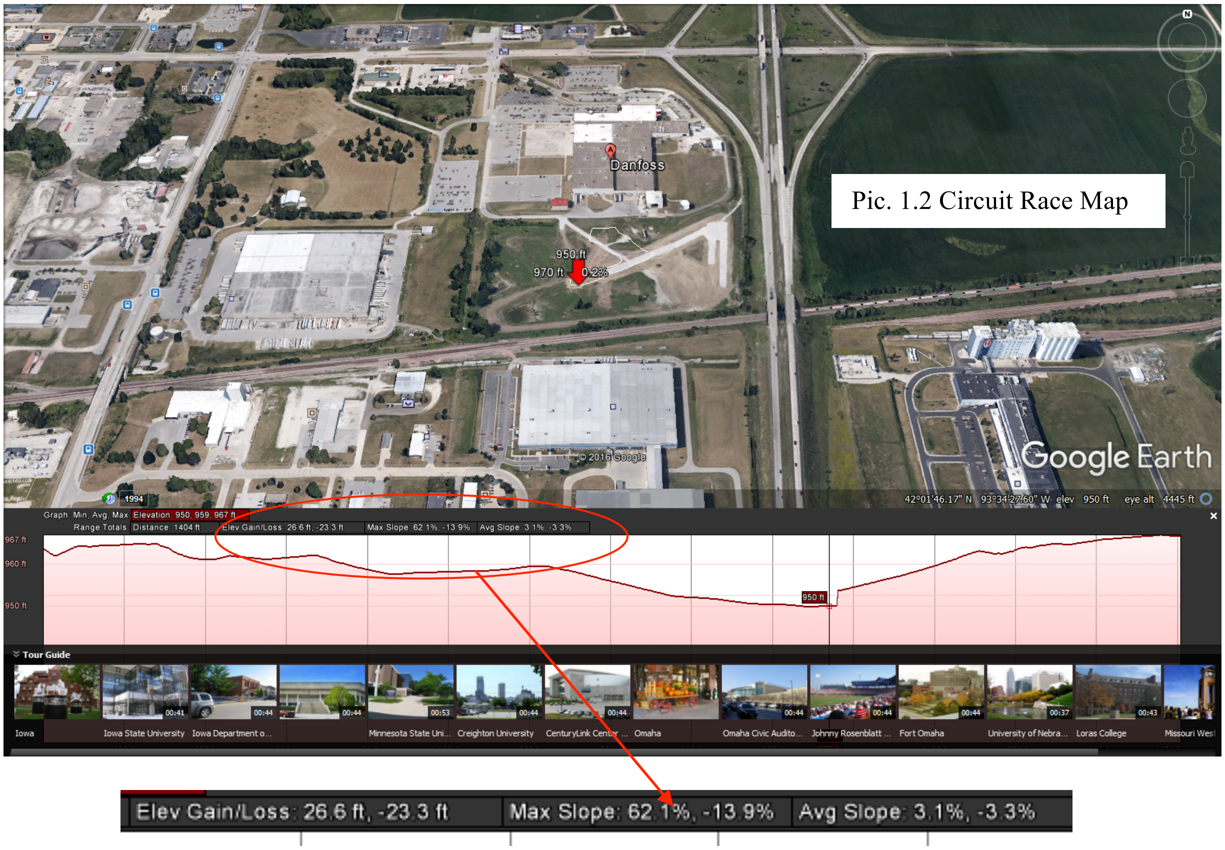
$$1\%Grade = (1ft\ Rise)/100ft$$

Figure 3: Course Analysis

$$HP = \frac{torque * rpm}{63{,}025}$$

Course Analysis

Table 1: Course Analysis



Pic. 1.2 Circuit Race Map

Graph: Min, Avg, Max Elevation: 950, 959, 967 ft
Range Totals: Distance: 1404 ft Elev Gain/Loss: 26.6 ft, -23.3 ft Max Slope: 62.1%, -13.9% Avg Slope: 3.1%, -3.3%

Elev Gain/Loss: 26.6 ft, -23.3 ft | Max Slope: 62.1%, -13.9% | Avg Slope: 3.1%, -3.3%

In order to calculate required torque there is another force that must be taken into consideration, friction. Friction does not account for as much energy loss as the hydraulic inefficiencies, however it must be considered. Testing found that friction for the system should be somewhere around 7lb. force. A 3 lb. "fudge factor" was then added to the 7 lb. friction force in order to account for other inefficiencies which are hard to determine such as mechanical gearing inefficiencies and wind resistance. This gave us a total friction force of 10 lb.

Motive force is simply the force needed for an object in motion or at rest to neither accelerate nor decelerate. In a downhill model the power from the rider and gravity combined are the motive force and friction is the only opposing force. In an uphill model power from the rider is the only motive force and gravity and friction combined are the opposing force.

Using the formula for motive force the team was able to calculate the motive force at the steepest grade. With an assumed total weight of the bike and rider at 300lb and the estimated 10 lb. friction force the motive force will need to be 19 lb. Later this paper will look at how the team used this motive force to determine gearing ratios.

Equation 4: Motive Force

$$\left(\left(\sin\left(\tan^{-1}\left(\frac{grade}{100}\right)\right)\right) * \text{Weight bike}\right) + \text{Friction}$$

4.2 Analyze Hydraulic Components' Characteristics

4.2.1 Create a Way to Test Hydraulic Components

To get performance curve data the team used a test bench setup that has been used in years past with success. To simulate the rider a three phase one horsepower electric motor was used with a variable frequency drive A tachometer and power input in watts were feed into a programmable logic controller (PLC). Torque and angular velocity were then calibrated to simulate a rider. See section 4.1.1 for information about the rider.

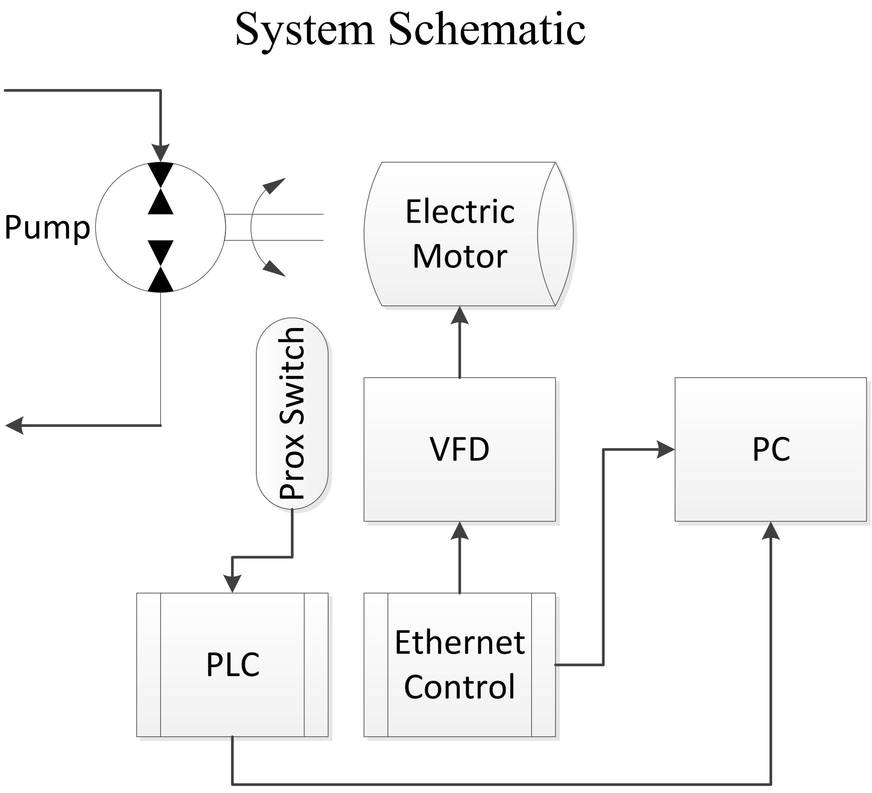


Figure 4: System Schematic

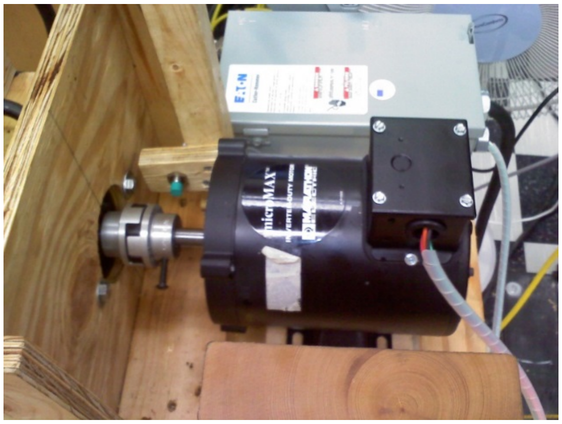


Figure 6: Motor with Improvised Tachometer Meter

Figure 5: VFD for Motor Control

To simulate the load on the motor a Prony break was used. The Prony break used a load cell to measure the load torque applied to the motor and another tachometer to measure the motor angular velocity. These readings were then used to calculate the system output power.

Using the system input and output characteristics the overall efficiency of each combination of parts could be calculated. By adding a flow gage and a pressure sensor to the system the individual efficiencies of the pump and motor could be calculated.

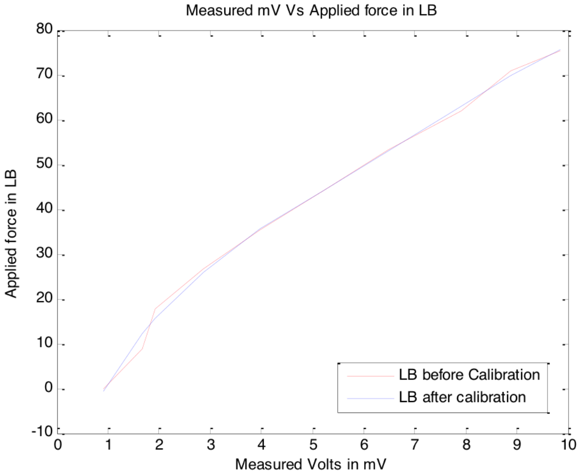


Figure 8: Load Cell Calibration with Polyfit in MatLab

Figure 7: Prony Break with Load Cell

4.2.2 Test All Components Available

Six system measurements were taken at each data point for each combination. Those data points were HP in, rpm in, torque out, rpm out, pressure, and flow. HP out, torque in, and system efficiency were all calculated from these 6 data points resulting in an ideal statistical view of the system.

The following data tables were developed for each of the pump/motor combinations available. Much of this test data was created by previous teams and verified by our team. Our results confirmed that there were only two viable pump motor combinations, the Marzachi Eaton (Table 2) and a pair of Marzachi (Table 3) serving as both the pump and the motor.

We fully anticipated testing a new Eaton – Eaton setup that had similar displacements to our original motors to see if efficiencies were any better, however by the time we received our single Eaton motor we did not have time to get any results from these test.

Figure 9: The Team at Work on the Test Assembly

Marzachi Pump with Eaton Motor

Table 2: Marzachi Pump with Eaton Motor

P in (w)	P in (HP)	T in (in*lb)	RPM in	RPM out	T out (in*lb)	PSI	GPM	P out (HP)	System Efficiency
120	0.16	20.69	490	182	6	65	2	0.017	0.107
140	0.187	24.24	488	182	12	77	2	0.034	0.184
150	0.201	26.19	484	180	18	80	2	0.051	0.255
150	0.201	26.3	482	180	24	80	2	0.068	0.34
170	0.227	28.62	502	186	30	89	2	0.088	0.388
180	0.241	30.42	500	186	36	98	2	0.106	0.44
180	0.241	30.54	498	184	42	102	2	0.122	0.507
190	0.254	32.37	496	184	48	107	2	0.14	0.549
200	0.268	34.35	492	182	54	112	2	0.155	0.581
260	0.348	41.77	526	194	60	142	2	0.184	0.529
								Average Eff.=	**0.388**

Marzachi Pump with Marzachi Motor

Table 3: Marzachi Pump with Marzachi Motor

P in (w)	P in (HP)	T in (in*lb)	RPM in	RPM out	T out (in*lb)	PSI	GPM	P out (HP)	System Efficiency
120	0.16	21.76	466	450	6	60	2	0.042	0.266
160	0.214	25.04	540	470	12	81	2	0.089	0.417
190	0.254	31.86	504	464	18	105	2	0.132	0.52
210	0.281	35.78	496	442	24	118	2	0.168	0.597
220	0.295	37.79	492	434	30	128	2	0.206	0.7
240	0.321	41.73	486	414	36	140	2	0.236	0.734
260	0.348	45.59	482	416	42	154	2	0.277	0.795
290	0.388	52.14	470	390	48	169	2	0.297	0.763
430	0.576	75.39	482	352	54	219	2	0.301	0.523
500	0.67	79.43	532	354	60	249	2	0.337	0.502
								Average Eff.=	**0.582**

Equation 5: Torque through Gear Ratio

$$Output\ Torque = \frac{Diameter\ of\ Second\ Gear}{Diameter\ of\ First\ Gear} * Input\ Torque$$

4.3 Analyze Gear Ratio

Equation 6: Gear Ratio RPM

$$Gear\ Ratio = \frac{Desired\ RPM}{Input\ RPM}$$

4.3.1 Front Gear Ratio

The first gear ratio we selected was the front gearing ratio. This ratio is used to give an ideal flow. Based on our test the ideal pump RPM is 480 which would produce a flow of 2 GPM. Refer back to 4.1.1 our ideal pedal angular velocity is 60 RPM. Using Equation 10 this would mean our ideal gear ratio would be 8:1. However we could not physically use this gear ratio due to size constraints.

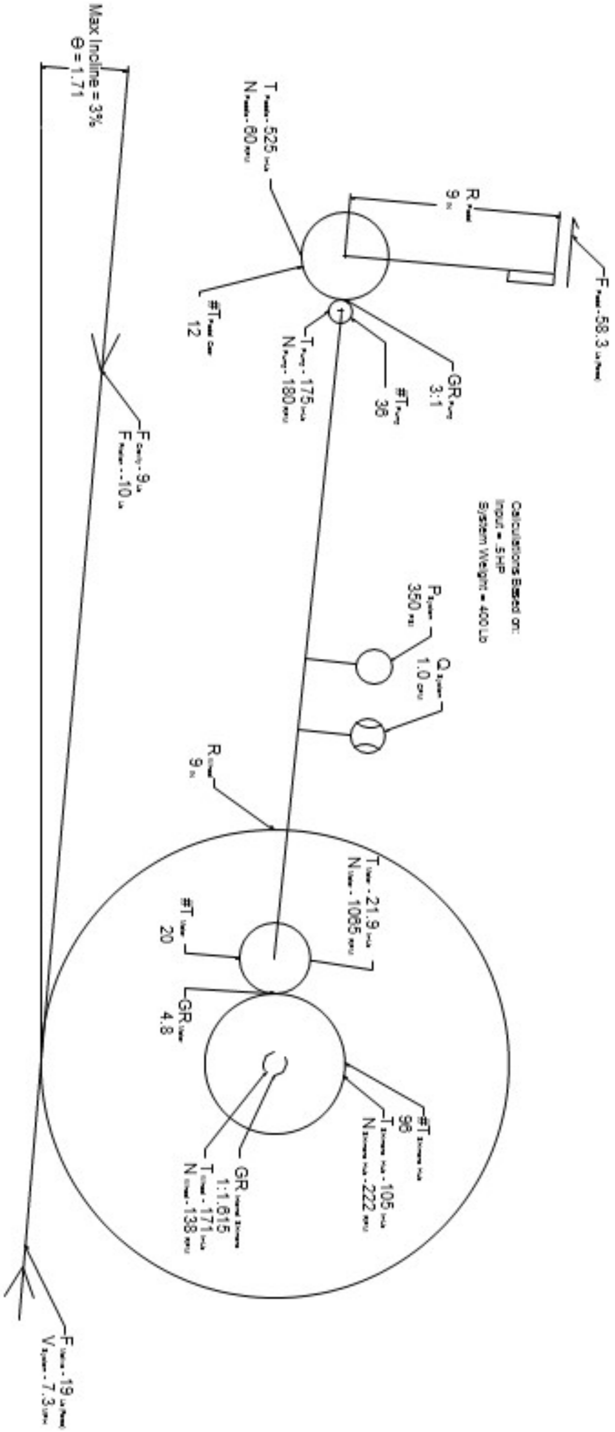
We settled on 3:1 which was using the largest drive gear we had on hand. We also anticipated putting an Eaton motor we ordered in place of the Marzachi that we had on hand. The Eaton motor has a smaller displacement than the Marzachi motor and would therefore require less flow to get a similar rpm. With a 3:1 ratio our pump angular velocity will be 180 RPM and our pump torque will be 175 in-lb.

4.3.2 Back Gear Ratio

Refer back to 4.1.2, our calculated motive force is 19 lb. on the steepest incline. We calculate based on the steepest incline to insure our bike will be able to navigate the course without resorting to pushing. 19lb of force with an 18 inch wheel will require 171 in-lb. of torque. There is a Shimano planetary gear hub that is being used change gear and has a maximum gear ratio of 1:1.615. Using Equation 9 this will require 105.88 in-lb. of torque on the hub.

Ideally at this point we could calculate the torque and angular velocity of the motor using data collected in 4.2.2 however because we have no data on the Eaton motor paired with a Marzachi pump we used the back gear ratio as a “fudge factor”. We ended up with a 4.8:1 gear ratio.

4.3.3 Forces Illustrated



5.0 DESIGN DRAWINGS

5.1.1 Create a Hydraulic Schematic

The hydraulic circuit was designed to be as simple as possible. While a closed loop “hydrostatic” system was explored and may have been slightly simpler by reducing the size of the reservoir, there wasn’t enough data to determine viability. This circuit does not have any regenerative circuit, however it does have all of the components necessary to complete every other function and compete in all three races.

Full Circuit

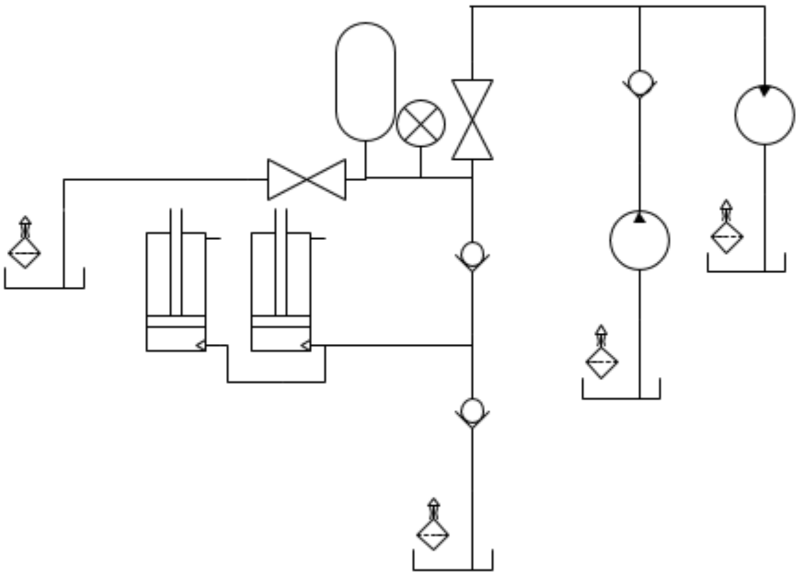


Figure 10: Full Circuit

The circuit includes sections to pre-charge the accumulator to a maximum of 3000 psi using “hand pumps”. There is a circuit for using the pump to power the motor during normal operation. There is a circuit for using the accumulator to power the motor during drag racing or during certain sections of the lap race. There is also a safety circuit for dumping pressure back to reservoir from the accumulator.

High Press Pre-Charger

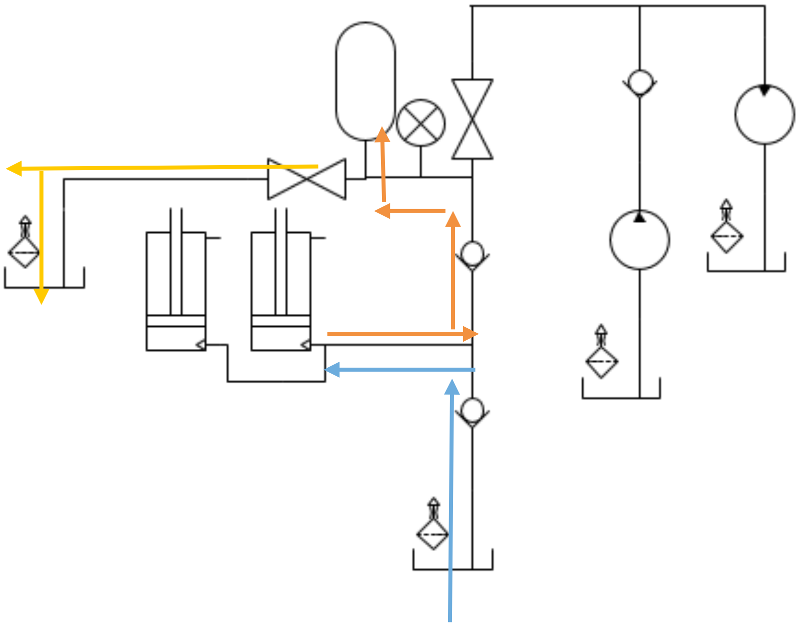


Figure 11: High Press Pre-Charger

The high pressure accumulator is primarily in the circuit for use in the drag and efficiency races, but it can also be used as a booster in the circuit race. The accumulator is pressurized via the high pressure pre charge circuit. The blue arrows show the flow of fluid during the intake stroke of the hand pump and the orange arrows show the flow of fluid during the power stroke of the hand pump. Pressure from the accumulator can be released via a ball valve in the event the user needs to depressurize the system without allowing the flow to go through the motor. That circuit is shown in yellow. Note that the check valves seen in the circuit are actually integrated into the hand pumps.

Drag-Efficiency Race System

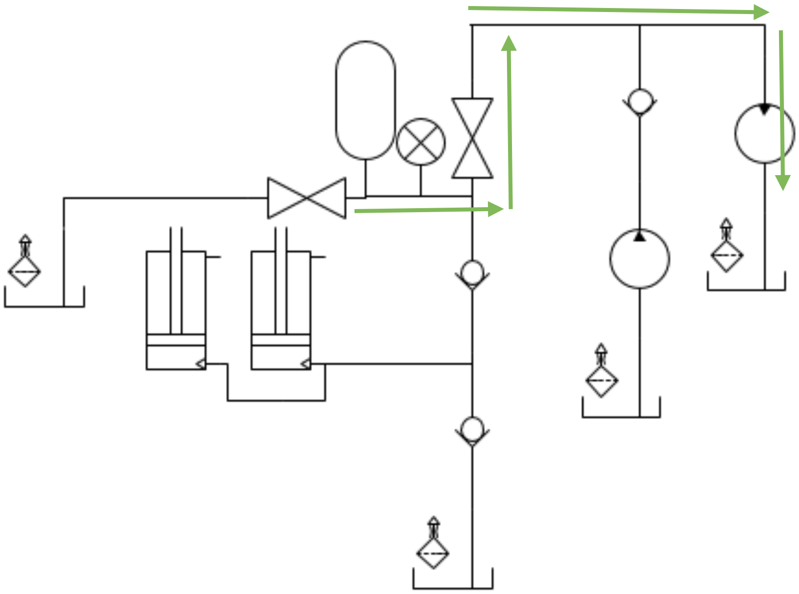


Figure 12: Drag-Efficiency Race System

The drag race / efficiency race circuit (shown in green) is controlled via a ball valve. This was intended to be controlled via a proportional control valve, however due to a lack of time in getting the control circuit complete this was omitted. The pump is protected from the high pressures via an external check valve.

Circuit Race System

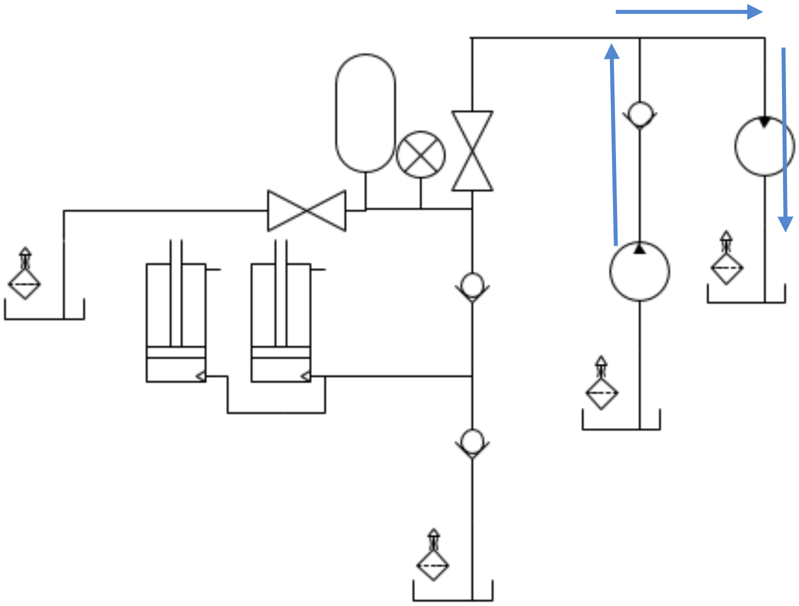


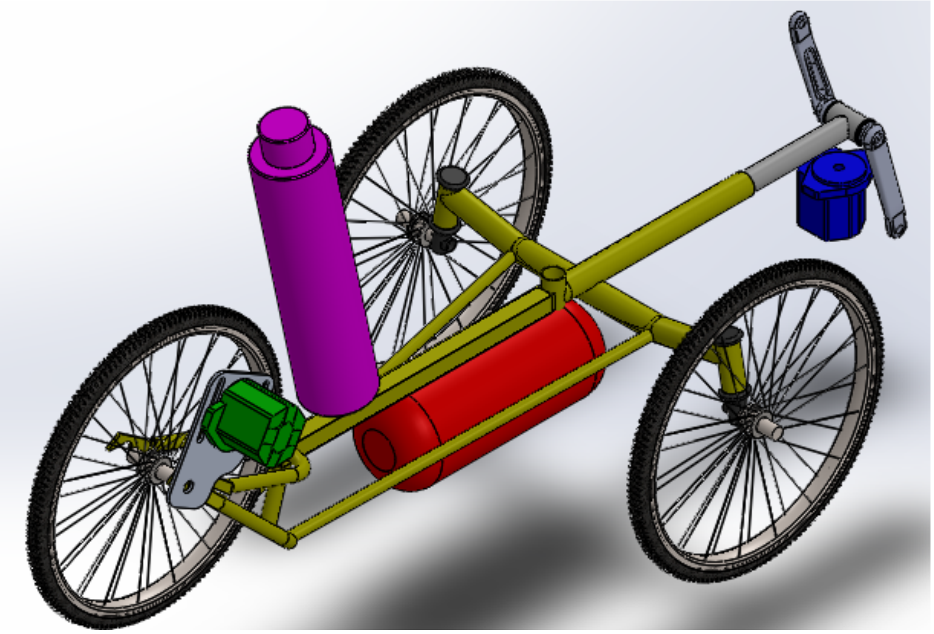
Figure 18B: Drag-Efficiency Race System

The circuit race circuit shown in blue is the primary mode of power input to the system. The circuit is open loop and has a large reservoir to make up for any fluid losses that the system my sustain.

5.1.2 Create a 3-D Model of the Bike

The team opted to reuse an old bike frame from previous competitions. The frame is a three wheel recumbent design, creating a more stable vehicle. This frame also gave us more options for mounting the components; the distribution of weight over three wheels allows for components to be mounted asymmetrically while not compromising the stability of the bike. The frame also lowers the center of gravity allowing for better maneuverability within the speeds anticipated in the competition.

The frame and components were modeled using the 3-D CAD program SolidWorks. Utilizing the program the team was able to position each of the major components onto the frame. We were able to test multiple positions of components using the software without having to manufacture and assemble mounts for each.



5.1.3 Acquire or Make All Parts Needed

After deciding on the design of the bike, the next step was to modify the frame to accommodate the new setup. We designed and constructed new bracing to attach the seat; allowing for enough space to mount the one gallon accumulator directly behind the rider. This was to avoid any clearance issues the bike may have encountered if the accumulator was mounted below the seat as initially planned. In previous years' bikes have used drive shafts and gear boxes to achieve the ideal mechanical advantage. This year our team decided to utilize an internally geared Shimano hub to cut the excess weight involved with a separate gearbox. This also allowed us to utilize the overrunning clutch and be able to coast the bike. We also manufactured an aluminum mount to hold the pump directly over the pedals. With this mount, we could use a bevel gear to direct the vertical rotation of the pedals into the horizontal rotation of the pump shaft. We also manufactured a mount for the motor using 1/4" aluminum. The part was cut using a CNC mill; it is designed to allow for adjustments in spacing in order to change gear ratios if needed on the final assembly. Both the pump and motor sleeves were manufactured in order to attach a gear to the shaft of each. We also manufactured a mount to allow for the hand pumps to attach directly to the frame. The pumps were placed on the opposite side of the rear wheel to allow for longer extension arms to be used when charging the accumulator.

A new reservoir was also constructed this year. We used PVC pipe as the main material to reduce cost and weight. The reservoir holds approximately one and a half gallons of fluid. It was designed with a single return point on the cylindrical face near the top, and a single suction from the bottom cap. The suction line is size 8 while the rest of the lines in the system are size 6. In addition to manufacturing these components ourselves we purchased several components from local parts dealers, such as motor/pump nipples, hydraulic fittings, and set screws. As well as the major components, we ordered through Sunsource such as the motor and hydraulic lines.

6.0 COMPONENT LIST

For the most part, the ordering process went rather smoothly. The team had never ordered parts from any company; however, parts were easy to find and the process proved to be easily understood. This being said the parts that we believed we ordered were not exactly what we received and most were received later than expected. This forced us to go ahead and use other pump and motor combinations for test purposes. Although it was a setback, the pump was received and has been useful in deciding which combination should be used for the final bike. Also there were complications with the Shimano hub which led to us ordering another hub. This proved to be a big setback. Initially we wanted to incorporate some electronics into our design but because we were grounded until we received the replacement hub we decided to make our bike purely manually operated.

Note: Refer to Cost Analysis for Full Component List

Table 4: Components Ordering

Item	Quantity	Brand Name	Specifications	Delivery time	Notes
and pumps	2	Doering	Displacement: 0.307cu.in Weight: 1.8 lbs. each	N/A	The team replaced a hydraulic lift hand pum with an onboard pump of 0.12 cu.in & weight of 2 lbs.
Bladder ccumulator	1	Parker	4000 PSI 1 gallon	N/A	________
Pump	1	Parker	Displacement: 1.2 cu.in/rev	6 weeks (poor timing)	————
Motor	1	Eaton	Displacement 0.7 cu.in/rev	2 weeks (Perfect)	————
Fluid	5 gallons	N/A	Biodegradable Mobile EAL 224H (5 gal.)	2 weeks (Perfect)	————
imano Hub	1	Shimano	————	4 weeks (Good)	__________
Spur Gears	2	N/A	96 tooth / 20 tooth	N/A	__________
evel Gears	2	N/A	36 tooth / 12 tooth	N/A	__________
ose fittings	15	N/A	43 series	N/A	————
Hoses	80 ft.	Parker	302/301-6 hoses 4000 PSI	N/A	————
heck Valve	1	Parker	5000 PSI	N/A	_________
Ball Valve	2	Parker	5000 PSI	N/A	__________
Vented Reservoir	1	N/A	6-in. Diameter 6-in. Diameter Caps	N/A	__________
Pressure gauge	1	AGSMART	————	N/A	————

7.0 ACTUAL TEST DATA

Note: Due to the fact that the analysis references much of the test data, more to this section can be found in the “Analyze Hydraulic Components” section of Design Analysis.

7.1.1 Make adjustments to the Bike

The bike was initially intended to include an electronic circuit to control shifting and the discharge from the accumulator. As the build progressed we opted for a more simplistic, easy to use, and cost effective design; we accomplished this by utilizing the shifting mechanism already present in the handle that came with the frame as well as using a ball valve to control the accumulator discharge instead of a proportional control valve or a solenoid powered DCV. By switching these components to be controlled manually we were able to test the hydraulic performance of our bike sooner.

Final Hydraulic Schematic

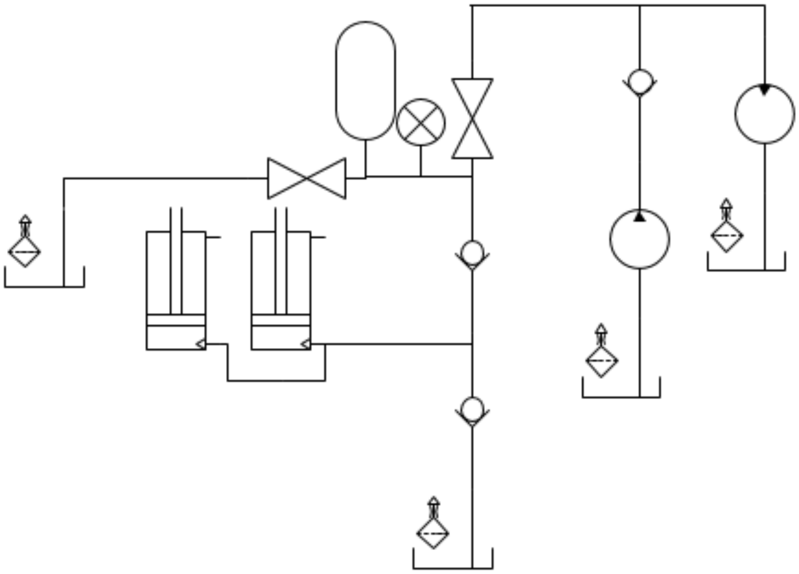


Figure 13: Final Hydraulic Schematic

One important feature that was added to the final system is the emergency dump to discharge pressure from the accumulator. The ball valve is in series with the return to reservoir so that excess pressure can be safely discharged after each event or in the case of a malfunction. An analog pressure gauge was also added to replace our initial idea of a pressure transducer. The gauge is in clear view when charging the accumulator using the hand pumps to prevent overcharging.

The proportional control valve we ordered and intended to use on the bike required a separate manifold to operate. We didn't realize this when ordering parts and found ourselves later having to replace the valve. Our first solution was to use a solenoid DCV in line with a needle valve to restrict the initial flow when first releasing the pressure in the accumulator to prevent damaging our hub. However we chose instead to use a manually controlled ball valve because of the lower k values associated with it. The ball valve also let us control the amount of flow to an extent where we could prevent damaging our bike.

7.1.2 Test Bike to Determine Actual Performance

Once these final changes were made to the design we mounted all of hydraulic components to the frame. With the components secured to the frame we measured the length we needed for our hoses and assembled the circuit. With this build we did all of our prototype testing.

After completing the first attempt at the prototype we had multiple issues. The first being that we had mistakenly used a fitting that contained a check valve and was blocking the flow from our suction line into our pump. The next issue we discovered was slightly easier to notice when we tested the bike. The motor we had designed our circuit around was a unidirectional motor, and doesn't run very efficiently when fluid is forced through the wrong direction. On the first test of the accumulator portion of the hydraulic circuit we experienced large losses in energy and fluid. After blowing the seal in the motor we replaced it with a low displacement 24 series motor we had recently received from our order in the fall semester. The bike seemed to maintain the function levels expected when using the new motor as testing continued.

As we prepared to go into the next stage of testing we encountered a major issue. The locking nuts we used on our hub had been damaged by the amount of torque the accumulator was creating. The lock nuts had cracked and in turn stripped the axel of our hub. After manufacturing new heavier duty lock nuts and rethreading the axle we discovered another problem. Along with the lock nuts the internal gearing in the hub had been damaged. It was damaged to the point that after rolling for a few yards the entire wheel locked into place. We then ordered a new hub and contemplated what may have been the cause of the problems so that we could prevent these problems at the competition. Ultimately we decided that the main issues was the age and life of the hub. It had been used on older hydraulic bike systems and repeatedly exposed to these high torques as well as disassembled and reassembled multiple times. We expect the new hub to function significantly better than the older version in durability because of this.

8.0 COST ANALYSIS

This project’s most cost effective component turned out to be the reservoir. This is due to the fact that in recent years an aluminum reservoir was used. This year we simply made our reservoir using a 6-inch diameter PVC pipe, 6-inch diameter PVC caps, and a vented reservoir cap. The reservoir used in recent years costed around 430 dollars, while the one we made costs around 50 dollars to make. We believe there are other items that could be redesigned to be easier to be made with mass production methods. Production time could be substantially reduced using materials that are easier to work with.

Certain items such as motor mounts would be more cost effective to buy a mold and have the parts cast. Other parts such as the pump, motor, accumulator, frame, ect. would be better bought and modified or simply assembled. This is an advantage because you can buy common of-the-shelf parts at a volume discount for mass purchases. Also, if we decided to mass produce this bike, assembly line processes along with advanced manufacturing methods would save in labor costs. It would reduce the time and labor per part which would improve cost and quality.

If this bike were to be mass produced one major cost savings could inevitably be found in the form of using cheaper alternatives to some of the more expensive parts. An estimation of these saving would be about 25% of the total amount that we spent on components. For example, the pump that we used costed around $245, while we could have bought a cheaper alternative for around $150. While it would be an advantage to save money by using the cheaper parts, this could negatively affect the bike’s performance and efficiency. We could also improve cost efficiency by utilizing the correct hose fittings and eliminating any unnecessary fittings. This is important because the cost of hose fittings can range anywhere from $2-$30.

Overall many things would change both in the design and bill of materials if the bike enters mass production. We have estimated these cost savings as closely as we can given the nature of what would change.

Table 5: Parts List & Cost Analysis

Category	Item	Part Number	Quantity	Cost	Mass Manufacturing Cost	Brand Name
Hydraulics	Cartridge Hand Pumps	S8542W-6	2	$106.00	$100.00	Doering
	Bladder Accumulator	BA01B3T1A1	1	$326.00	$310	Parker
	Pump	Alpha series Serial #: 13016083501	1	$244.00	$230.00	Parker
	Motor	26701-RSC(A170125SM)	1	$330.00	$315.00	Eaton
	Fluid	Mobile EAL 224H (5 gal.)	1	$113.25	$0.00	Parker
	Hoses	(N/A) 301/302-6	1	$65.00	$15.00	Parker
	Hose Fittings	43 series	15	$7.50	$105.00	Parker
	Pressure Gauge	N/A	1	$15.00	$14.00	AGSMART
	Check Valve	C600S 10HJ	1	$50.00	$47.00	Parker
	Ball Valve	D 378 2000 WOG	2	$85.00	$80.00	Parker
	Hydraulics Total Cost			**$1635.25**	**$1,216**	
Frame	Bike Frame, Carriage, Seat	N/A	1	$800.00	$760.00	Custom
	Spill Resistant Vented Reservoir	N/A	1	$50.00	$47.00	Custom
	Shimano Hub (Nexus)	SG-C3000-7R	1	$202.00	$190.00	Custom
	Bevel Gears	N/A	2	$20.00	$19.00	N/A
	Spur Gears	N/A	2	$20.00	$19.00	N/A
	Frame Total Cost			**$1132**	$1035	
	Labor Work per hour		80 hours	**$1300**	$500	
	Total Cost			**$4067.25**	**$2751**	
	Total Cost for 500 unites			**$2,033,625**	**$1,375,500**	

9.0 LESSONS LEARNED

Many of the lessons learned have already been addressed in this paper. Some specific lessons learned as a team were time management, communication skills, and group decision making skills. Each team member had some strengths and weakness going into this project; however, many of the team members' strengths were tested and refined while the weaknesses were improved greatly. To this end, the team feels it is important to state specifically what they learned from the project as each member has had a different experience based on these fundamental differences.

Daniel Moreland who was primarily involved with the hydraulic drive system and testing components writes,

"One of the most important ideas I've taken away from this project is that when working in a group it's important to have meetings and discuss ideas but at the end of the day we need to try to be more proactive and structured in our goals. As a team, I found that we often had excellent ideas and several different ways to implement them into the overall design but spent too much time discussing the best way to do it and lost the opportunity all together. I feel this is impacts areas outside of just the standard class project because deadlines are very much a real thing in industry and to lose an opportunity because of time management when the skill and talent is there is regretful."

Jameel Aljohani who was mostly involved with assembly writes,

Lessons Learned:
* Order the parts early and know what to order.
* Check all fittings twice and make sure they are all fastened before running a test.
* Some fittings have the function of a check valve.

While the project was a success the end result can still be improved upon. This is great because many team members will be able to do this project again and implement those lessons learned to improve the bike next year. Every individual feels like they have gained valuable skills that will be useful in industry.

10.0 CONCLUSIONS

The design process this year was much different than in previous years. Previous years design was focused on efficiency of the hydraulic system or implanting new ideas for a complex system. This year we focused on a simple system implemented on a light weight frame. This involved using a frame that had not been used for almost a decade and redesigning the mounting scheme for many of the newer components we decided to use.

There are many things that the team had planned to execute on but failed to deliver but will certainly be a point of interest for next year's team. These items include: exploring a hydrostatic option, exploring temperature regulation of the fluid as a function of system efficiency, exploring the power curves of small displacement piston pumps, and creating a completely electronically controlled system for releasing accumulator pressure and changing gears.

Overall, the bike performed in all areas as expected. In both the drag and circuit race the bike performed consistently. The team feels like the overall experience has been positive. The entire project has provided the team with invaluable lessons that will be used later in life in a variety of situations. These lessons ranged from gained knowledge of hydraulic and electrical components to the experience of working together to achieve a common goal. It is the hope of this year's team that the lessons learned and the time and effort put into the data will prove to be invaluable to the future of the "Fluid Vehicle Challenge" at Murray State University.

Figure 14: 2016-2017 Fluid Vehicle Challenge

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