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Fluid Power Vehicle Challenge

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CAPSTONE PROJECTS FINAL REPORT

SENIOR DESIGN

MECE 471

HONORS PROJECT

MECE 497

By

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Abstract

Tasked with designing and building a hydraulic-fluid powered bicycle for the National Fluid Power Association (NFPA) 2022-2023 Fluid-Power Vehicle Challenge (FPVC), our team at the University of Akron was able to develop several innovative design features that allow our bike to travel at higher speeds efficiently. After deconstructing the bike of the 2021-2022 team, our team redesigned the hydraulic circuit, manifold, component placement, hydraulic reservoir and controls. These design improvements were intended to allow our vehicle to perform well in all four races during the competition in Littleton, Colorado. These races include: the sprint race, efficiency race, endurance race, and regen race where regenerative braking must be utilized. This regenerative braking capability stems from a specification of the NFPA for the utilization of an accumulator, which is used to store energy and then propel the bike forward. Through research, innovation, and assistance from NFPA, we were able to accomplish our task and had a fluid-powered race-ready vehicle to take to competition. At competition, we preserved through adversity to push for top spots in the event races.

Contents

1. Introduction

Hydraulic power is the utilization of fluid to move components in a predictable and controlled manner to desired locations. Common examples include hydraulic lifts or hydraulic cranes, which push pressurized fluid up in order to lift heavy objects. As evidenced by the large requirements needed to lift objects much heavier than humans can lift, hydraulics is a very powerful application and is used in a myriad of industries and applications. Anywhere where pressure can be used to propel components such as hydraulic cylinders and motors, hydraulics has an application. Perhaps one of the more unique uses of fluid-power is in the fluid-power vehicle challenge sponsored by NFPA. In this annual competition among universities across the country, undergraduate engineering students are challenged to safely design and build a bicycle that is propelled with fluid power. Additionally, it must include an energy storage device in the form of an accumulator, which stores fluid under pressure that can be discharged at a later time.

The competition is judged by a panel of experts in the fluid power industry with scoring based on a variety of factors, including design safety, innovation, and performance in the races. The four races that occur at Norgren's (fluid power company and competition sponsor) facility in Littleon, Colorado are sprint, efficiency, endurance, and regen. The sprint race tests the power able to be generated by the pump of the vehicle, which is connected to the pedals, and the winner is determined by the fastest vehicle to traverse 500 feet of track. The efficiency race starts by charging the accumulator through human power and then measuring the distance the bike travels after discharging the accumulator. The endurance race measures how far each bike is able to travel utilizing both pedal power and regenerative braking in fifteen minutes. The regenerative race is similar to the efficiency race, but instead of charging the accumulator before the race, the accumulator is charged by rolling down a hill and utilizing "regenerative braking" which takes the

energy from the wheel and stores it in the accumulator. Since the University of Akron had a successful team in the previous year, the task for our team was to improve upon their design in order to win the competition.

2. Design Considerations

2.1 Introduction

The four areas of the vehicle where our team concentrated our energy on improving were the hydraulic circuit/ manifold, the placement of components/ mounting frame, the controls, and the hydraulic reservoir. Since we felt the previous year's team's vehicle was rather awkward to pedal, we hoped by shifting and redesigning components, we were able to create a more ergonomically friendly experience for the rider, who needed to concentrate on the race. This was just one of several goals we had established for the team, which also included safe operation, reducing weight, incorporating electronic controls, and winning the competition.

2.2 Design

2.2.1 The Hydraulic Circuit

Before any other design step could take place, our team focused on re-designing the hydraulic circuit since this was the most critical aspect of our project and would determine the entire operation of the bicycle. Since this would drive the bike, it was crucial that every detail was accounted for, and the circuit was free of any errors in order for our bike to function as planned. After multiple brainstorming sessions and too many sketches to count, our team was finally satisfied with a hydraulic circuit that included an innovative new-feature: a closed-loop system to directly connect the pump and motor. By selecting three specific solenoid valves, our team was able to develop a hydraulic circuit that accomplished all the needed drive modes (charge/regen, discharge, pedal power) and had an option to bypass the hydraulic reservoir to send fluid directly from the pump to the motor and back to the pump. The goal of this was to reduce the needed power to pedal the bike as we are eliminating multiple losses on the hydraulic line since we are not going through the manifold, valves, or long stretches of piping. The drawback of this was that in other modes we would be going through valving after the

motor in the low-pressure section of the circuit. However, after calculating the anticipated flow rates, we determined the low flow rates would not put too much back-pressure on the motor and we could proceed with our plan. Sketches and calculations can be seen in the appendix.

Once we had a sketch of the circuit, with the aid of computer software supplied by VEST Inc. and Sun Hydraulics, we drew our circuit in CAD and selected/ specified valving. The full circuit seen in figure 1 was drawn through VEST's software and the model of the manifold developed with Sun Hydraulics software is shown in figures 2 and 3. The machined manifold is shown in figure 4. The decision of the inclusion of the manifold was based on the reasoning that manifolds organize valving nicely, will be easier to mount than loose valves, and will make for a more aesthetically pleasing design. We determined that the benefits of the manifold outweighed the small detriment that since it was to be manufactured out of aluminum, it would be a significant weight. However, once we received the manifold, we were pleasantly surprised to find that since our circuit was fairly complex, most of the manifold was hollow space for the fluid. Once the manifold and circuit were fully designed, Sun Hydraulics and IFP assisted in manufacturing our custom manifold. After receiving our manifold and specified valving, the "brain" of our circuit was complete, and we could proceed with several design areas that had been being developed simultaneously to the manifold. We were also on the verge of moving to the next phase of placing valves into the manifold and setting relief valves to ensure the system pressure never exceeded 3000 psi.

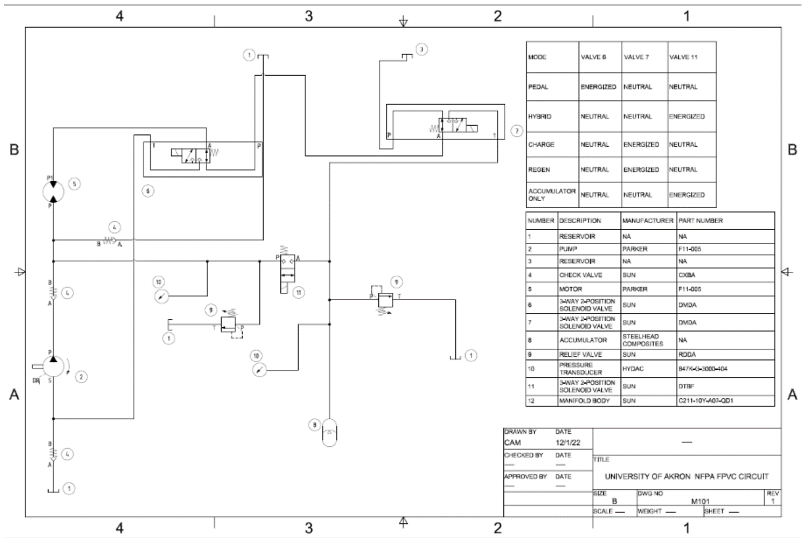

Figure 1: Full Hydraulic Circuit

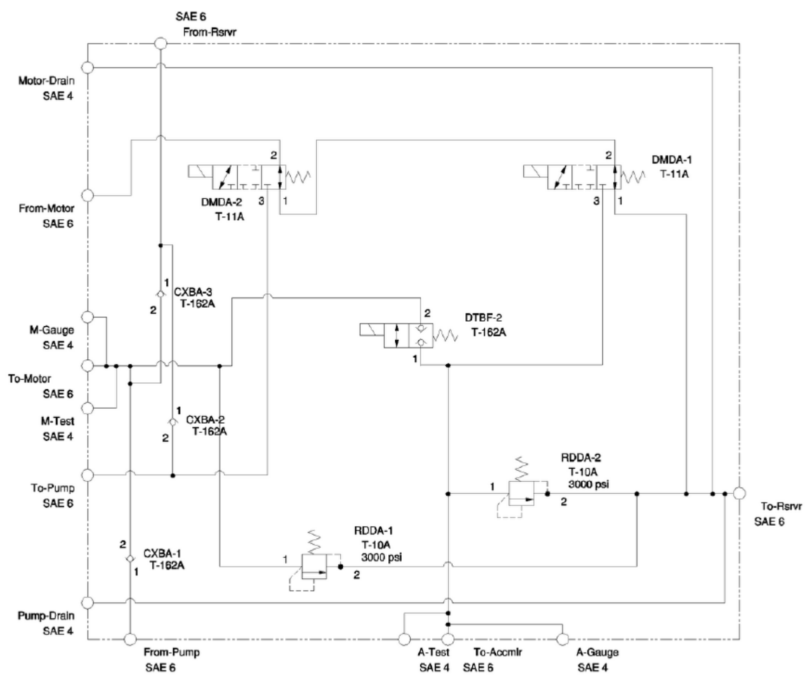

Figure 2: Manifold circuit with specified valving

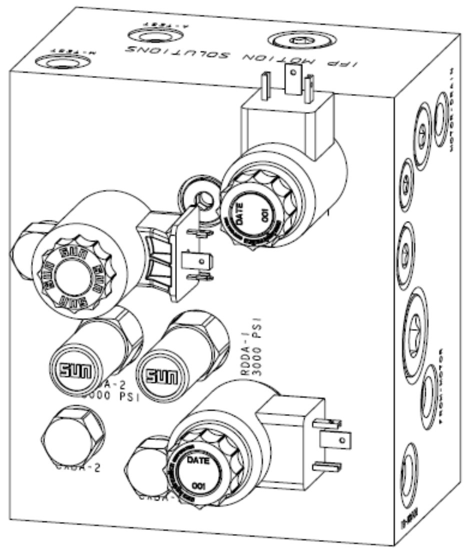

Figure 3: 3D-CAD drawing of our designing manifold

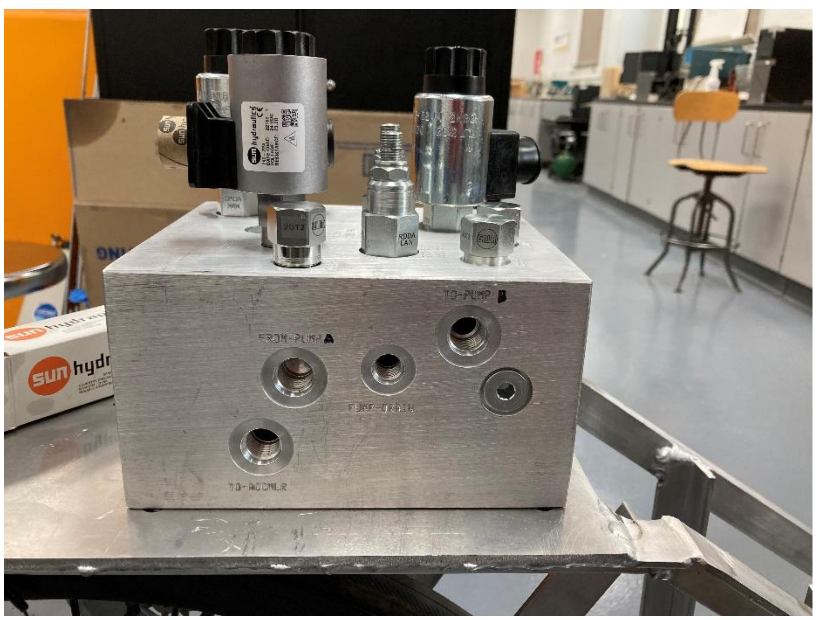

Figure 4: Fabricated Manifold

2.2.2 The Hydraulic Reservoir

Although the previous year's team had a custom designed 3D-printed hydraulic reservoir, which we thought was an idea with much merit, we wanted our reservoir to stick out less since the previous reservoir brushed against the legs of the rider when pedaling. We also recalculated the amount of needed volume with our redesigned circuit to find we needed around 1.6-1.8 gallons of

usable space in the reservoir. Our reservoir was designed to maximize the use of the space underneath the bottom bar of the bicycle frame while not having a width exceeding the width of the pump. The goal was to reduce the needed length of the hydraulic lines and not hinder the rider's pedaling ability in any manner. Since we wanted the reservoir to fit into a certain shape of the bicycle frame, the design was straightforward and derived mainly from the measurements between bicycle tubing with a few inches taken off for adjustments. Additionally, we planned to re-use the holes drilled in the frame from a previous mount and "wrap" the reservoir around the bicycle frame so that it was secure. The most difficult aspects of the design were the fill area, which had a neck that sits just past where the rider's knee passes when pedaling. A "baffle plate" was also added internally to force the fluid returning to the reservoir to take the longest possible path in hopes of reducing turbulence by the time it returned to the circuit.

Once the design was complete, we chose the material of PETG as this plastic has some of the best properties of all 3D-print filament with high temperature and chemical resistance. It will not degrade in hydraulic fluid, which was essential to our purposes for obvious reasons. We worked with Schmidt-Proto, a third-party vendor to fabricate our design using FDM printing techniques as our 1.6-gallon tank had maximum length of 18" and was far too large for the printers in the University of Akron laboratory. There were a few hiccups during the printing process with the most notable being the reservoir was cracked during shipping. However, we remedied this issue by applying RTV silicone and then a thin epoxy designed to smooth 3D-prints to the exterior of the reservoir. Once this was complete, we also sealed the interior with por15, gas-tank sealer, to fill any micro-gaps that were not observable to the naked eye. With the tank printed and sealed, it was able to be tested to ensure a liquid-tight seal, which will be discussed in 2.3. The completed reservoir is seen in figure 5.

Figure 5: 3D-printed hydraulic reservoir, which was sealed with epoxy and por15

2.2.3 Controls and 3D-prints

There are several different methods of turning the solenoid valves on and off, which include a simple series of switches, pneumatics, or electronics. Since the University had all the needed components required for an electronic control system including an exor700 controller seen in figure 7, we elected to control our solenoids electronically. Essentially, the electronic controls interrupt the signal between the batteries and the solenoids, so the solenoid valves only see 24 V and activate when certain buttons are pressed in the program. Additionally, an added advantage of an electronic controller is the inclusion of pressure gauges within the program so the rider can see the system's pressure at all times during the ride. A pressure transducer is wired into several fittings in the manifold for the purpose of monitoring pressure in the high-pressure parts of the system, the motor and the accumulator. We worked alongside an engineer from Iowa Fluid Power to activate our controller. He was able to program most of what we needed the controller to do, which left us with mostly only the wiring to perform ourselves. Once we had all the wires connected to the correct signal, 24 V, and ground wires, we were able to "dry-test" the valves to

ensure they functioned properly.

With the knowledge that our controller worked as we required, we designed and 3D-printed several components in Akron's lab, including the controller housing shown in figure 6. The 3D-prints allowed us to be very flexible in our design while minimizing weight since plastic is not very dense and is relatively light. Although we needed several iterations of a few designs, the advantage of 3D-printing in-house is that we obtain a very fast prototype and are able to test it only a few days after the design is finished. This allowed us to make small adjustments to the design if needed, such as filleting corners to ensure that nothing was rubbing and creating friction. The list of 3D-printed parts designed and printed include housing for the accumulator (shown in figure 8), controller housing, and batteries and a chain guard for safety.

Figure 6: Controller with 3D-printed housing

Figure 7: The program for the controller includes functions for switching between drive modes by changing which solenoids are activated and pressure gauges for the accumulator and supply side of the motor

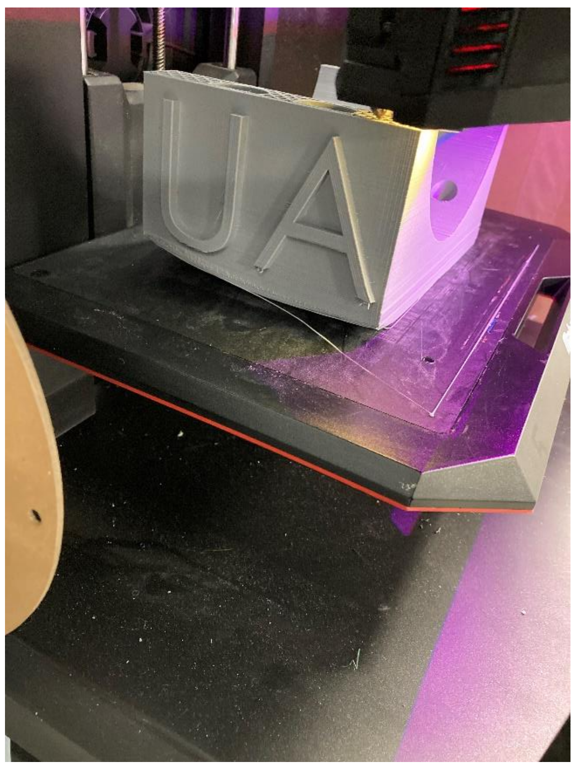

Figure 8: 3D-print of the accumulator housing being printed at the University of Akron mechanical engineering 3D-print lab

2.2.4 Frame

The final significant change we made to the previous year's bike was the mounting frame for the manifold, motor, and accumulator. The placement of several components of the previous

year’s frame gave us concern, most notably the proximity of the rider’s legs to the accumulator and the lack of distance between the foot of the rider and the motor when pedaling. We designed and drew in Solidworks a new mounting frame to be welded by us with aluminum angle iron as the selected material. The Solidworks model is shown in figure 1 This frame would include three aluminum plates: one for the accumulator, one for the manifold, and the other for the relocated motor location further behind the rider. This frame would bolt to the rear axle and the bolt of the rider’s seat for rigidity. Although this would mean adding more weight to the back of the frame and potentially creating a fairly large moment arm that could tip the bike, we considered the fact that the reservoir being mounted in front of the rider would help counterbalance and offset the added weight to the rear.

With the design complete, we decided to weld the frame ourselves since our shop had the capabilities and we felt the more work we performed ourselves, the better we would be scored by the judges. After learning how to Tig weld 6061 aluminum, as seen in figure 9, we welded the frame over a two-week period. Once all supporting angle-iron pieces were in place and all welds were firm, we used the plasma cutter to precisely cut our mounting plates and then welded these in the needed locations after ensuring hole locations would align with the manifold, motor, and accumulator housing. The completed frame is shown in figure 10. In addition to the frame, our team also elected to select hard-lines as the plumbing option between components in the hopes of reducing head loss compared to tubing.

Figure 9: Andrew Sobel welding our frame

Figure 10: Completed aluminum frame. Plates for mounting components are visible on the back (accumulator), top (manifold), and motor (far side)

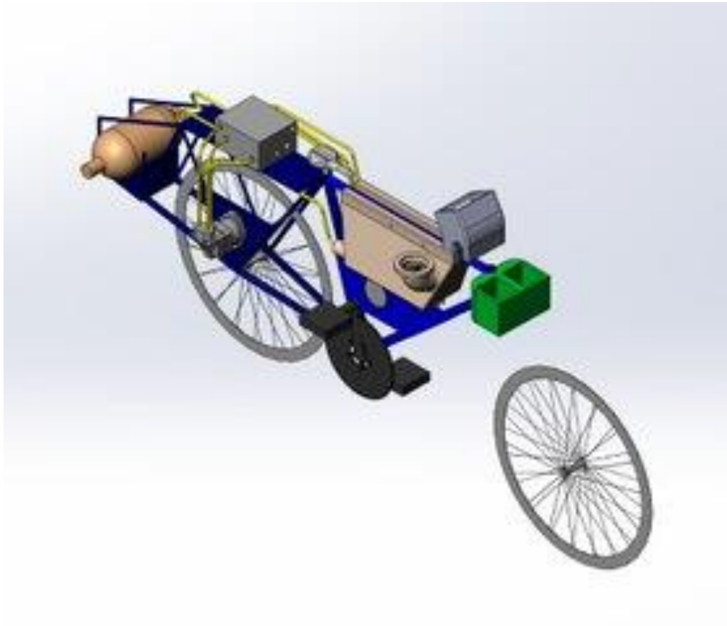

Figure 11: Solidworks rendering of the completed bike with all needed components.

2.3 Verification

With the design and assembly fully complete, we could begin testing of our both the bike and the circuit. The first step after tightening all bolts and securing all band clamps was to add fluid to the reservoir and check for leaks. After letting the reservoir sit with fluid overnight with paper towels underneath as a leak-detecting device, we were confident that there were no leaks in the reservoir after coming in the next day and finding dry paper towels. With the system full of fluid, we could bleed the system of air and began turning the pedals, which were connected to the hydraulic pump via a chain. The motor began to turn, and we monitored pressure as we slowly increased the rate of pedaling. With full confidence that everything was functioning correctly and pressure would not exceed 3000 psi, we could have a rider pedal on the stand. The first tests saw the motor turning at a fairly low rate, but we did notice it was significantly easier to pedal when in the "closed-loop" mode compared to the standard pedal only mode which sent fluid to and from the hydraulic reservoir. Additionally, with all solenoids functioning correctly and with the accumulator pre-charged to 850 psi, we both charged and discharged the accumulator on the bike stand. Results were successful and indicated that both our manifold and

circuit were correct and functioned as we thought they would.

When rolling friction was added and we took the bike outside to test, we found that we would lose significant pressure when climbing hills and we could only charge the accumulator to around 1500 psi when it was rated for 3000 psi. We suspected that the relief valves were set too low, which was confirmed when the system was able to achieve higher pressures after we increased the spring tension in the relief valves to increase the amount of pressure needed to push them open. Additionally, we lowered accumulator pre-charge to increase amount of available usable fluid in the bladder of the accumulator. We simulated all four race competitions and were able to achieve the following results summarized in table 1.

Table 1. Test Results for the fluid-powered bike

Mode/ Race	**Result**
Sprint	500 ft. in 37 seconds
Endurance	3.25 miles in 15 minutes
Efficiency	2000 ft on a pre-charge of 2000 psi.
Regen	150 feet on a regen charge of 800 psi

We also recorded data, such as the rpm of the pedals for verification calculations to compare to our calculations we performed before the build. This would verify several key assumptions we made during this stage and justify the use of 3/8" hard line, which was selected based on a flow rate calculation of between 0.25 and 0.5 gpm. Full calculations can be seen in the appendix, but on a pedal speed of 50 rpm, the calculated flow rate was 0.32 gpm at a pressure of around 1700 psi, which was consistent with what was being displayed on the pressure gauges. The calculation gave us confidence that our design choices were correct. To check the pressure gauges displayed from the pressure transducer, we plugged a device into the test-ports to compare pressure readings. Although they varied slightly, we attributed this to

signal noise and determined that the pressure readings were approximately correct. With everything tested and functioning properly, the final product was ready to ship to competition.

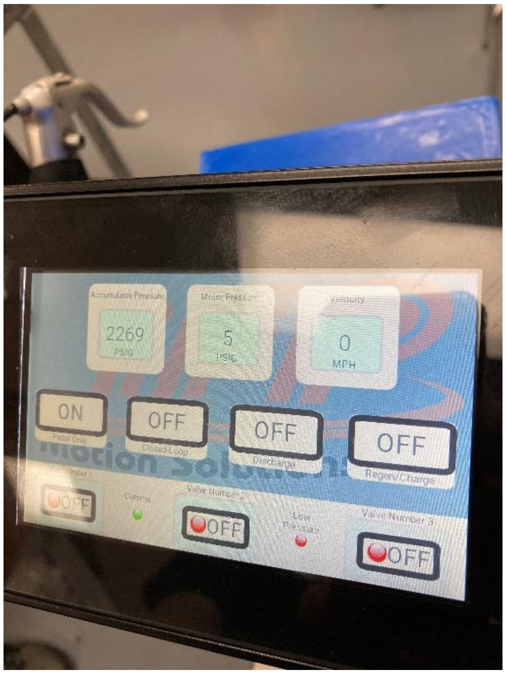

Figure 12: Pressure readings displayed on the controller during the charge mode

Figure 13: Pressure reading from the test point during the charge mode

Figure 14: Completed University of Akron fluid-powered vehicle for the 2022-2023 NFPA Fluid-Powered Vehicle Challenge

2.4 Costs

With the budget of $3,000 provided by NFPA, we were able to purchase all needed components and re-use several expensive components from previous years' teams. Purchases included all needed aluminum from the frame, the 3D-printed reservoir, and all hard-lining and fitting. The total cost of all purchases can be seen in table 2. The approximate value of all re-used components can be seen in table 3.

Component	Quantity	Approximate Value	Total Value
Bike frame sheet aluminum	1	$170	$170
Bike frame angle aluminum	3	$22	$66
Wire for electronics	1	$20	$20
Wire nuts	1	$40	$40
Gasket Maker	1	$20	$20

Neodymium magnet	1	$20	$20
Hose Clamps (10pk)	1	$15	$15
General Hardware	1	$68	$68
Hard lining fittings	1	$125	$125
Hard lines & flaring	1	$165	$165
POR-15 Fuel Tank Seal	1	$18	$18
JB Clear weld	1	$13	$13
JB Weld	1	$6	$6
Foam brushes	1	$7	$7
XTC-3D Epoxy coating	2	$40	$80
PPE	1	$50	$50
Motorcycle Tachometer	1	$18	$18
Speed Computer	1	$70	$70
Metal strap	1	$5	$5
Shipping crate lumber	1	$120	$120
Power Tools	1	$100	$100
Dremel set	1	$34	$34
Polyethylene sheet	2	$10	$20
3D Printed reservoir	1	$475	$475
Cable ties	1	$15	$15

Table 3. Re-used components with their approximate value

Component	Quantity	Approximate Value	Total Value
Bicycle frame and wheels	1	$1,000	$1,000
Parker Hannafin F-11-005 Hydraulic pump	2	$3,000	$6,000

3. Conclusions

Armed with the incredible power of hydraulics, we were able to design and fabricate a working bicycle that is propelled by fluid power. Included in the design is the capability for energy storage and discharge with the utilization of the accumulator. Although the primary driving function was fluid power and a large portion of our time was spent with the hydraulic aspect, there were several other key areas that needed to be considered for the project to work. We had to practice skills in 3D-prints, stress calculations, and controls in order to build and control the bike.

3.1 Competition Results

The results of the competition were mixed with a tire failure preventing us from fully evaluating the capabilities of our vehicle. Although we were not in the top three for the regen and sprint races, this was expected as we had set up our bike to do well in the efficiency and endurance races. However, during the first lap of our efficiency race, the bike hit a bump, which punctured the tire and resulted in a flat. As a result, we were not able to fully discharge the accumulator as the flat tire eventually brought the bike to a halt after 1170 feet traversed. We managed to change the tire in time for the endurance race where we traveled 9750 feet in ten minutes before the tire again went flat, possibly due to rim damage from the first flat.

While it would be easy to attribute these flat tires to design failure, this would be an overreaction. The tires used were carbon fiber racing tires, which had been used successfully during all testing

and used by the previous year's team. While we did add more weight to the rear of the vehicle, we had no reason to believe this would be enough to ruin the tire. The "pinch-flat" type of flat tire is a common occurrence and has happened multiple times to team members personal bikes that didn't have any added weight to the frame. We made a design decision to trade the increased stability and strength of a thicker tire for the decreased rolling resistance of the racing tire, which turned out to be a decision that did not pay off.

3.2 Awards

Despite the unfortunate race results, our vehicle was awarded the best craftsmanship award and came in third place during the endurance race, despite racing for five minutes less than all other competitors. Because we were averaging around forty seconds laps and only lost the endurance race by two laps, it is our firm belief that we would have won this race had the tire not gone flat. Additionally, we achieved a top speed of 18 mph during the efficiency race, which we believe is the fastest any vehicle had gone during the entire competition. It is again our belief that had the tire not gone flat, there was a very good chance we had a podium finish for the efficiency race. These results were enough to establish that our hydraulics functioned as intended and gave us a high degree of confidence that our design was sound. While it may be easy to instantly attribute the blown tire to a design flaw, it is worth noting that even the most perfect designs can go wrong and ignoring the luck component would be a mistake. There were certainly actions we could have taken to decrease the chance of a flat tire, but since the tire had been fine during all testing, it is our belief that had we not hit the large pothole on the track, the tire would not have gone flat and we would have pushed for a podium spot for the overall competition.

4. Codes and Standards

Pressurized hydraulic fluid is both powerful and dangerous. One of the most important things for us to consider while building our vehicle was the dangers of working with pressurized hydraulic

fluids. The designing of hydraulic systems has numerous safety codes and requirements. Some of these are outlined within the ISO 4413 standards[1]. According to Health and Safety Executive, "although serious reported instances of hydraulic injection have occurred at pressures over 100 bar (1450 psi), anecdotal evidence suggests hydraulic injection injury may occur at pressures as low as 7 bar (101.5 psi)"[2]. With pressures in our system reaching upwards of 3000 psi, it was important to be aware of the damage that can be caused by the hydraulic oil. Hydraulic fluid at these pressures can penetrate skin and cause massive amounts of surface damage. Additionally, the hydraulic fluid can also enter into the bloodstream and cause necrosis of the limbs effected as well as induce serious blood poisoning. It is extremely important to see an orthopedic hand surgeon or other specialists as soon as possible if any injection of hydraulic fluid is assumed[3].

Because of the hazards outlined above, it was important to refer to the ISO and ASTM engineering standards that relate to our project. In general, these standards have been developed using lessons learned over the years by engineers with much more experience in the field than we have and with safety of both the people building projects, as well as the end users in mind. Considering how new student engineers are in the field, using these established and time-tested standards can prevent us from making both costly and potentially life-threatening mistakes while designing products and machines. These standards not only outline safety procedures, but also allowed us to make new designs that held up to intense testing and were used without catastrophic failure. Nothing is as disappointing as being an end user of a product that doesn't last nearly as long as anticipated or requires a considerable amount of maintenance in order to ensure proper functionality. Using engineering codes and standards gives us important insights as product developers into how to stay within the strengths of certain types of systems and materials.

5. References

[1] "List of All Codes and Standards - ASME." *Www.asme.org*, www.asme.org/codes-standards/find-codes-standards?type=Standards&page=1&perPage=100&sortBy=bestselling&sortByDir=desc. Accessed 30 Nov. 2022.

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[3] McCaslin, Dr. "Hydraulic Fluid Injection - Do You Understand the Dangers?" *Info.texasfinaldrive.com*, info.texasfinaldrive.com/shop-talk-blog/hydraulic-fluid-injection-do-you-understand-the-dangers#:~:text=A%20stream%20of%20hydraulic%20fluid. Accessed 30 Nov. 2022.

Appendix A

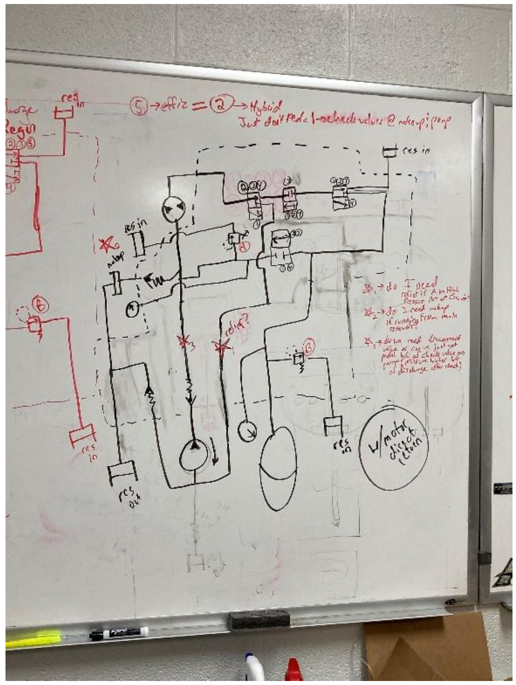

Figure 15 Hydraulic Circuit Sketch

Calculations for gpm flow with design verification were performed using the following formulas:

Basic formulas for hydraulic motors

Flow (q)

$$q = \frac{D \times n}{1000 \times \eta_v} \; [l/min]$$

Torque (M)

$$M = \frac{D \times \Delta p \times \eta_{hm}}{63} \; [Nm]$$

Power (P)

$$P = \frac{q \times \Delta p \times \eta_t}{600} \; [kW]$$

D - displacement [cm^3/rev]
n - shaft speed [rpm]
η_v - volumetric efficiency
Δp - differential pressure [bar] (between inlet and outlet)
η_{hm} - mechanical efficiency
η_t - overall efficiency ($\eta_t = \eta_v \times \eta_{hm}$)

$$n\ (rpm) = 4 * 50\ (4\ is\ gear\ ratio\ and\ 50\ is\ tested\ rpm\ of\ pedals)$$

$$q\left(\frac{l}{\min}\right) = \frac{4.9\,\frac{cm^3}{rev}\ x\ 200\ rpm}{1000 * .8} = 1.23\ l/\min = 0.324\ gpm$$

$$\Delta p\ (bar) = \frac{63*11.75\ Nm}{4.9\frac{cm^3}{rev}*.8} = 120.85\ bar = 1754\ psi$$

Using torque and friction resistances for the calculation and comparing it to the calculations done before the build, the below table summarizes the calculation. The result with the actual mph (14) matches the values found using the hydraulic motor formulas.

Calculations Table				
Parameter	**Theoretical Value**	**Actual Value**	**Testing Value**	**Units**
Assumed Max Incline Angle	2	2	2	% Grade
Angle of Ascent	1.146068403	1.1460684	1.146068403	°
Rolling Resistance	0.002	0.002	0.002	
Assumed Weight of Bike + Rider (Load)	350	350	350	lbf
Force Required to Bike Uphill	7.000466639	7.00046664	7.000466639	lbf
Lateral Force Required to Overcome Rolling Resistance	0.699859967	0.69985997	0.699859967	lbf
Total Pull Uphill	7.700326606	7.70032661	7.700326606	lbf
Radius of Wheel	13.5	13.5	13.5	in
Torque	103.9544092	103.954409	103.9544092	lbf*in.
CIR of Motor	0.653164816	0.3	0.3	in^3/rev.
Assumed Maximum Speed of Bike	10	10	14	mph
Wheel Revolutions per Minute	124.4444444	124.444444	174.2222222	rpm
Gallons per Minute for Motor	0.511815712	0.23507805	0.329109275	gpm
CIR of Pump	0.950057915	0.43636364	0.436363636	in^3/rev.