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Hydraulic Vehicle Challenge

Jacob Steiner
jas471@uakron.edu

David Kotovets
dmk139@uakron.edu

Evan Blitz
edb42@uakron.edu

Luke Fetherston
lbf9@uakron.edu

Alex Colucy
agc46@uakron.edu

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By

Evan Blitz

Alex Colucy

Luke Fetherston

David Kotovets

Jacob Steiner

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Faculty Advisor: Dr. Scott Sawyer

Faculty/Honors Advisor: Dr. Dane Quinn

Faculty/Honors Reader 1: Dr. Christopher Daniels

Faculty/Honors Reader 2: Dr. Alper Buldum

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Abstract

The target goal of this project is for a team of students to design a vehicle which is based on human power as the primary mover of the system and achieves vehicle propulsion through the required use of hydraulics and pneumatics. In summary, the rider will power a pump that will generate pressure in order to move the fluid that drives the motor. This will result in the powered rotation of the wheels. As there are many possible designs, naturally, this means that the final design for the vehicle will have specific limitations such as weight and the required use of certain components. The primary motivations behind this project include providing an opportunity for students to gain a greater knowledge of hydraulics and pneumatics as part of the Fluid Power Vehicle Challenge (FPVC), and possibly preparing the students for a future career involving fluid power. In addition to expanding mentioned knowledge, the students will be able to enhance their creativity, design, teamwork, and planning skills as they take on an open-ended and hands-on project that allows them to practically apply what they have learned throughout their education. The approach to completing this design project will include application of current knowledge of fluid power, further research on the operation of hydraulics and pneumatics, designing and building a vehicle that abides by the set standards, and ultimately competing in order to compare the team's design against other vehicles.

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1. Introduction

When the use of hydraulics is brought into question, the typical application noted is for large scale operations and generation of large amounts of force. Typically hydraulic power is not used for lower pressure uses, especially in combination with human power. Therefore the scope of this project was to combine this uncommon pairing of forces in order to design and build a vehicle that would be powered by hydraulic pressure, with a functioning pneumatic element as well. Upon completion of the vehicle, the team was given the opportunity to compete against other universities and their designs in the Fluid Power Vehicle Challenge. The motivation for the group to join this team and take upon this specific project was to learn more about pneumatics and hydraulics, meet people from the industry, and to compete for the University of Akron. The main requirement for the vehicle is that the vehicle propulsion must be accomplished through hydraulics with human power serving as the prime mover in the system. This means that the bike will still be pedaled to generate movement, but the pedaling will generate the pressure to drive the hydraulics of the vehicle. Other requirements for the challenge include: the vehicle must utilize an energy storage device, the driver of the vehicle must be able to enter, exit and stop the vehicle by him/herself, and the weight has to stay under 210lbs or 1% of the score will be deducted per pound. The scope of this project is very open ended. Although Akron has had many entries into this contest, each year's team is responsible for their own design and vehicle build. The report will go into detail of the design of the vehicle, design of the hydraulic and pneumatic circuit, vehicle construction, costs, and future improvements of the vehicle.

1.1 Objectives

The guidelines of the project are laid out by the National Fluid Power Association (NFPA). Even though the vehicle challenge is open-ended, an extensive set of rules and recommendations are provided that will guide the vehicle progress. The team's intention was to make a two-wheeled vehicle (bicycle) that will be driven by hydraulics which are powered by the rider's pedaling. In preparation for the design, the NFPA supplied the team with several video webinars on the basics of fluid power and the circuitry involved. The team was able to use the knowledge gained from these videos to create the final vehicle's fluid circuit. Once the vehicle would have been constructed, tested, and approved, the next step would be to travel to the off-site competition to represent the University of Akron. However due to COVID restrictions, the challenge would end up taking on a different format as will be described later in the report. As mentioned, the goal was to create a highly successful and efficient fluid power vehicle that would allow the team to rank high against other designs at the competition in April. The overall design experience would eventually provide the team with real-world engineering experience including simulations, ordering parts, building, testing, and abiding to a strict timeline of deadlines. Through the aforementioned webinars and assistance from a NFPA-appointed mentor (in addition to the

faculty sponsor), a key objective was to gain an extensive knowledge of fluid power capabilities and the systems that power them. This broad experience could also become a gateway to a future career in fluid power.

2. Design

2.1 Hydraulic Circuit

As the hydraulic circuit is the basis of all functionality for this project, it was critical that the team went through a thorough design process when designing this system. The functions of the circuit were first discussed so design and component selection could begin. This process led to the first original design which was presented to NFPA judges in mid-January. Later adjustments to the design will be discussed in the Design Verification section.

2.1.1 Circuit Objectives

The NFPA provides several criteria[1] for the team's hydraulic circuit through the different requirements for each race. In the sprint race, the team is to propel the vehicle to the finish line in as little time as possible. In the efficiency challenge, the bike must not be propelled, but operate solely on stored energy in an accumulator. Lastly, in the endurance challenge, the rider must start with no stored energy in the accumulator, but be able to recoup some energy via regenerative braking. A full-stop is required at the halfway point to prove that the energy recovered is enough to move the vehicle at least 10 ft. Using the structure of these three races, it was clear that there would be a minimum of three functions that the circuit would need to perform. The first was a direct drive. In the endurance race, no stored energy is allowed to be present at the beginning of the race. Since pedal power is the only other allowed source of propulsion, the circuit had to connect the pedals to the rear wheels, like on a conventional bicycle. The second function was the charge function. For both the efficiency and endurance sections there would need to be a way to accumulate pressure in the accumulator to be able to move the vehicle at a later time. The last function is now obvious. That stored energy will need a path to the rear wheels to propel the bike forward.

To make the bike easier to operate, it was acknowledged that a coast circuit would also be needed. Ideally, this circuit would operate in conjunction with the direct drive circuit. Within the idea of the charge circuit, it was also realized that there are multiple ways to charge the accumulator. The first option would be to design the circuit to allow pedal power to build up pressure. The second option was a regenerative braking function which would allow energy recovery from momentum that the vehicle already has, via the rear wheel. It was decided early on that the bicycle would encompass both of these options to provide flexibility to the rider.

2.1.2 Design Methodology

Now that the required functions of the circuit were clear, the design could develop, but first it was necessary to learn how these circuits are normally constructed. By sifting through previous teams' designs and watching recommended training videos by the NFPA, a greater knowledge of hydraulic components and the valves needed to combine functions was attained. Since the NFPA requires a new circuit design every year, this year's design started back at the drawing board. First, each function of the circuit was mapped out individually by hand so the needed connections between pumps and motors could be seen. Another important step in this process was making sure check valves were placed in the lines where they were required. This was based on intuition, as well as the example of previous designs. Once the needed components in each circuit were clear, the individual components were drawn out on a large sheet of paper. Then, by transferring each of the needed circuits onto the drawing, one by one, it was seen when an existing line could be used, or when a new line was needed to connect different parts of the circuit. It was also seen when flow needed to be bidirectional and check valves could not be installed in those segments. This methodology led to the first design (Figure 1), which was presented to an industry mentor, Brian Shields, a Parker-Hannifin CFPHS (Certified Fluid Power Hydraulic Specialist).

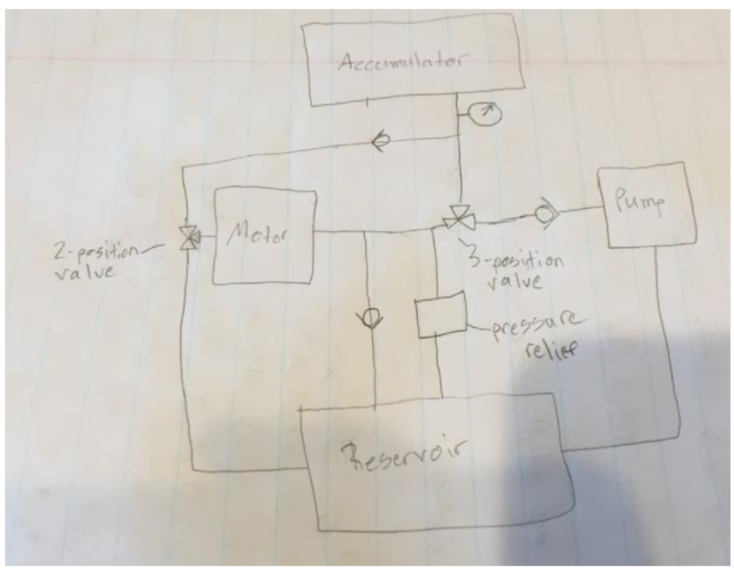
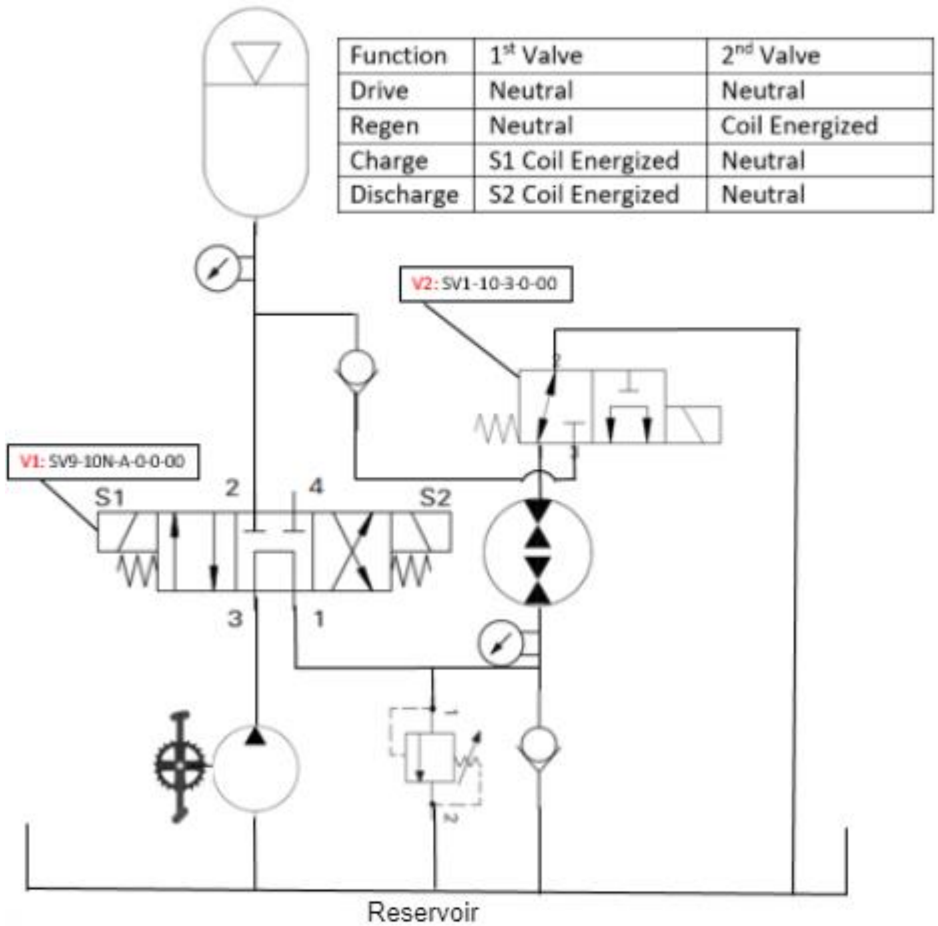


Figure 1: The Original Hydraulic Circuit Design.

At that meeting, it was expressed that for easier on-the-go control of the circuit, the design would need reconfigured to incorporate solenoid valves instead of ball valves. Concern about the check-valve immediately off of the pump was also expressed since it had been seen before that air pockets from the pump could cause issues in the lines. Taking into account this feedback, two solenoid valves were selected that could provide each needed function of the circuit with a different combination of the positions of the valves. A crucial design consideration in this stage

of the development was what function the system would default to in case of power failure. As shown in the table embedded in Figure 2, when both the first and second valves are de-energized the bike reverts to direct drive, which is highly desirable.



Function	1st Valve	2nd Valve
Drive	Neutral	Neutral
Regen	Neutral	Coil Energized
Charge	S1 Coil Energized	Neutral
Discharge	S2 Coil Energized	Neutral

Figure 2: Hydraulic Circuit Design at the Time of the Midway Design Review

At this point in the competition, the deadline for ordering parts was nearing, so the design was approved by Mr. Shields. Section 2.1.3 will discuss the components chosen and pictured in Figure 2. The last stage of the circuit design occurred immediately after the Midway Design Review, which was in mid-January. The purpose of this presentation is to update NFPA members on progress being made and to give an opportunity for them to give feedback. While the judges complimented the simple circuit design, they did point out several items that would need addressed. First, the lack of a check-valve off the pump was criticized because there was no protection for the pump if the accumulator would happen to already be charged. The other feedback provided to the team (relevant to the hydraulic circuit) was that the pressure relief valve in its current position was not protecting the motor in every state of the circuit. It was suggested that another relief valve be added right off the motor to fix this issue. When adding these components to the schematic, another line was added to the circuit that would allow pedal power

to supplement accumulator discharge power. This line had not previously been depicted, but it was discussed at the meeting and the judges approved the addition. This additional line would later become crucial to the success of the project, particularly in the sprint race. The final schematic is presented in Figure 3.

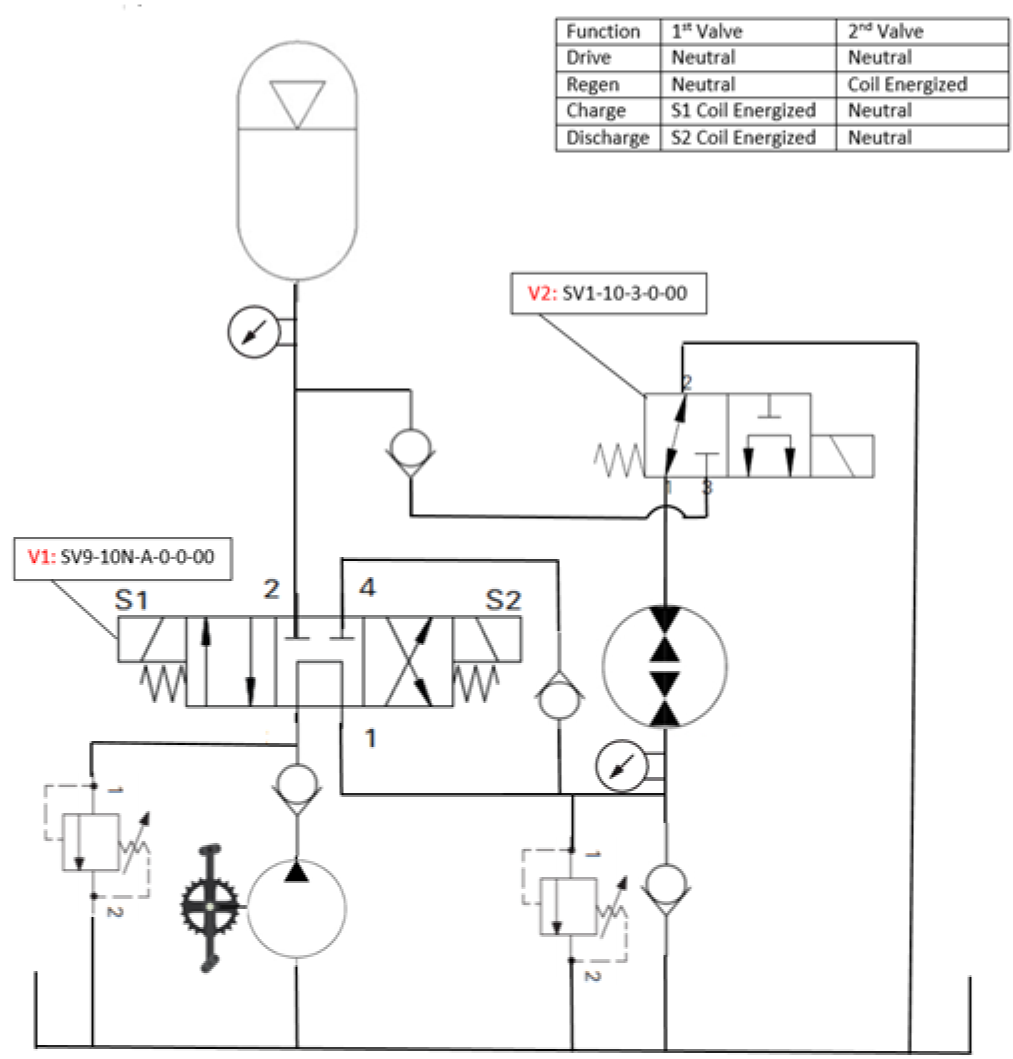


Figure 3: Final Hydraulic Circuit.

2.1.3 Components

Through the FPVC sponsors, the team was able to obtain all of the hydraulic components needed for the design of the vehicle, free of charge. The NFPA also provides several stipends that allow purchasing of parts that are not available from the sponsors. Previous years' teams used their stipend funds to purchase some fairly expensive items that were reused this year in the interest of keeping costs down and making the project as economical as possible.

2.1.3.1 Pump & Motor

Reused from last year, the pump and motor units are Parker F11-5 models[2], which provide relatively high amounts of torque at low revolutions per minute. It was advised to the team that these motors would be a great choice, and since last year's team was unable to test their design with these motors, it was thought best to incorporate them. These models have three ports, two for either input pressure (depending on desired direction of rotation) and one for case drain.

Figure 4: Parker F11-5 Motor/Pump

2.1.3.2 Accumulator

The accumulator used for the project was also a reused item. It is a Steelhead Accumulator[3] with a capacity of one gallon at a maximum pressure 3000 psi. As a bladder style accumulator (Figure 5), it provides an excellent weight to capacity ratio coming in at just under 11 pounds. The basic functionality of the accumulator is as follows. A precharge of gas (normally Nitrogen) is placed in the bladder. This pressure provides resistance to the charging the accumulator, but more importantly, forces the stored oil out of the accumulator when the discharge circuit is activated.

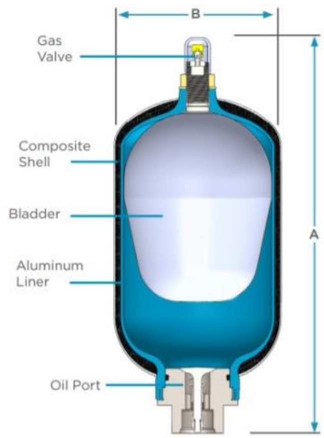


Figure 5: Steelhead Accumulator AB30CN010G0N.

2.1.3.3 Solenoid Valves

The solenoid valves available from the FPVC sponsor were Eaton-Vickers screw-in cartridge valves. For the main 4-way valve in the circuit, a SV9-10N-A-0-0-00 spool valve[4] was ordered along with a VC-10-4 line body that provides ports for the valve. The secondary 3-way valve[5] is a SV1-10-3-0-00 that works in conjunction with a VC-10-3 body. Both of these valves work in conjunction with a 12V Eaton coil that activates a given valve position when powered. As pictured in Figure 6, the SV9 valve uses two coils to activate two of its three positions, the SV1 valve only uses one. As far as required pressures, the cartridge fatigue pressure listing is 3000 psi on both valves, so this was ideal considering the pressure would only ever reach this reading when the accumulator was first being discharged if charged to its maximum capacity.

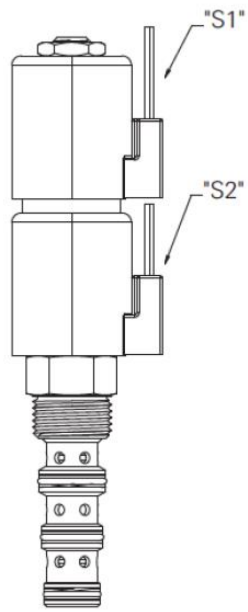


Figure 6: Eaton-Vickers SV1-10-3-0-00 Valve Profile.

2.1.3.4 Other Components

In addition to the motor, pump, accumulator and valves, there were several other key circuit components that were used frequently in the circuit design. Most frequently, check valves were used in lines that needed to be unidirectional. For instance, fluid needs to be able to flow into the accumulator, but if pressure from the accumulator were to backflow to the motor, that could have serious consequences on the system. A check valve in this line allows the fluid to flow in one direction, offering an important safeguard for the system. Overall, four Eaton CV3-8 check valves[6] are used in the circuit for this purpose. Similar to the valves, they have a fatigue pressure of 4000 psi, meaning failure was not a concern.

The last type of hydraulic component incorporated in the circuit is a pressure-relief valve. Pressure relief valves constantly “monitor” line pressure and if the pressure reaches a critical preset value, they relieve the line pressure to a reservoir. The final circuit design includes two relief valves[7] that were originally

specified as RV10-10-S-0-5, but during testing, it was found that the maximum relief pressure setting (500 psi) was too low and was causing standard operating pressure to be relieved to the reservoir. These valves were switched out with RV1-10-S-0-36 valves[8] that had a much higher cracking pressure of 3600 psi, thus allowing pressure to flow past the relief valves and on to the motor as it should have originally.

2.2 Component Mounting

Taking into consideration that the base for this designed vehicle was a standard two-wheeled bicycle, the simplest method of providing additional mounting space was the installation of a standard rear bike rack. As will be discussed in a further cost breakdown section, this was a purchased universal component. This would end up serving as one of the two main mounting locations on the vehicle, and would support two of the heavier components, the accumulator and hydraulic reservoir. Shown below is the simplified initial component mounting plan, where red represents the reservoir, orange represents the pump and motor, green shows possible additional circuit component locations, maroon is pneumatics, gray shows electronics, and blue is the accumulator.

Figure 7: Initial Mounting Design.

The goal for the initial layout was to position as many components as low as possible, in order to maintain a lower center of gravity. In order to accomplish this, the accumulator and pump/motor components would be mounted within the double triangle directly to the frame.

As with most initial designs for any project, the mounting design went through various iterations before the final vehicle was assembled. One of the most evident alterations is the relocation of the accumulator to the rear rack. The accumulator size had been much larger than expected and was not able fit within the frame in the desired location. After multiple considerations, such as side and front basket mounting, it was decided that the best option for preserving right vs left weight distribution would be to mount the accumulator to the rear rack, along with the reservoir. The accumulator and reservoir mounts were designed in Solidworks and printed in the

university's 3D Printing Lab (See Figures 8 and 9). This decision to relocate the accumulator guided other mounting adjustments, such as mounting the reservoir at an angle, and relocating the pump and motor to custom-made side mounts.

Figure 8: Accumulator and Reservoir Design

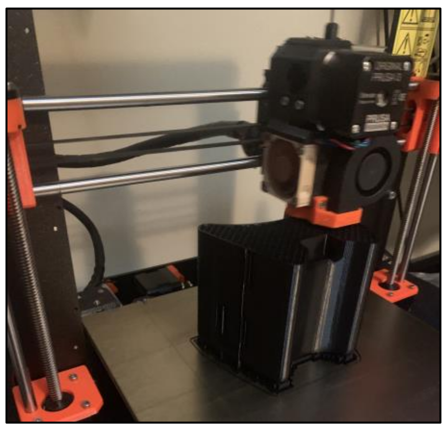


Figure 9: 3D Printing of Mount

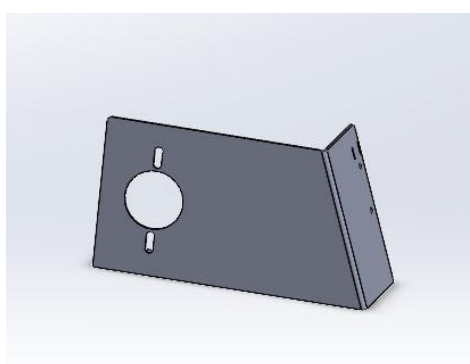


Figure 10: Initial Pump Mount

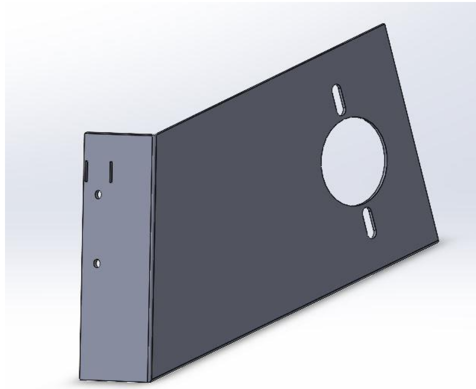


Figure 11: Initial Motor Mount

As seen in Figures 10 and 11, originally the plan was to mount the pump and the motor with two separate mounts; one being on each side of the bike to balance the weight. Once the prototypes were made in the 3D print lab, it was decided to redesign the mounts as they were in the way of the rider. In the figure below (Figure 12), the new and final mount was a singular mount made of sheet metal is pictured. Once a design for the sheet metal mounting plate was created and drawn up, it was then fabricated by members of the University's machine shop. The mount was cut to shape and the tabs were bent at the top for mounting to the bike frame. This was then secured by drilling holes and utilizing u-bolts to secure the plate in position. Once the mount was on the bike, simple testing found that additional stability was needed (See Figures 12 and 13 below). To compensate for side to side swaying motion, an L bracket was added onto the frame of the bike to stabilize the frame so that the pump and motor chains would stay in the correct alignment. The mount also had additional space which was used to mount the line bodies shown in the final design image below. This gave additional versatility when mounting the rest of the components to the bike.

Figure 12: Mounted Mounting Plate

Figure 13: L-Bracket Reinforcement

Shown below is the final vehicle design consisting of all of the mounted hydraulic components including other components discussed further in the report.

Figure 14: Final Mounting Design

2.3 Pneumatics

The pneumatics requirement was a new feature in this year's FPVC. With the complexity of the project already quite high, it was set out to design and install a pneumatic braking system utilizing air cylinders. This idea was selected since it was easily executed and very practical due to the additional weight a hydraulic bike has over a standard bicycle. The most important design consideration was to place the brake on the rear wheel only, so that it would not cause a moment force that would be detrimental to the rider when used. The brake would be activated by toggling a switch that was mounted near the handle bar of the bike. Similar to the hydraulics requirement, working with pneumatics was a new experience to this year’s team. Taking full advantage of the resources made available through sponsors, much advice was obtained, including the

components that would be best used for this application. Once a list was assembled for components needed, the team ordered the following components to make the system:

- Non-Repairable Reservoir
- Original Line® Air Cylinder
- Heavy Duty 2-Position 3-Way Normally Closed Switch
- 0 Series Regulator
- ⅛' tubing.

The pneumatic brake was able to take advantage of some of the spare brakes from prior years' bikes by use of a standard caliper brake.

Figure 15: Mounted Air Cylinder and Brake

The end of the air cylinder piston is fitted with a rung that is then able to be connected to a wire that connects to the brake. The theory is as follows: The air flows in the specified path.

Reservoir → Regulator → Switch → Air Cylinder

The air pushes the piston into the cylinder and causes the wire to pull the brake shut.

Mounting of the pneumatic system also utilized 3D printing in order to design and print a secure air reservoir mount, seen in the figure below.

Figure 16: 3D Printed Air Reservoir Mount

2.4 Electronics

With the design of the hydraulic system, it was evident that an electronic system would be needed to control the valves. Since many of the parts on this year's bicycle were recycled from last year's bicycle, there was ample room in the budget to purchase a programmable touchscreen interface. The electronics sponsor for the FPVC had human machine interfaces (HMIs) offered in startup kits, making it clear what items would be needed to get the circuit setup. In all, the system would take inputs from the rider as to which circuit he was wishing to use and send power to the appropriate coils for that circuit.

2.4.1 HMI (Human Machine Interface)

The HMI selected for the bicycle was an eXor 705. This model has a 5" touch screen and runs off of a 24V power supply[9]. For convenience, it came pre-installed with a CAN interface that made it possible to monitor the device in real time. A license of JMobile Studio was also included that allowed for a custom design for layout of the touchscreen. Basing the design off of a sample provided by the sponsor, the home screen was modified to include simple buttons for each circuit and the University logo. When a circuit is selected, the button glows green until another circuit is selected, or the same button is tapped again. An interlock works behind the scenes to ensure that it is not possible for two circuits to be selected at once.

Figure 17: Customized HMI.

2.4.2 Controller

The controller used on the bicycle came pre-programmed as part of the kit mentioned earlier so it would function well with the HMI that had already been selected. This Hydac TTC-32 controller[10] was accessed using CoDeSys 2.3, which was also provided in the packaged deal. By modifying the existing program, a circuit could be selected on the HMI and the logic could be seen functioning when a computer was connected via PEAK-Can. Unfortunately, this was the most functionality that was obtained from the system. Much trouble shooting was done with an expert in the field, but due to limited time and the remote work situation, this issue was never fully resolved. As it stands now, it would appear that there is either an issue with the wiring harness that connects the controller to the coils (see Figure 6) or with the other wiring, as a second controller did not fix these issues. This will be discussed further in the troubleshooting section.

2.6.1 Wiring

Wiring was done using wiring already in the lab, but ended up being more complicated than initially thought due to a difference in power supply voltage between the HMI and controller. Since the coils mounted to the valves required a 12V power supply, it was advised that the controller should also be operated on 12V, since it has a range of acceptable power voltages. Since the HMI requires 24V, two 12V batteries were used in series for the HMI portion of the circuit, while only one of the batteries was used to operate the controller. A common ground was used for both circuits. Using 14 gage wire, a combination of soldering and crimping was used to

create the circuit; soldering for the permanent connections, and crimping for those connections that were temporary to test the working of the hydraulic circuit. Some of these “temporary” connections became permanent as the controller was not providing the needed 12V to the coils.

2.6.1 Component Mounting

As the electronic components were not particularly heavy components and would not require custom sheet metal mounts, 3D printing was the ideal option for battery and HMI mounting. Ideally, the HMI should be positioned in an easily accessible location for someone riding the bicycle. Therefore the mount shown in Figure 18 was designed, printed, and secured to the center of the handlebars and allowed for the HMI to sit secured inside of it.

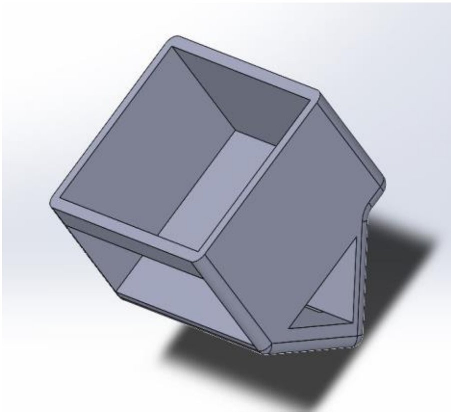


Figure 18: HMI Mount Design.

Figure 19: Mounted HMI.

The battery mount was also 3D printed and sat snugly on the top bar of the bicycle frame. The open sides allowed for simple removal of the batteries for charging purposes. The batteries were then secured with a secure, yet removable, band to keep them from sliding out on their own.

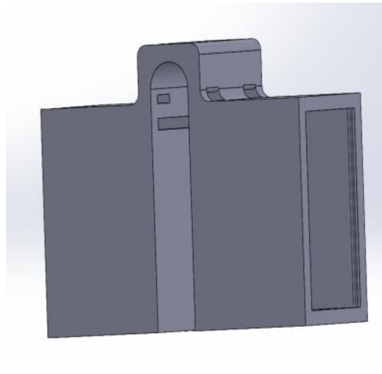


Figure 20: Battery Mount Design.

2.5 Valve Mounting, Hose Routing

After all the large hydraulic parts (accumulator, reservoir, pump, motor) had been mounted, more serious brainstorming could begin on where the valves were to be placed. It was desirable to have the main 4-way valve mounted as centrally located as possible to minimize hose lengths, but enough space was still needed that hoses would be able to make turns. After experimenting with some different locations, the valve was mounted directly to the sheet metal mount where it would not interfere with the chain path (Figure 21). This was generally thought to be the most accessible location, but in hindsight, it would have been advantageous to extend the sheet metal piece towards the rear of the bike to be able to pull the valve body further away from where the thighs would be traveling while pedaling.

Figure 21: Location of the Main 4-Way Valve.

Since the second valve only needed to connect to the motor and the reservoir, it could be mounted towards the rear of the vehicle. In Figure 22, it is pictured all the way at the back, mounted on the rear rack.

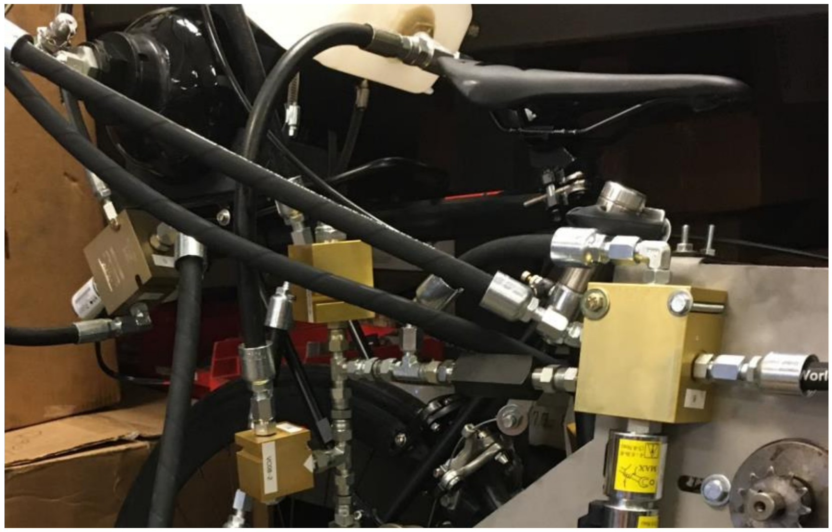


Figure 22: Location of the 3-Way Valve (Leftmost body).

Once the solenoid valve bodies were installed on the vehicle, the bicycle was taken to the Parker store on Gilchrist Rd. in Akron. NFPA competition rules stated that no team was allowed to manufacture their own hose assemblies, so by going to the Parker store, it was expected that the hose assemblies would follow all the appropriate standards as set forth by the various institutions. While at the store, the routing of each line was determined. Several check valves and relief valves were plumbed using rigid fixtures to attach them to previously mounted components. This reduced the need for further mounting and allowed for some weight savings. Once the rigid lines were in place, each connection was given specific attention so the best configurations could be made as at each end, there were straight, 45°, and 90° fitting options. By deciding which fitting ends would be the best and cutting a piece of hose approximately to length, the entire circuit of the bike was laid out before any hose got crimped to ensure that there would be no issues. Once the team was content with the layout, the technicians crimped the hose ends and everything was tightened down. Figure 23 shows the bike as it left the shop.


Figure 23: Bike with Hose Assemblies Completed.

2.6 Vehicle Operation

As mentioned in the introduction, this vehicle would function under the combination of hydraulic power and human power. The design features three driving modes which can be electronically activated through switches by the rider.

In regards to the direct drive system, the first step in the vehicle operation process would be for the rider to turn the pedals as they typically would when riding a standard bicycle. However rather than being directly connected to the rear sprocket by a chain, the chain from the pedal sprocket would spin the sprocket on the pump. As the pedals turn, the pump draws fluid from the reservoir and pushes it through the hydraulic system. Due to the fact that the design is a closed system, the pressure formed within the hoses and valves forces the hydraulic oil to move through the system in the direction of returning back to the reservoir. On its way there, the hydraulic oil is pushed through the motor on which sits a sprocket that is connected by chain to the rear wheel sprocket. So in complete summary, the rider pedals the bike which forces the hydraulic fluid through the system, spinning the motor, which spins the rear wheel and propels the bike forward.

During operation, a feature which the rider can take advantage of is utilizing the regenerative braking switch. While the rider is coasting the rear wheel spins by itself, which spins the motor, which draws the hydraulic oil within the system into the accumulator.

The final aspect of vehicle operation occurs when the rider uses the third switch to activate the accumulator discharge feature, which will cause the hydraulic fluid to be forced out of the accumulator and through the motor which will spin the rear wheel and propel the bike forward with no need for pedaling. At this time the rider can also pedal themselves, as they wish, and use the accumulator discharge as an assistance to pedaling.

2.6.1 Fluid Routing

For each different function of the bicycle, fluid takes a different path through the circuit, pressuring specific lines. The simplest route the fluid can take through the system occurs when both valves are in their neutral states. This was designed to also be the direct drive circuit in case of power failure. In this valve position, fluid flows to the pump from the reservoir, where it is pressurized using the rotational energy from the pedals. The pressurized fluid flows through a check-valve and past the relief valve which ensures the pressure is not too high. The 4-way valve directs the flow to the motor, where it turns the rear wheels via a chain drive. from the motor, depressurized fluid flows back to the reservoir through the 3-way valve, as displayed below.

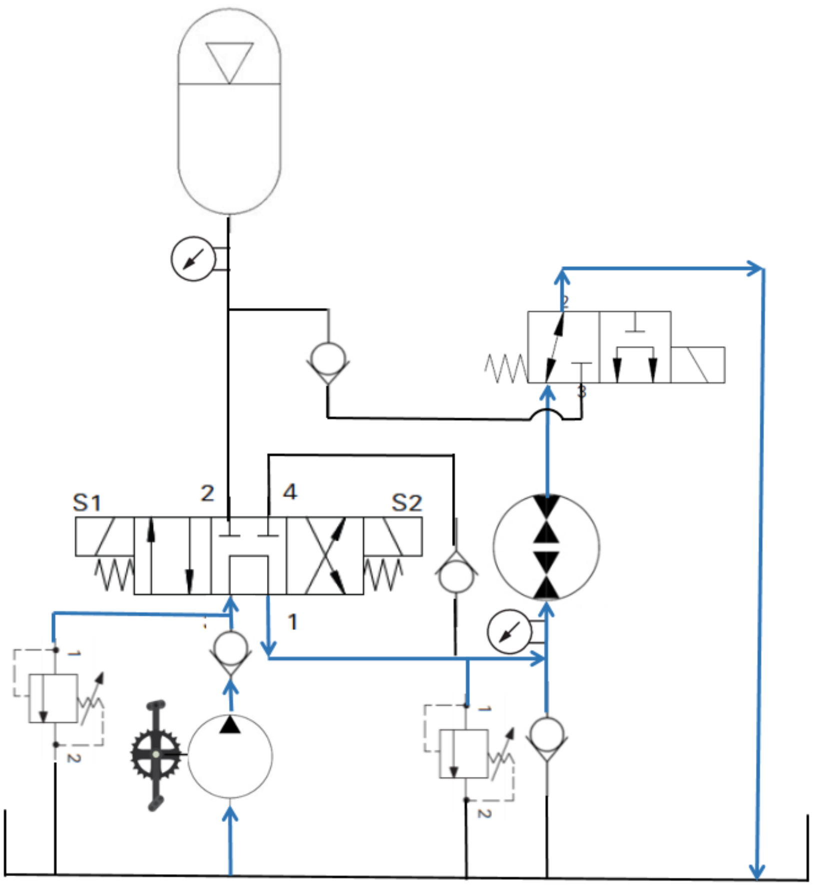


Figure 24: Direct Drive Fluid Flow Diagram.

In the accumulator discharge circuit, the S2 coil on the 4-way valve is activated. This drives the stored fluid from the accumulator through the valve and to the motor. On its way to the motor, it can be supplemented with fluid pressurized by the pedal pump. After the motor, it flows through the neutral state of the 3-way valve and back to the reservoir. This is shown in Figure 25.

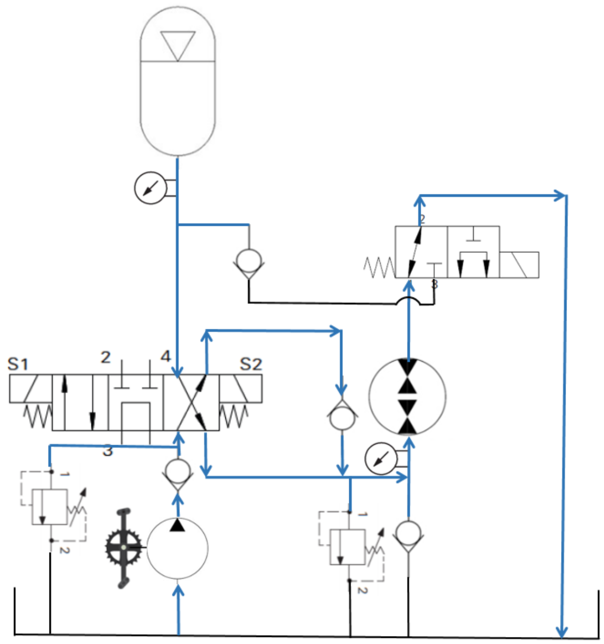


Figure 25: Accumulator Discharge Fluid Flow Diagram.

The charge circuit (Figure 26) is by far the simplest flow as there is no return flow to the reservoir. The flow simply goes from the reservoir to the pump where it is pressurized and sent past the aforementioned check-valve and pressure-relief valve. The 4-way valve (with the S1 coil energized) sends the fluid straight to the accumulator. In this circuit, the check-valve is of utmost importance. It prevents the accumulator pressure from back-flowing into the pump, turning the pedals the wrong way, and most unfortunately, losing all the stored energy.

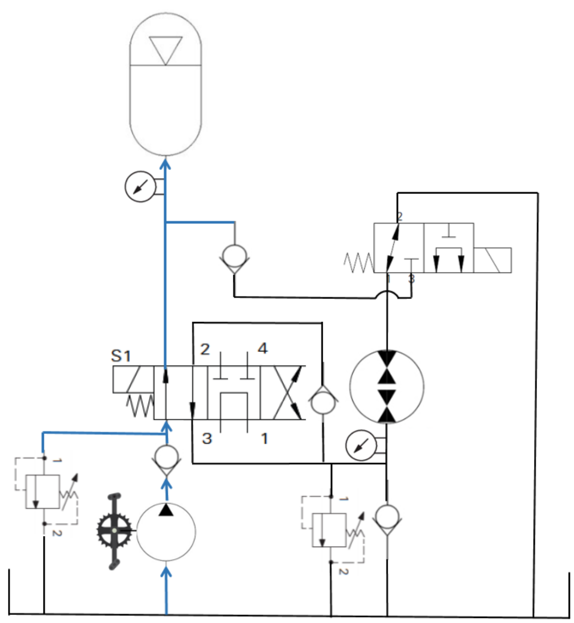


Figure 26: Pedal Charge Fluid Flow Diagram.

One of the most important circuits, the regenerative braking circuit, is the only circuit that requires power to the 3-way valve. In this circuit, the motor acts as a pump and pulls fluid out of the reservoir through the check valve that normally prevents pressurized fluid from dispensing into the reservoir. From the "motor" (acting as a pump), flow proceeds to the 3-way valve where it is directed to the accumulator. On its way, it passes through a check valve which protects the accumulator from discharging pressure to the motor. Using the motor as a pump in this setting enables the rear wheels to act like brakes, which was very helpful when charging the accumulator. For a flow diagram, see Figure 27.

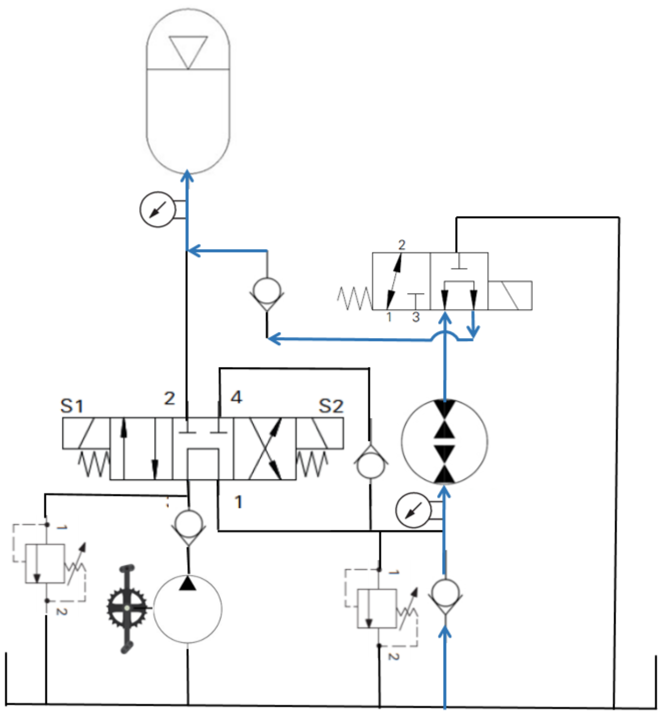


Figure 27: Regenerative Braking Fluid Flow Diagram.

Lastly, the coast circuit fluid flow diagram can be seen in Figure 28. While the valve positions are the same as the direct drive circuit, the fluid flow is different through the system. The flow is actually similar to the regenerative braking flow until it reaches the 3-way valve, where it is routed back to the reservoir instead of to the accumulator.

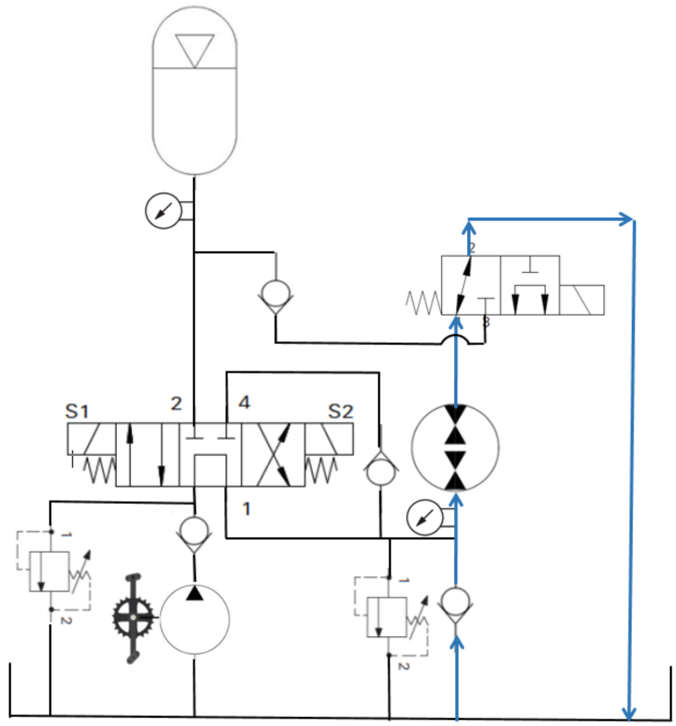


Figure 28: Coast Circuit Fluid Flow Diagram.

3. Design Verification

Throughout the course of the project, several measures were taken in order to verify that the decisions made and final design were the best possible options or routes that could be taken. This included iterative testing and consideration of rules, standards, and regulations.

3.1 Design Midway Review

The NFPA's Fluid Power Vehicle Challenge involves a Midway Design Review halfway through the year, around December/January. In this review, the planned design, progress, hydraulic circuit, pneumatics, and other midway progress checks are presented on. The purpose of this is for industry experts to judge the feasibility of what the team has designed and offer improvements before the individual projects progress too far. During the team's presentation in mid-January, several good suggestions were received from the judges, including changes that should be implemented to both the hydraulic circuit and the pneumatic circuit. Other concerns were also voiced that helped the team push towards progress in other key areas. First discussing the hydraulic system, the judges were quick to compliment the simplicity of the circuit that was presented to them. While the design did not include a custom manifold as some other teams across the country chose, the simplicity of the circuit did not require it. However, the judges recommended that an additional check valve be added to protect the pump from accumulator

pressures during accumulator charge. Interestingly, a check-valve had been included in the first complete design presented to an industry mentor, but it was removed over fears of air bubbles getting stuck in the valve. Nevertheless, it was added back in, as well as an additional pressure relief valve. Judges noted that in all circuits but one, the pump had pressure relief protection. The circuit that was unprotected was the accumulator charge circuit; the circuit to most likely utilize the pressure relief. Because of this oversight, another relief valve was added immediately adjacent to the pump to guarantee it was protected in all circumstances.

Besides the hydraulic circuit, the judges also gave recommendations for improvements to the pneumatic system. Most of the components that were previously selected were considered to be too heavy duty for what this project was trying to accomplish. After exchanging contact info, a meeting was scheduled with one of the judges from Norgren to go over more appropriate components. This meeting led to the final design as outlined earlier.

3.2 Testing of Hydraulic Circuit

The hydraulic circuit was tested in the lab for ease of tool access and easy cleanup. After all the valves, fittings, and hoses were attached and sufficiently tightened, the reservoir was filled with Lucant provided by Lubrizol. The bike had to sit while the fluid filled the system, allowing most air to rise to the reservoir. With the rear tire raised, the pedals were hand cranked slowly to create pressure, forcing any remaining air to the reservoir. The system was then checked for leaks and fittings were adjusted accordingly. This proved to be a continual process as over time, different fittings would leak at different times and would have to be adjusted as necessary. After all leaks were repaired, the bike was taken outside for a proof of concept test. In this test, the direct drive and discharge circuit were tested and demonstrated.

3.3 Nitrogen Pre-charge Pressure of the Accumulator

Nitrogen Pre-charge is an important parameter in the working of the discharge circuit of the vehicle. While on one hand greater precharge pressures provide a more forceful exit of the fluid, since the accumulator is a bladder style, that means that as the pressure of the precharge increases, the capacity of the accumulator decreases. With that principle not in mind, an initial error in thought process caused the accumulator to get pre-charged with far greater precharge than what was needed for the competition. However, this was an opportunity in disguise. During testing of the discharge circuit, the overpressuring of nitrogen allowed for the discharge to be tested at many different pre-charge pressures, until the final precharge of 800 psi was reached. After filling the accumulator with hydraulic fluid to its full capacity, the bike traveled much farther than what was anticipated, making this pressure a great success.

3.4 Troubleshooting

During the assembly and trialing of the bike the team ran into several issues. The largest of these issues was the alignment of the chain sprockets with the motor and pump sprockets. Had everything gone perfectly in the machine shop, the mount that was fabricated would have been better secured to the bike so that the alignment would be more in line. The mount was supposed to have been welded, but was instead bent into form, due to time constraints .Ultimately, this caused a need to add more reinforcement to the mount in order to get better alignment between the pedal drive sprocket and the pump sprocket.

The next issue the team ran into was that one of the motors that was reused from prior years seemed to have a bent axle. This caused the force required to turn the motor to be much greater than the bike could be pedaled at. This was discovered after several hours of troubleshooting. Ultimately the team was able to find a replacement motor.

Lastly, a large hurdle in the final days of the project was the malfunctioning electronics. Programs had been adjusted for use on both the team's HMI unit and controller, but when it came time to transfer the program to the controller, the team was unable to connect with the controller with two separate computers, prompting the sponsor to overnight a controller that was pre-programmed with the program the team sent him. This unfortunately did not solve the issues as will be discussed later in more detail.

3.4.1 Chain & Sprocket

As mentioned in the previous section, there were many issues with the alignment of the chain sprockets. This was due to the nature of the mounting bracket's initial iteration, which lacked some supporting features. This problem only exacerbated another issue as the chain would come off anytime the team would attempt to build pressure in the system. After experimenting at great lengths with varying lengths of chain, including the usage of a half-link, the alignment issue was solved with the addition of an L bracket, held against the mounting plate to give additional support. This corrected the misalignment between the sprockets, however, on occasions the front chain would still come off. This was due to the chain being improperly sized for the updated alignment and after resizing the chain to ensure the optimal tension, the issues went away. Similar issues were encountered in the rear of the bicycle. Once the correct length of chain was determined, different width spacers were experimented with, adjusting the offset of the motor from the frame.

Another advancement in the way of transmitting power from sprocket to sprocket was the addition of properly sized keyways on the motor and pump shafts. These keys allowed the motor/pump shafts to act as one rotational unit with the attached sprockets, increasing the stability, rigidity, and reliability of the chains.

3.4.2 Resistant Motor

Along with the sprocket alignment issues, the first installed motor was very resistant to turning. This issue exacerbated the chain alignment problem as the motor would not turn and create pressure in the lines. This would in turn put additional tension and force on the sprockets and chain, further bending the mounting plate. After replacing the motor with a spare that turned much more freely, the issue was resolved and the new motor worked as expected. Instead of the surges of motion that were occurring with the original motor, the new motor provided a smoother, evener rotation.

3.4.2 Electronics

Unsurprisingly, the electronics on the bicycle turned out to be one of the biggest headaches for the mechanical engineers working on this project. As delays in the 3D printing lab had delayed the battery mounts, the final wiring was pushed into the final days of the project. Once the wiring had been completed, transfer of the modified programs to the HMI and the controller could begin. While the HMI program transferred without a fuss, the controller prohibited the user from "logging in" to it, a required step before any data transfer can occur. Through contact with the controller supplier, it was recommended that another computer be used for this transfer, but this computer encountered the same error messages. With the sponsor out of ideas, there were not many options as the competition was just days away and some sort of electronic control was needed so the rider could switch between circuits during the various races. But there was one old-school option: individual switches. With some assistance from an Electrical Engineering colleague, a temporary system was wired up to power the coils while the sponsor transferred the team's program to a controller at their site, and overnighted it to the University. Later that day, it was discovered that a baud-rate mismatch between the computer and controller was what was causing the error messages, and for the first time, the controller could be accessed via a computer.

Much to the dismay of the team, even with the new program downloaded, and proper communication between the HMI and controller observed, there was still no power getting to the coils. Even the overnighted controller from the sponsor gave no improvement. However, proper logic action could be observed using the PEAK-Can bus. When a mode was selected on the HMI, the controller was shown to be activating the proper output pins. But for some reason, still unknown today, the coils were not getting the 12Vs they needed from the controller. With the Electrical Engineering colleague also stumped, the team decided to make the temporary solution a little more permanent in hopes that next year's team will be able to replace the wiring harness, as well as some other components to track down the electrical issue here.

3.5 Design Standard Compliance

In a production environment, this project would need to satisfy NFPA (National Fluid Power Association) standards. Notably, "NFPA/T2.12.11-1 R1-2009 (R2019) Fluid Power Systems And Components - Reliability Analysis, Field Data Reporting Format, and Database Compilation" would apply to our system. This standard includes recommended practices for the collection of data relating to reliability, maintainability, availability and maintenance of fluid power components and systems operating in the field. If proper fluid had not been supplied by a sponsor, NFPA/T2.13.14-2007 (R2017) could have been used to choose an environmentally acceptable fluid. For a better long-term design, NFPA/T2.24.2 R1-2007 (R2017) would be used to guard against external leaks, of which this bike did have some issues. In a more rigid environment that did not have such hard deadlines and competitive angles, many other standards such as NFPA/T3.5.24-2001 (R2016) could have been used to verify the set pressure of the pressure relief valves. Given more time for fabrication, NFPA/T3.5.1 R2-2002 (R2015) would have been used to mount the various valve bodies. In the end, the competitive element of the challenge meant that cost, performance, manufacturability, and reliability all had to be balanced, leaving little room for adherence to design standards.

4. Costs

As with any project, it is important to take into account the cost of manufacturing and production when analysing the success of a design.

4.1 Parts

The following is a breakdown of the cost of parts utilized in the chosen design. The chart features the retail cost for each of the items, the cost of buying in bulk, and the actual spending the team completed. As seen in the table, actual cost for hydraulic, electronic, and pneumatic components were recorded as $0. This is due to the fact that these parts were ordered from event sponsor catalogs and did not count towards the purchasing and spending. The team simply had to choose the components that were needed and the event sponsors shipped out what was requested. In addition to free catalog parts, there was easy access to previous teams' builds, parts, and equipment. Therefore, many of the components, particularly some of the more expensive investments such as the accumulator, pumps, and motors were able to be reused. This saved a large sum of money spent on this project.

Table 1: Parts Costs

Part	Manufacturer	Retail Cost ($)	Bulk Purchase Cost ($)	Actual Cost ($)
Bicycle	Golden Cycles	$276.89		$276.89
3D Filament (x2)	TecBears	$36.70		$36.70
Bike Rack	Dirza	$36.71		$36.71
Wide Crank Shaft	DONSP1986	$17.27		$17.27
12 V Battery (x2)	Interstate	$46.42		$46.42
Crank Puller Tool	Park Tool	$17.23		$17.23
Battery Charger	BeikAlone	$14.03		$14.03
Wiring Adapters (x2)	TOMALL	$19.42		$19.42
Hoses/Crimping	Triad Technologies (Parker)	$424.38		$424.38
Tubing Components	McMaster	$26.54		$26.54
Hydraulic Components		$8099.00		$0
Electronic Components		$1523.39		$0
Pneumatic Components				$0
Total				**$915.59**

Shown below in Figure 29 is a visual representation in the form of a pie chart of the transactions made in utilization of the sponsor stipends for purchasing components not directly supplied by event sponsors. The largest contribution for external spending can clearly be seen as being the hose and fitting purchasing from the Parker Store.

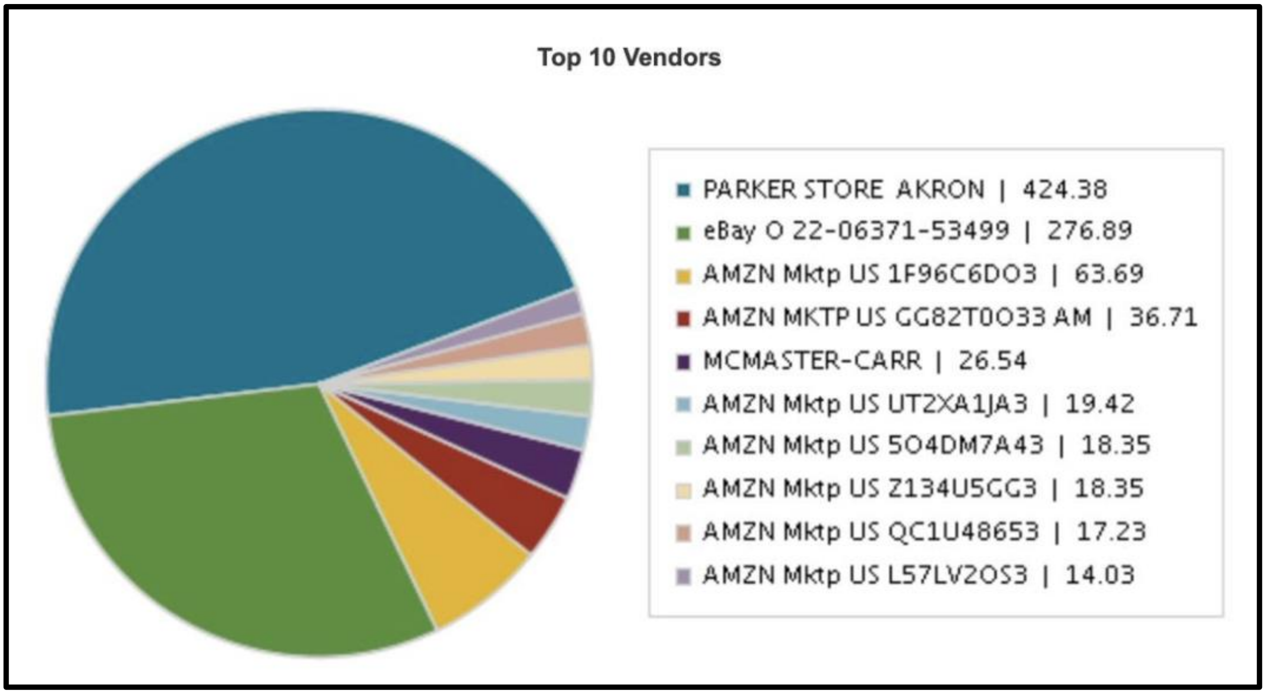


Figure 29: Purchasing Division

4.2 Labor

In addition to the cost of parts and materials, in a real world job environment, it is also important to take into consideration the cost of labor in completion of a project such as this one. This breakdown can be seen in Table 2 below. The hourly wage was chosen based on a typical starting engineer average of $30.

Table 2: Labor Cost

Team Member Name	Man Hours	Hourly Wage	Total Compensation for Project
Alex	400	$30	$12,000
Evan	400	$30	$12,000
David	400	$30	$12,000
Luke	400	$30	$12,000
Jacob	400	$30	$12,000
Totals	2,000		$60,000

5. Conclusion

Looking back at the introduction, the purpose of this project was to create a functional vehicle which combined the use of human and hydraulic power. Some secondary goals included gaining a better understanding of hydraulics and pneumatics, meeting with industry professionals, and taking on this hands-on experience to test the knowledge of the students. Ultimately these combined into a more official goal of being able to compete well against other universities in the NFPA sponsored Fluid Powered Vehicle Challenge. The subsection below discusses the team's accomplishments and future considerations.

5.1 Accomplishments

Throughout this project the team worked extremely hard and well as a team. The bike was designed and built to completion according to necessary deadlines, and the team was able to compete in the NFPA competition against other universities. As mentioned earlier, the competition was scheduled to be in Colorado, however due to COVID limitations the competition had to be completed remotely. Each of the universities in the event completed the three races remotely, on their own time, under strict rules and guidelines. Part of these guidelines included capturing all race footage on video with timestamps so that judges could thoroughly judge each vehicle. With the results of the competition finalized, the team found that the

designed vehicle competed well in all challenges across the board and even won first place in the endurance challenge. This was a mile long time trial in which halfway the rider had to come to a complete stop and then continue at least 10 feet solely by accumulator discharge filled by regenerative braking during the first half of the race. Winning this specific challenge proved to feel the most accomplishing to the team as it signified that all three drive modes of the design functioned well.

5.2 Ethical considerations

The EPA has strict guidelines on the disposal of "used oil" as detailed in Title 40 Chapter 1 Subchapter 1 Part 279. Hydraulic fluid is considered to be hazardous to the environment as well as hazardous to humans. Special care was taken during the testing of the vehicle to ensure that a minimal amount of hydraulic fluid was spilled. An oil drain pan was used to collect hydraulic fluid when components were removed or adjusted to contain the spills. Along with the special care that was used, the fluid used was biodegradable, typically vegetable oil adapted and modified to be used as hydraulic fluid.

5.3 Future work

When looking at future work considerations were made to set future groups up well. As seen in competition, the current outcome is a well thought out design that with some tweaking and more time could be a winner across the board in the NFPA competition next year. There are a few things that future groups could work on. One of the things that presented a difficult time was the electronics portion of the competition. A key aspect of this struggle was getting the designed electronics to control the valves due to an issue with the controller. Future groups could use the equipment purchased along with a new wiring harness or controller in order to add these electronics to compete at a higher level in this part of the competition. Another option for a future group would be to design a hydraulic manifold to tidy up the bike, making it look more appealing. This would condense all of the hoses and valve bodies into a simpler, smaller physical presence. It is also recommended to reduce the number of fittings in order to reduce the possible points a leak could happen. Another way to reduce leaks is to mount all valves securely and consider vibration damping as many fittings can self loosen during operation. In vehicle testing, it is highly recommended to test different precharge pressures for the accumulator.

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Appendix A - Requirement and Verification Table

Table 3: System Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. Functional Direct Drive Circuit	1. Physical Testing a. Pedal with rear wheel of the ground b. Riding the bike around outside c. Competing in event challenge	Y
2. Functional Regenerative Braking Circuit	2. Physical Testing a. Rolling bike around in order to draw fluid in b. Lifting rear wheel and activating discharge to see if fluid was stored c. Testing with rider coasting downhill	Y
3. Functional Accumulator Discharge Circuit	3. Physical Testing a. Lifting rear wheel and activating discharge to see if wheel spins b. Actually riding the bike to test if discharge will support weight	Y
4. Safe operation at high pressure	4. Professional Hose Crimping a. Completed at Parker Store	Y