Fluid Power Vehicle Challenge
Final Design Review

April 18, 2019

Prepared by

Jacob Torrey
jttorrey@calpoly.edu

Aaron Trujillo
artuji17@calpoly.edu

Kayla Londono
klondono@calpoly.edu

Bryson Chan
bchan19@calpoly.edu

Sponsor
Dr. Jim Widmann
jwidmann@calpoly.edu

Advisor
John Fabijanic
jfabijan@calpoly.edu

Mechanical Engineering Department
California Polytechnic State University
San Luis Obispo, CA

Statement of Disclaimer

Statement of Disclaimer Since this project is a result of a class assignment, it has been graded and accepted as fulfillment of the course requirements. Acceptance does not imply technical accuracy or reliability. Any use of information in this report is done at the risk of the user. These risks may include catastrophic failure of the device or infringement of patent or copyright laws. California Polytechnic State University at San Luis Obispo and its staff cannot be held liable for any use or misuse of the project.

ABSTRACT

Final Design Review (FDR):
"Fluid Power Vehicle Competition (FPVC) 2020 Final Design, Manufacturing and Testing"
Bryson Chan, Aaron Trujillo, Kayla Londono, and Jacob Torrey

The FPVC combines mechanical engineering disciplines to design and manufacture a vehicle that utilizes hydraulic power. The FDR covers the final manufacturing process and verification processes developed during the front end of research and analysis built upon the Critical Design Review (CDR) and the PDR (Preliminary Design Review). This report showcases the design decisions and extensive research that supports the continuing efforts by the Team Pump My Ride, to build upon the accomplishments of Cal Poly's previous team, The Incompressibles. The FDR presents how Team Pump My Ride produced the design changes from the CDR and PDR to achieve improvements to the vehicle's performance. The FDR is detailed with the procurement methods, validation procedures, results, conclusions, recommendations for next year's team. In addition, details about the virtual competition are included in this report. Major changes that were made during manufacturing included reconstruction of the rear drive train, installation of the new manifold with soft lines, mounting the controller unit, re-designing the controller software and hardware, installation of new bike tires, and re-orientating the accumulator. Testing that was completed include a full trial run for competition as well as testing different pre-charge pressures. In addition, a user manual was developed in order to aid the next team's members to operate the bike. This report proceeds to conclude team Pump My Ride's efforts to improve the vehicle and finish as a high-ranking competitor in the 2020 Fluid Power Vehicle Challenge.

<u>Disclaimer:</u> This report is meant to be used as a guide for basic orientation with the 2020 Cal Poly Fluid Powered Vehicle. This is a dangerous machine that can cause grave bodily injury if misused. This report is in no way complete and should not be treated as such. High pressure hydraulics are inherently dangerous, and care should be taken whenever in the vicinity of the vehicle. Likewise, the Li-Po battery used on this project must be fully understood to prevent injury or fires. By using the vehicle, you take full responsibility for your safety and the safety of those around you.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

The National Fluid Power Association (NFPA) holds the Fluid Power Vehicle Challenge (FPVC), an engineering competition which prompts students to design and build a human-powered vehicle propelled with a hydraulic system. The vehicles were meant to compete in a sprint race, endurance race, and efficiency challenge with additional scoring based on safety and a final presentation. In addition to the existing competition events, a new independent challenge was proposed and judged based on the best use of pneumatics within the vehicle design. However, since March 2020, the COVID-19 pandemic forced the competition to go virtual. As a result, team vehicles were not judged by physical challenges, but by online presentations only. Nonetheless, the judges, professionals from the fluid power industry, evaluated the holistic design. Prior to the unprecedented pandemic, Team Pump My Ride built upon the work completed by the previous Cal Poly team, The Incompressibles, to improve vehicle performance and compete for first place overall at the FPVC. The NFPA and Cal Poly, SLO, represented by advisor Dr. James Widman, were the main sources of funding for the vehicle, as well as the stakeholders for the team. The goal of this report is to provide details for Pump My Ride's final vehicle design—including the manufacturing process, testing operations, and virtual competition results. The background section includes meeting summaries, previous competition information and our team's research on component selection and performance. The objective section emphasizes the goals and specifications the team accomplished to arrive at the end goal of a high-performance vehicle. The concept design has been updated to reflect new design changes and transitions into the decisions for the final design of the vehicle. The project management section includes new important dates that were needed in order to be approved for competition, complete milestones for development of the vehicle, receive funding and further steps needed for testing and manufacturing. Three new sections were updated since the CDR including Section 5 Final Design, Section 6 Manufacturing, and Section 7 Design Verification. Section 5 showcases the team's final design, how it works, and how it meets our engineering specifications. Section 6 provides detail on our procurement, manufacturing, outsourcing, and assembly of the vehicle. Section 7 details verification processes needed to prove that the vehicle meets the design specifications. Since CDR, we added Section 8 Project Management, Section 9 Competition, and Section 10 Conclusion & Recommendations. Section 8 provides detail on deadlines and accomplished tasks. Section 9 includes the results from our midway review and final review for the NFPA FPVC. Lastly, Section 10 summarizes the most important results and gives recommendations for Cal Poly's future teams.

Team Members:

Bryson Chan: *Sponsor Contact, Treasurer*
Jacob Torrey: *Testing Coordinator, Editor*
Kayla Londono: *Modelling, Project Planner*
Aaron Trujillo: *Manufacturing Coordinator*

2 BACKGROUND

This section of the report discusses customer, product, and technical research to identify important aspects and considerations for our vehicle design. Some additions since CDR have been made to

reflect the change of circumstances from COVID-19, such as the move to a virtual competition. However, most of the background research is unmodified because it drove our problem definition, engineering specifications, and design decisions until March 2020.

2.1 JUDGMENT CRITERIA AND AWARDS

The Design and Specification Midway Review, final presentation, team interactions with industry mentors and the competition results are all factors considered in determining the award winners. The original award categories and monetary values are presented in Table 2.1, followed with descriptions of the competition challenges. The efficiency challenge formula is provided in Appendix A. This information was used to make decisions throughout the project timeline and was only changed after the competition became virtual, as presented in Appendix B.

Table 2.1: Competition Information

AWARD	Challenge Description	Judgement Criteria
Overall Champion 1st place: $3,000 2nd place: $2,000 3rd Place: $1,000	See Judgement Criteria.	First place overall champion will not be eligible to win more than one of the following: sprint race, endurance, or efficiency challenges.
Best Presentations: $2,000	See Judgement Criteria.	Midway review score to be included in evaluating winning presentation.
Sprint Race: $1,000	Heats of vehicles will compete on a 400 – 600 ft course to achieve the fastest time.	Top three scores to be considered for placement. Final 1st place will be determined by a number of factors.
Efficiency Challenge: $1,000	Vehicles will test storing and expelling efficiency capabilities using only stored energy.	Top three scores to be considered for placement. Final 1st place will be determined by a number of factors.
Endurance Challenge: $1,000	Vehicles will attempt to complete a set distance course that tests reliability, durability, regeneration, and repeatability.	Top three scores to be considered for placement. Final 1st place will be determined by a number of factors.
Best Use of Pneumatics, Sponsored by Bimba: $500	See Criteria	To be considered for award, teams must display creativity, efficiency, and safety.
Best Design: $500	See Criteria	To be considered for award, teams must display innovation, uniqueness and originality of the design. Selected by Student Teams.
Best Reliability and Safety: $500	See Criteria	To be considered for award, teams must take sufficient steps to prevent injuries from hardware and surpass a 1-year warranty.
Best Workmanship: $500	See Criteria	Best degree of skill, expertise and quality in vehicle.
Best Teamwork: $500	See Criteria	Best attitude and cohesiveness of team.

2.2 REGULATIONS AND STANDARDS

For the NFPA to hold a safe and sustainable competition, all teams were required to build vehicles that adhere to competition rules. The vehicles needed to pass a technical inspection before official entry. The rules from the previous competition were largely kept the same with some alterations and additions. The major rules and regulations are listed below:

The previous rules implemented by the NFPA have included the following:

- Vehicles are human powered and propelled with a fluid link between the pump and motor.
- Vehicles must have an energy storage device (typical designs use an accumulator), which is to be used within its safe working limits. Vehicles will be pre-charged before each event, and once an event is begun, only human power can be used for recharging.
- Vehicles must be capable of regenerative braking.
- The hydraulic oil used must be environmentally friendly.
- Only a single rider is allowed. The rider must be able to enter, exit, start, and stop the vehicle unassisted.
- Maximum weight for the vehicles is 210 lbs. if the vehicles are to be shipped. There is no weight limit if the vehicle is not being shipped.
- Zero external hydraulic leaks will be allowed.

Rules explicitly changed or added to the 2019-2020 include the following:

- The maximum volume of all the accumulators must not exceed one gallon.
- One pressure indicator is *recommended* to be in front of the motor but where it can safely be read to determine the normal peddling pressure and for proper charging of the accumulator.
- All pressure indicators are subject to judges verifying their accuracy with the use of SunSource supplied diagnostic test point.
- A second pressure indicator is required to be between the accumulator port and any other valve in the system.
- All components on the competition bike need to stay on for all races although the configuration may be altered.
- Each bike will be weighed in advance of the event races. The initial weigh in is the weight that will be used for all the races. 1% of your score for each pound over 210 lbs. will be deducted from each of the 3 event races.
- teams will be able to order parts from this list, up to $4000 in total value (used to be $2000)
- Be sure to include two pressure indicators (1) at the outlet of the accumulator with the test port and (2) before the hydraulic motor.

The complete set of rules and regulations held by the NFPA can be found at NFPAhub.com [1].

2.3 CUSTOMERS

The customers that were addressed for the 2019 – 2020 Fluid Power Vehicle Challenge, include Pump My Ride, Dr. James Widmann, Advisor John Fabijanic, and the NFPA FPVC judges, with Pump My Ride as the primary customer. The team has handled the manufacturing, operating and optimization of the selected vehicle for the competition. The team designed a vehicle with a scope

of work which is reasonable and challenged them to exceed at competition. Dr. Widmann advised and funded the project. John Fabijanic contributed to progress by advising the team in the senior project class. Both advisors' major concern was the completion of the project. The challenge advisor assigned to us by the NFPA, Kevin Lingenfelter, met with us four times to discuss design considerations. We were also fortunate to have industry mentorship from Mark Decklar with HydraForce who helped with the design of the hydraulic circuits and components. Our NFPA mentor and judge for the competition, Kevin Lingenfelter, helped our team prepare for the midway review and final review and to navigate the competitions rules and guidelines. Additional concerns included performance, weight, manufacturability, cost and most importantly safety. There was a substantial concern for safety because we were working with high pressures and electronic circuitry. The NFPA customer needs were defined as competition guidelines in the form of requirements and events meant to take place at the in-person competition. These events included a sprint race, an endurance challenge, efficiency challenge, best presentation, best design, best teamwork, best workmanship and best reliability and safety. Pump My Ride acknowledged these interests and designed a comprehensive vehicle that meets the advisors' expectations to excel at competition.

2.4 MEETINGS/INTERVIEWS

James Widmann (4/16/19) - The interview with Dr. James Widmann covered background information, advice for the competition, and general advice for a successful senior project. Dr. Widmann's expectations for the competition emphasized safety, engineering design process, teamwork skills and the overall learning from the project. Widmann recommended that Pump My Ride reach out to Ernie Parker from the NFPA, the previous team, The Incompressibles, Dr. Owen (a hydraulics emeritus professor from Cal Poly), and Mark Decklar from HydraForce. Regarding vehicle design, Widmann advised increasing the efficiency of converting input power to output power. Additionally, Dr. Widmann advised exploring the possibilities of increasing speed by using a larger accumulator, building a composite frame, and installing a clutch.

The Incompressibles (4/23/19) – The meeting with The Incompressibles team members, covered the process they followed in creating their vehicle, the challenges faced as a team, and obtaining further information about the competition they participated in recently. The Incompressibles focused on winning the endurance challenge because it was safer for them to create an endurance focused bike. This design also proved advantageous for the efficiency challenge. For modeling, the team used Simscape to find the inputs their hydraulic circuits needed to hit performance goals in each challenge. The Simscape model covered four different drive modes which included coast, direct drive, regeneration, and discharge. The Incompressibles' vehicle was a comprehensive redesign from the previous model. The new model took the existing dimensions from a Trek bike frame and used the Patterson control model to improve low-speed handling characteristics. They provided us with their project documentation, of which their FDR was a helpful reference [2].

Industry Advisor Mark Decklar (4/23/19) – The interview with Mark was an introduction to Pump My Ride's hydraulics advisor. Mark Decklar works at HydraForce, a company that sells and distributes hydraulic components. Mark answered questions regarding fittings, hard/soft lines, and the use of a linear pump for competition. Mark also gave The Incompressibles a purpose-built

hydraulic microcontroller for the team to test, but it arrived after their mechatronics plan was made and they were unable to begin using it.

Nick Gholdoian (4/29/19) - Our team met with Nick a member of team Incompressibles. We discussed how to use the Simscape modeling for verification of the bike. An improvement to the modeling was to get real time data and implement them into the model. The Simscape model is designed to be very general and this year we plan to improve the model to verify this year's bike.

James Widmann (4/30/19) - Discussed in this meeting was the submission of the scope of work. Widmann found the scope of work to be acceptable and has allowed our team to proceed to PDR. Some action items that our advisor suggested were to assign a safety lead for the team, contact Jim Gerhart for pre-charging our accumulator. Widmann also mentioned a potential budget for the project to be around $4000, contingent on the left-over money from last year and the future funding from the NFPA.

James Widmann (5/14/19) - The meeting addressed our team's design considerations and our current progress. We discussed ways to bleed the accumulator, additional use of the power pedals, endurance testing and the different type of valves. A suggestion Dr. Widmann made to the NFPA was to limit accumulator energy for safety. This will be addressed when the rules are released. Other important discussions were the comparison of poppet valves vs. Ball valves, using a manifold, flipping the orientation of the accumulator and different ways to store the hydraulic fluid. Our team agreed with Dr. Widmann to focus on improving hydraulic efficiency and to keep the frame of the bike.

Mark Decklar (6/3/19) - Our discussion with Mark Decklar covered our goals and components that we will focus on for the competition. Mark has provided multiple devices for testing which included, linear pumps, manifolds, slow opening poppet valves, and solenoid drivers. We discussed ideas for the fluid circuit diagrams for the different drive modes that will be incorporated with the redesign of the manifold. The new fluid circuit diagrams will allow us to eliminate the coast mode by using a control valve where fluid can only go in one direction. This means that coast mode will be activated whenever the rider is not pedaling. In addition to this, by replacing one of our BOSCH rotary pumps with a linear pump, we can use the extra pump in parallel with the back motor to replicate gear shifting by increasing the torque output. With further research and developments, we will be keeping in contact with Mark to discuss redesigning the manifold in terms of using multiple manifolds for different systems or redesign the internal structure itself.

Jim Widmann (10/3/19) – This was our first meeting back with Dr. Widmann after the summer break. The damage to the bike components were discussed and addressed. Dr.Widmann connected our team to the Mustang 60 Shop Advisor, Eric Pulse, to potentially store the bike at the shop for easier access to the bike when testing. New rules for the competition and important dates were discussed in order to recieve funding for the project from the NFPA.

NFPA (10/4/19) – The NFPA held a webinar for students, advisors, and NFPA members to initally meet. We met Stephanie and Ernie Parker, who are both representatives of the NFPA FPVC. Important rule changes, location, and important dates were discussed in the meeting. The first stipend was awarded to our team for the participation of all our members and advisor.

Mark Decklar (10/9/19) – This was the first meeting with Mark Decklar after the summer break. Important ideas discussed at the meeting was the usage of parallel pumps with the free pump that would be left over after incoporating linear pumps to the bike. Fluid schematics using I-Design were introduced to simulate fluid flow and pressure points in the system. Access to HydraForce software was also introduced to our team.

Mark Decklar (10/16/19) – At this meeting the team discussed using a new controller due to the mechatronics failing. The ECDR 0506A and software packages for programming was introduced. Fluid schematics were being finalized for the CDR presentation.

Jim Widmann (10/17/19) – Our team met with Dr. Widmann to discuss the practicality of proceeding with pumps in parallel. Dr. Widmann also discussed final budget for this year‘s competition with the requirement of maintaining $2000 for the next year‘s competition. A major discussion that was addressed was clarifying that the changes produced by our team for the CDR were justified for our team to compete in the competition.

Mark Decklar (Updated) – The following meetings with Mark detailed software and hardware assitance, reciving of the manifold and LCD monitor, and update to hydraulic designs. Mark was a major factor in mentoring our team and providing resources and hydraulic components.

Kevin Lingenfelter (Updated) – Kevin Lingenfelter was our mentor and judge for the competition. He assisted our team with competition rules and guidelines and preparation for midway review as well as final presentation. The meeting summaries submitted to the NFPA competition for points are provided in Appendix C.

2.5 EXISTING DESIGNS

This section covers the vehicle designs of the 2018-2019 Fluid Power Vehicle Challenge. The five designs cover the first, second and third place overall winners, as well as the winner for reliability and safety, and the rookie of the year. Each year, teams must prepare a 15-minute presentation about their vehicle for judges and peers which give insight into designs for future participating teams. An understanding of the top teams' component selections, testing results, lessons learned, and overall performance led to a better course of action for Pump My Ride.

2.5.1 2019 COMPETITION RESULTS

The Incompressibles, the 2019 Cal Poly team, won first place for the endurance challenge with a significantly faster time than the other teams, as seen in Table 2.2.

Table 2.2: Endurance Challenge

Place	University Name	Time
1st	Cal Poly, San Luis Obispo	4:50:45
2nd	Cleveland State	5:40:00
3rd	Montana State University	5:45:48
11	University of Cincinnati	-
15	Western Michigan University	-

Western Michigan University won the efficiency challenge by obtaining the highest score, determined with the formula; efficiency score= (WxL)/(PxV), where W is the total bike weight including the rider in lbs, L is the distance traveled in inches, P is the pre-charge pressure of the accumulator in psi and V is the accumulator volume in cubic inches. The scores and distances travelled for the teams to be discussed is presented in Table 2.3.

Table 2.3: Efficiency Challenge

Place	University Name	Efficiency Score	Max Distance
1st	Western Michigan University	31.62632	1943
2nd	Cleveland State	10.46315	466
3rd	Cal Poly, San Luis Obispo	7.535498	515
4th	Montana State University	4.160544	605
13th	University of Cincinnati	1.706769	1044

The overall winner, Cleveland State, won first place for the sprint challenge, closely followed by Murray State University. Both teams had very competitive times as presented in Table 2.4.

Table 2.4: Sprint Challenge

Place	University Name	Best Time (s)
1st	Cleveland State	14.71
2nd	Murray State University	14.94
3rd	Western Michigan University	21.75
4th	Purdue University	22.24
5th	Cal Poly, San Luis Obispo	23.09
8th	Montana State University	35.70
9th	University of Cincinnati	36.91

The scores and times presented assisted our team in developing goals for the 2020 competition.

2.5.2 COMPETITION WINNERS

Overall 1st Place Winner- Cleveland State

Figure 2.1: Cleveland State - Overall 1st Place

Cleveland State finished first in the sprint competition and was awarded best presentation. They rebuilt their previous model from a bicycle to a tricycle. The components they used for this design was a bent axis displacement pump, a manual ball valve, and a 2.5-gallon carbon fiber accumulator, sourced from Steel Head. Their sprint time was 25.62 seconds and in a mock endurance challenge, traveled an estimated 3660.38 ft (with 2.5-gal accumulator) and 695.42 ft (with 0.5-gal accumulator). They charged the accumulator via chain and sprocket which was powered by the pedals at the front of the vehicle. Cleveland suggested several improvements could be made including an increase to the back-end gear ratios for the hydraulic pump, adjusting the motor orientation, moving the idler gear, and relocating the bearing housing. They also replaced the 2.5-gal accumulator with a 0.5-gal accumulator to increase their weight to distance ratio for the efficiency challenge.

Overall 2nd Place Winner- Cal Poly

Figure 2.2: Cal Poly SLO - Overall 2nd Place

The Cal Poly team, The Incompressibles, finished first in the endurance competition. They designed and built a custom steel frame that was modeled after the Trek FX Sport 4 bike frame with significant changes to improve low speed stability. The front drivetrain used a 2-speed crankset with a derailleur. They utilized an Apex Dynamics Right-Angle Planetary Gearbox in addition to a two-speed crankset to give primary gear ratios of 10.3:1 and 6.3:1. The hydraulic pump they used was a Bosch AF20-5 bent axis pump. For the rear drivetrain, they used a chain drive with a 3:1 gear ratio and another Bosch AF20-5 bent axis pump. The mechatronic subsystem used by this team was an Arduino Nano Microcontroller with solenoid drivers that controlled solenoid valves, pressure sensors, and speed sensors. The PCB board was designed using eagle. MATLAB Simscape and FEA models were used to simulate bike performance and frame analysis. The testing results found were a 4:15 mile time, 21.5 sec sprint time, and 52-55 points for efficiency testing based off the competition guidelines. The team encountered several problems with their vehicle: chain slipping on the front chain ring, insufficient chain wrap on planetary sprocket, and poor chain tension. A proportioning valve was added to reduce pressure spikes, to keep accumulator pressure blowing through seals in the motor. For future teams, The Incompressibles suggested having a designated welder for fabrication, redesigning placement of the front drivetrain for better chain tensioning, investigating pump cavitation while pedaling and in regen mode, begin manufacturing as soon as possible, and to check torque on fittings.

Overall 3rd Place Winner- Western Michigan University

Figure 2.3: Western Michigan University – 3rd Place

Western Michigan University finished 1st in the efficiency challenge. This team selected the TOBUL4.5AL accumulators because of its low "weight to volume ratio of 1.08 gallons to 20 lbs. in weight. They custom built their frame from aluminum due to its light weight and manufacturability. Some problems they faced were, leaks in the pump at high pressures, the battery dying after a short time of use, regenerative energy recovery not working well, uphill pedaling was difficult, feet sliding off pedals, need for a longer bar for hand pump, and vehicle was very close to max weight of 200 lbs. Some revisions made were attaching a gear train for regenerative braking and adding straps to pedals for feet. Suggestions for future competitors were to design the hydraulic circuit to be in direct drive when valves are not energized, start fabrication as soon as possible, and to understand major hydraulic components before designing.

Rookie of the Year - Montana State

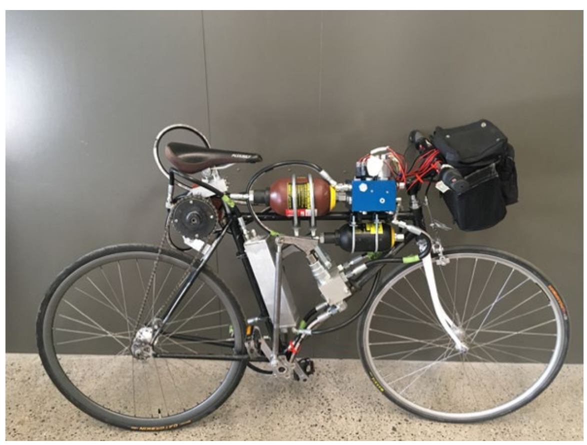


Figure 2.4: Montana State – Rookie of the Year

The rookie of the year team, Montana State, has a selection of components which included an accumulator from Accumulator Inc. one having a pint and the other being a quart of volume. An Eaton IN-Line Axis Motor and HydraForce hand pumps were also selected for components. For the controls of their project they used electrical solenoid controllers, proportional control valves for the throttle and a direction control valve for the switches. The manifold they selected was came

from HydraForce. Some improvements needed were an increase in gear ratio, the need for a charging mechanism and to adjust linkage placement. For future designs their team would focus on better organization to keep track of components to reduce surplus costs, having a purpose-built frame for better component placement and interference issues, hose management to reduce excess hose lengths to improve system efficiency and better time management to make adjustments to optimize the system.

Best Reliability and Safety- University of Cincinnati

Figure 2.5: University of Cincinnati – Best Reliability and Safety

The University of Cincinnati was ranked highest in reliability and safety. The PLC they selected was an IDEC FC6A-C40R1DE because of its ease to program and the rider could control solenoids using buttons or switches near the handlebars. Some cons to this PLC was that it was costly, bulky and needed to be covered. Future improvements were to increase starting torque to overcome statics by increasing gear ratio, considering multiple designs, and to improve communication.

2.6 COMPONENT RESEARCH

The unique challenge of using fluid power to propel the vehicle requires an extensive knowledge of many components of a hydraulic system. The fundamental layout and function of components utilized by competition teams consists of a power input supplied by the rider which is converted to pressure in the hydraulic system by a pump to be supplied to the motor. The energy in the system is stored as pressure in the accumulator which can then be discharged through the motor to propel the vehicle. When in regeneration mode, the motor acts as a pump by putting energy into the system, and as a motor when in boost mode. The individual components which may be incorporated into the design were researched with specific emphasis placed on the parts chosen by The Incompressibles.

2.6.1 FRAME

Research states that there are three elements to consider in frame design: geometry, material, and wheel size. These elements aim to optimize the vehicle stability, handling, reliability, weight, and cost.

Geometry

Frame geometry primarily influences handling, stability, strength and weight. For brevity, we list the most important rule of thumbs (ROT) to summarize how geometric changes affect performance, refer to Figure 2.6 and Figure 2.7 [3].

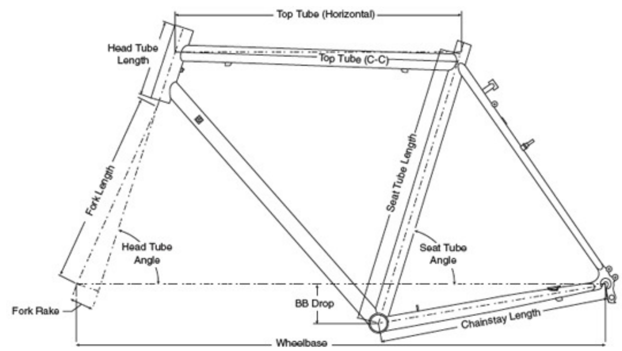


Figure 2.6: Bicycle Frame Geometry [3]

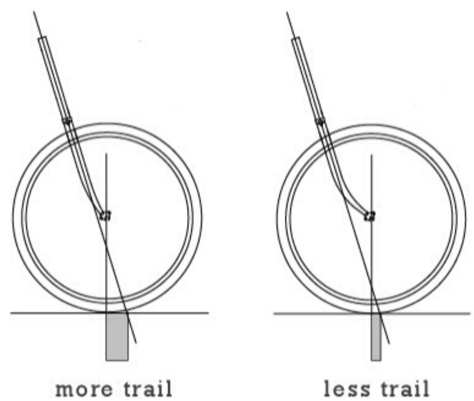


Figure 2.7: Trail [3]

ROT #1: Increasing the head tube angle makes the steering slower.
ROT #2: Increasing the fork rake makes the steering slower.
ROT #3: Less trail equates to faster steering.
ROT #4: Increase in overall geometric proportions increases weight and size.
ROT #5: Lower bottom bracket (BB) drop lowers center gravity and ground clearance.
ROT #6: A longer wheelbase increases the stability at faster speeds.

Cal Poly's 2018-2019 team, The Incompressibles, built a custom frame mirroring a Trek FX 4 cross-country bicycle. Thus, the geometry reflects the "middle ground" between a road bike and a mountain bike. The Incompressibles reported satisfactory performance in terms of handling, stability, and reliability. Additionally, their custom frame significantly improved upon Cal Poly's 2017-2018 team by reducing weight from 13.8 lbs to 8.6 lbs.

Material

The frame material is important in terms of manufacturability, cost, and weight. Aluminum, steel, and composite frames are actively used in the bicycle industry. Last year's team used 4130 Steel

because of its weldability and strength. An aluminum frame might be worth exploring; however, strength and manufacturability may be significantly reduced for a small reduction in weight and cost.

Wheel Size

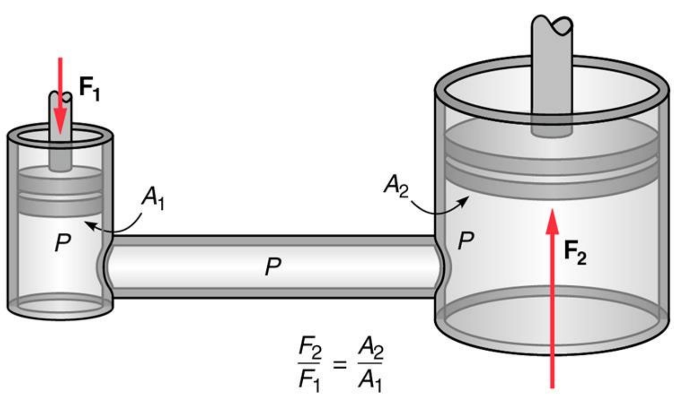
Wheel diameter and width are the most important considerations when sizing wheels. The wheel diameter adds to the overall weight and friction in bearings. In comparison, a 650c makes 823 revolutions to travel one mile while a 700c makes 763 revolutions to travel one mile. More revolutions over the same distance traveled equates to more work done by friction. As a counterpoint, 650c are typically on the order of 8% lighter than 700c wheels.

Tire width affects rolling resistance and energy absorption from road imperfections. Traditionally, it is thought that narrower tires roll faster. However, VeloNews tested a variety of tire sizes to determine how width affects vehicle speed. They concluded, "If a wider tire is made of the same materials in the same thickness as a narrower one, it will roll faster, because (1) the internal friction and hysteresis within the tire's materials will be lower, and (2) because the surface imperfections in the road will be absorbed into the tire more easily (since it has more deflection available), thus lifting the bike and rider slightly less with each little impact" [4]. Based on this evidence and the knowledge of competition road conditions, Pump My Ride retained 700C X 32 tires.

2.6.2 HYDRAULICS

Hydraulic Circuit

The hydraulic circuit consists of all components that hydraulic oil flows through. Hydraulic oil is incompressible and is therefore ideal for transmitting pressure from one location to another within a hydraulic system. In an ideal model, all points in a continuous hydraulic system are subjected to the same pressure. According to Pascal's law, as seen in Figure 2.8, both area one and two are at the same pressure; therefore, the force at each point is dependent upon the area of the piston. This type of hydraulic force multiplication is commonly used in automotive braking systems such that a relatively small force at the pedal applied by the driver is converted to a large force at the braking surfaces. In the hydraulic system we are using, the hydraulic oil acts as a medium to transmit work from a rider to the tire of the vehicle. In a typical bicycle, this job is accomplished by a system of chain and sprockets.



$$\frac{F_2}{F_1} = \frac{A_2}{A_1}$$

Figure 2.8: Pascals Law Diagram

The hydraulic circuit design will be adapted to the overall vehicle design and the individual components selected. The one requirement specified by the competition rules is that there must be three modes; direct drive, regenerative braking and accumulator discharge. Additional modes may be included for enhanced performance or safety. The modes are developed with multiple hydraulic circuits connecting the required components. The mode is chosen with the opening and closing of valves which direct fluid flow through the required components.

Valves, Lines and Fittings

A significant aspect of the hydraulics design is the choice of valves used to control the vehicle mode. The most advantageous valves minimize leakage. The lines and fittings of the vehicle had a significant impact on vehicle performance. The Cleveland State team at the 2019 competition tested a variety of fittings on their vehicle and found that removing a single elbow reduced their sprint speed by two seconds, which is significant considering their speed was already capable of winning the sprint challenge. The adjustment of fittings and lines on The Incompressibles' bike had potential to greatly improve vehicle performance. Their bike experienced large pressure losses when changing between drive modes which could be addressed by minimizing the number of fittings and connections, or with different procedures to change drive modes. Pump My Ride investigated the implementation of hardlines as a replacement for the soft lines used by The Incompressibles. Hydraulic soft lines are easier to include than hardlines because their position can be adjusted without manufacturing new lines. The incorporation of hardlines would require detailed planning at the start and additional manufacturing if changes were made. However, the soft lines are only available in pre-determined lengths which required excess length to be incorporated into the bike by The Incompressibles, increasing weight and decreasing efficiency, two of the main considerations for the overall vehicle design. The selection of valves, line and fittings presented an opportunity to increase the efficiency of the hydraulics and decrease vehicle weight.

2.6.3 POWER TRANSFER

Pumps and Motors

The past two Cal Poly teams have used the Bosch hydraulic pump for both the pump and the motor. This unit is a "bent-axis" design, that makes use of a swash plate to drive a number of small pistons in a reciprocating motion. This pump design allows for a smooth pressure delivery and comparatively high efficiency. In addition, the Bosch unit is much lighter than the Parker F-11 pump/motor used by other teams using a rotary pump design (Bosch-5.5 lbs. vs. Parker-12 lbs).

Another pump design considered was the linear piston style used by Murray State. This design was relatively simple with a piston inside a cylinder used to compress fluid, like a floor jack. One goal for our preliminary design phase was to obtain this style of pump and test its viability as an alternative to a more "conventional" design. Linear pumps had potential to prove more advantageous from a biomechanical viewpoint, as using two pumps in a "stair-stepper", or in a piston and crank arrangement, like a stationary engine. By changing the arrangement in this way, it could have been possible to get away from the sinusoidal power input that is inherent to a typical

bicycle's crank and pedal arrangement. The plan post PDR was to perform linear pump feasibility testing once Mark Decklar provided the correct fittings. Further details on pump investigation post PDR are provided in Section 5.7.2.

Accumulators

According to the rules of the 2020 Fluid Powered Vehicle Challenge, the vehicle was required to be capable of storing energy. In hydraulic systems, energy storage is usually accomplished with an accumulator. There are many different types of accumulators, but the two styles in common use in previous Fluid Powered Vehicle challenges were piston and bladder. In a piston accumulator, energy is stored by forcing hydraulic fluid into a cylinder against a piston that is pre-charged either with a spring or a high-pressure gas. A bladder accumulator operates in a similar manner, but instead of fluid being forced into the accumulator against a piston, it is forced against a rubber bladder inside the accumulator that is pre-charged with high-pressure nitrogen.

Brakes

There are a variety of options for bicycle braking designs. The simplest is the cable actuated rim brake that is in use on most bicycles. Cable actuated brakes are simple, inexpensive, and not prone to failure. The downside of cable actuated brakes is the limit of mechanical advantage. The other commonly used style of bicycle brake is the disc brake. Disc brakes are available in cable and hydraulic actuation. Disk brakes are self-cleaning and offer increased mechanical advantage which enables a rider to better modulate braking force. The disadvantages of disc brakes include increased cost, complexity, and the need to use frame parts that are designed for disk brake use.

2.6.4 MECHATRONICS

The microcontroller selected for the vehicle functioned as the controller for switching solenoid valves which determined the vehicle driving mode. The microcontroller was also meant to collect data for pressure in the accumulator and speed of the bike. The Incompressibles used an Arduino controller to control these tasks. An LCD display was mounted to the handlebars of the bike that tells the rider which driving mode the rider is in and the pressure left in the accumulator. There were two main microcontroller types explored as options for integration into our vehicle design; an Arduino Microcontroller and the Raspberry Pi Microcontroller.

Figure 2.9: Arduino UNO Rev 3 Microcontroller

The Arduino Microcontroller, pictured in Figure 2.9, is versatile and simple. The platform allows for a variety of applications without complicated hardware redesign. Libraries exist for the solenoid driver circuits, sensor data collection circuits, and switch circuits. Arduino is a proven industry controller which helps save time in debugging and board design. The Arduino also provides the advantages that it is cheap, simple to set up, and easy to connect electrical and mechanical components. A disadvantage for this system is that it can only run one code at a time, does not have internet connection capabilities, and requires the user to know C++ [5].

Figure 2.10: Raspberry Pi Microcontroller

The Raspberry Pi is based off a Linux operating system. The Raspberry Pi, as seen in Figure 2.10, has more complex features not necessary for the applications of this project. Additionally, it is a faster operating system than the Arduino, includes built-in Bluetooth, Ethernet, audio, camera, USB and HDMI outputs. However, the microcontroller is more expensive than the Arduino and requires a longer set up with the need of external components. It may be also necessary to install programs to get the controller to perform simple actions [5].

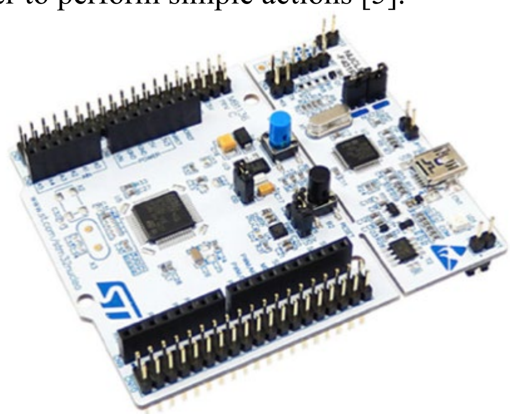


Figure 2.11: STM 32 Nucleo Development Board

The L6206 device is designed for motor control applications. The microcontroller combines isolated DMOS power transistors with CMOS and bipolar circuits on the same chip. Features include thermal protective shutdown and a non-dissipative overcurrent detection. The STM32 Nucleo, presented in Figure 2.11, can be easily extended with many specialized application hardware such as the Arduino Uno. STM32 Nucleo users have access to embed online resources allowing to build a complete application in only a few minutes.

Hall effect sensors work by measuring the magnitude of magnetic forces, as shown in Figure 2.12. The output voltage is directly proportional to the magnetic field strength. Hall effect sensors can be used for multiple applications such as proximity sensing, speed and distance. For this project the hall effect sensors could be used to measure distance as well as velocity of the vehicle. This could be done by attaching a magnet to the wheel and having the hall effect sensor measure when the magnet passes the sensor.

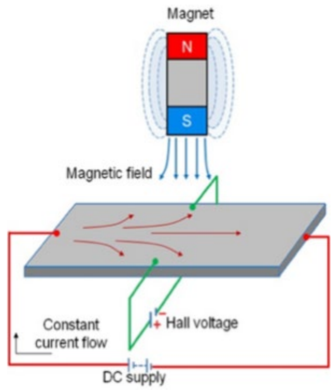


Figure 2.12: Hall Effect Sensor Diagram

Valve drivers manufactured by HydraForce offer fully configurable control of proportional valves or time-based ramping. These drivers are Arduino compatible and take an input voltage to activate or no voltage to deactivate. The valve drivers can be modified to control solenoid valves to the user's preference. Users can set the control signal of the valves and each valve will perform identically. These drivers are compact and reliable when controlling valves.

Figure 2.13: Single-input Valve Drive

The software is programmable and can control the speed at which valves could be opened. In Figure 2.14 a ramp control could be implemented into the valve driver to control the speed at which the valves open. This is an advantage because dispelling pressurized fluids at a ramped rate will increase the efficiency and protect against motor blowout venting all accumulator energy into the reservoir.

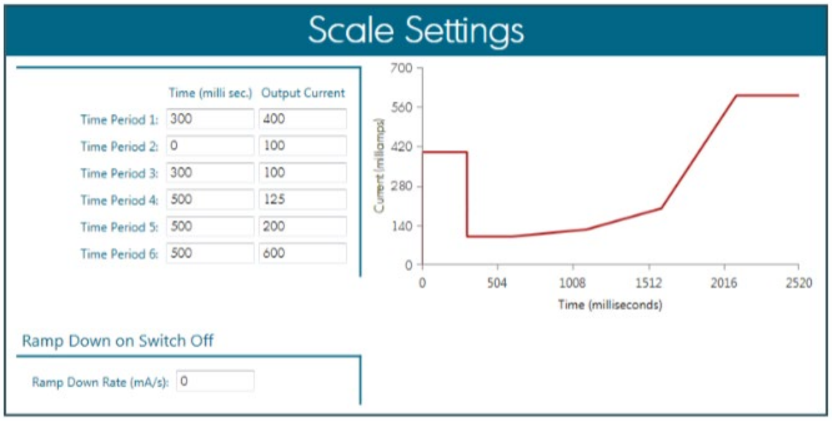


Figure 2.14: Valve ramping as a function of time.

2.7 VEHICLE OPERATION

When The Incompressibles' bike was delivered to us, it was not in working order, and we were not aware of the proper bike operating condition. We were unable to charge the accumulator past 800 psi, and even reaching this level took far longer than expected. It was eventually determined that air had entered the hydraulic system which was manually bled from the system. The hydraulic circuit was charged, and a line was opened at the highest point in that circuit to force the air out. On the current bike, the manifold is the highest point in the system and does not have a bleed screw. If a bleeder could be added at the highest point in each circuit, it would vastly simplify the process to bleed the system reducing the time required.

3 OBJECTIVES

Pump My Ride determined objectives which defined the project goals, evaluation criteria and deliverables.

3.1 PROBLEM STATEMENT

Pump My Ride set a goal to design and build a fluid powered vehicle (FPV) that places Cal Poly as overall winner at the annual FPV Challenge in Littleton, CO. In order to achieve this goal, the team made additions and improvements upon designs created by previous teams from Cal Poly. In general, Pump My Ride focused on improving the vehicle's hydraulics, power train, manufacturability, modeling, and testing. Specifically, our design work centered on removing flexible hydraulic lines in favor of hardlines, minimizing the number of hydraulic circuit restrictions (i.e. eliminate fittings where possible), investigating the addition of a clutch, and completing manufacturing early to allow time for sufficient testing of vehicle performance.

3.2 BOUNDARY DIAGRAM

Figure 3.1 displays Pump My Ride's system boundary diagram. The boundary diagram is a sketch of the relationship between various sub-systems. A single-ended arrow represents a one-way

interaction, while a double-ended arrow represents a two-way interaction. The two most prominent sub-systems included the hydraulics and powertrain. These sub-systems involved multiple components interacting within its own system and other sub-systems.

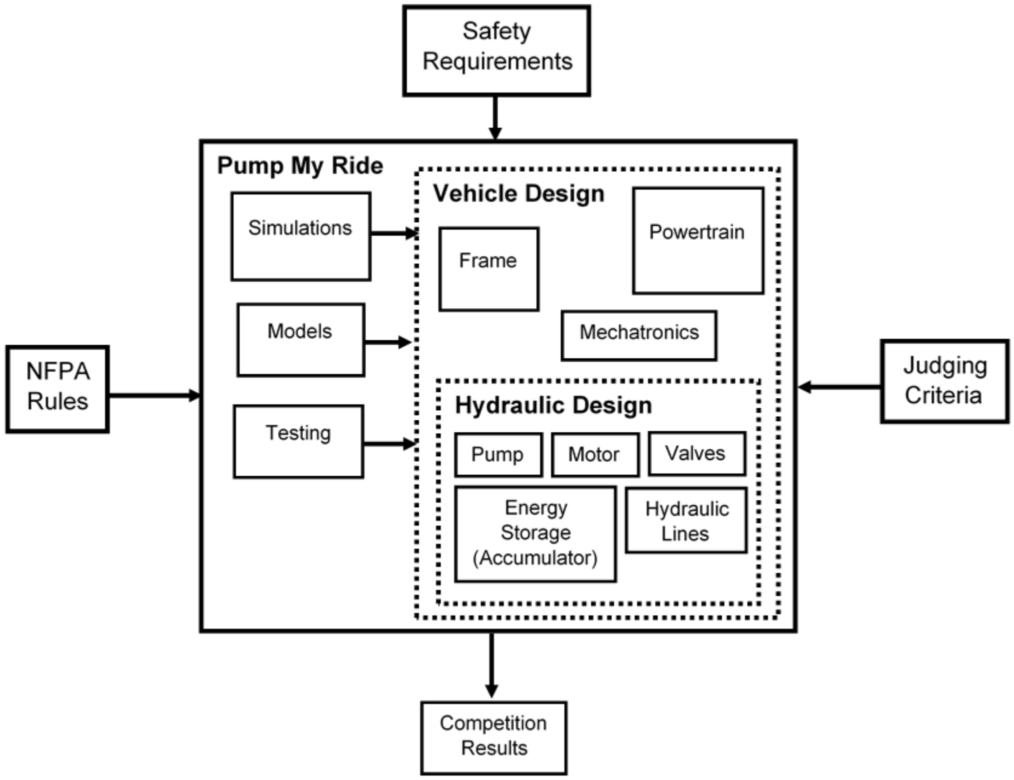


Figure 3.1: System Boundary Diagram

3.3 CUSTOMER WANTS AND NEEDS

This project was unique among senior projects in that we were included as one of the customers for the project. Additional customers were our project advisor, Dr. Widmann, and the competition judges. The team's wants and needs included winning the overall competition by designing, building, and testing a quality vehicle that satisfies all rules of the competition, and capable of winning the three individual events. Dr. Widmann's primary concern was safety and the improvement of the engineering skills of the team, while his secondary concerns included cost, weight, and performance of the vehicle. The competition judges had the same primary concern of safety, and secondary concerns that were outlined in the rules and judging criteria. Additional customer needs are identified in Appendix D.

3.4 ENGINEERING SPECIFICATIONS

The Quality Function Development (QFD) process guided our team in determining engineering specifications based on the needs and wants of our customers through the creation of a House of Quality, located in Appendix E. The engineering specifications are presented in Table 3.1 with their associated requirement or target value, tolerance, risk level (high, medium or low), and compliance check method (Analysis, Testing, Inspection, and/or Similarity).

Table 3.1: Engineering Specifications

Spec. #	Parameter Description	Requirement	Tolerance	Risk	Compliance
1	Sprint Time	18s	Max.	H	A, T
2	Endurance Time	4 min 30 s	Max.	M	A, T, I
3	Efficiency Score	23%	Min.	M	A, T
4	Weight	100 lbs.	Max.	H	A, T
5	Top Speed	40 mph	Max.	M	A, T
6	Braking Torque	FoS= 2 Compared to Motor Torque	Min.	M	A, T
7	Turn Around Time	7 min	Max.	H	A, T
8	Power Required by Rider	300 W	Max.	H	A, T
9	Life of the Vehicle	2 years	Min.	M	A, T
10	Internal Leakage	2 psi/s	Max.	H	A, I
11	External Leakage	0 drips	Max.	H	A, I

A description of each engineering specification and how they were measured are as follows:

1. *Sprint Time* - A sprint time of 18s is an improvement of about 20% from The Incompressibles, a reasonable goal to be competitive against other teams. An anticipated 15% improvement by competing teams would put Cleveland State at a winning time of about 12 seconds, but we guessed this would be unlikely by rule changes to limit their accumulator energy, as their last bike had a 2.5-gal accumulator at 3000 psi. The sprint time was simulated in the Simscape model and validated with a mock challenge event of the final vehicle design.
2. *Endurance Time* - A four-minute endurance time is an improvement of about 15% from The Incompressibles endurance time of 4m and 50s which greatly surpassed the other teams at the 2019 competition. The Simscape models were used to compare the previous bike performance and the performance of our design to predict the endurance speed. Vehicle tests, following the NFPA challenge guidelines, verified the specification.
3. *Efficiency Score* – The Incompressibles competition score was 4% but achieved 23% previously in practice under the new efficiency formula. Our goal for our bike was to do no worse than last year, which would be competitive in the field.
4. *Weight* - The vehicle was planned to be shipped to competition, which the rules limit a weight of the vehicle to 210-lbs. The frame and components of the bike was designed around the weight requirement. The overall weight of the bike was calculated based on component and frame weight throughout the design phase and verified on a scale once construction was complete.
5. *Top Speed* - The competition rules required the vehicles to run at a safe speed. A 40-mph limit allowed for design freedom while remaining at a safe speed. During the design phase. models predicted the top speed and verified with testing after build.
6. *Braking Torque* - Brakes on the vehicle must be sufficient to hold the vehicle at a stop against a fully charged accumulator. The maximum amount of braking capability was measured by how much braking torque the brakes are able to supply to the tires.

Calculations and testing with accumulator discharged at maximum pressure verified the design.

7. *Turn Around Time* - The competition rules specified a time limit of 10 minutes between challenges to fully prepare for the next event, including pressurizing the system. Analysis and similarity was used to determine the expected turn-around time when designing the vehicle. After manufacturing, timed tests verified the 10-minute limit was not exceeded.
8. *Power Required by the Rider* - The vehicle relied on human-power to assist the hydraulic system. We must ensure the power required by the rider to reach our endurance challenge goal is within human capabilities. The MATLAB model for losses and input requirements was used to predict the expected rider power which was verified with testing. 300 W was chosen as this is the value that, according to a NASA human power output chart, "healthy men" can output for a duration of 10 minutes (discussed in Section 4.4).
9. *Life of the Vehicle* - The vehicle may be reused by future teams if designed for a 2-year lifespan. The lifespan was predicted with modelling and analysis of the individual components and overall system.
10. *Internal Leakage* – Any internal leakage decreases the efficiency of the vehicle. Past teams had issues with valves leaking down and accumulator pressure blowing through the motor when switching modes, which wastes accumulator charge and ruins efficiency. The system models predicted pressure loss over time and motor blowout to indicate the internal leakage which was verified with testing components and the overall bike.
11. *External Leakage* - The competition rules specified a zero-tolerance for external leakage. The signs of leakage are visible or indicated by pressure loss. The vehicle was inspected for signs of leaks during each use and after major builds.

The engineering specifications with the highest risk were sprint speed and power required by the rider. Both specifications required a large increase in efficiency of the hydraulics circuit. A comprehensive redesign of the hydraulic circuit and elimination of restrictions from The Incompressibles' vehicle is the only way to achieve these goals. Additionally, eliminating the front drive-chain issues decreased energy losses that need to be overcome by the rider to put power into the machine.

4 CONCEPT DESIGN

This section of the report describes the vehicle design direction and concept development process utilized by Pump My Ride. Once a thorough background knowledge on the competition, current vehicle, and individual components was developed, the team moved forward with the design process. We conducted ideation sessions for overall vehicle designs and potential improvements to The Incompressibles' bike. The most useful method of ideation was brainwriting in which four rounds were held where each team member generated three ideas in five minutes, an example is provided in Appendix F. Also included in Appendix F, are very simple concept models the team utilized to investigate the mechanisms of a linear pump and the component layout on the bike. Further discussions of the design considerations explored are provided in the following section.

4.1 MODELS

The vehicle performance with alternative design considerations and the adherence to the engineering specifications were evaluated with Simscape models originally developed by The Incompressibles, and with the Patterson model. The models provided a basis for determining the optimal allocation of resources and assisted in making design decisions to build the most competitive vehicle possible.

4.1.1 THE PATTERSON MODEL

The Patterson model is the dynamic model used to design bicycles at Cal Poly. The model is designed from a comprehensive dynamic analysis of a bicycle system as a whole. The Patterson model is unique among existing dynamic models in that it accounts for the intention of the rider in control of the machine. Inputs to the model included wheelbase, location of the center of mass, handlebar radius, radius of gyration, bike/rider system mass, head tube angle, wheel radius, and trail. For this analysis, a MATLAB script was written to output both control spring and control sensitivity as a function of vehicle speed. As can be seen in Figure 4.1, the curve of control spring begins positive and becomes exponentially more negative. The point at which the curve passes through zero is the point at which the bike becomes self-stable (~12 mph).

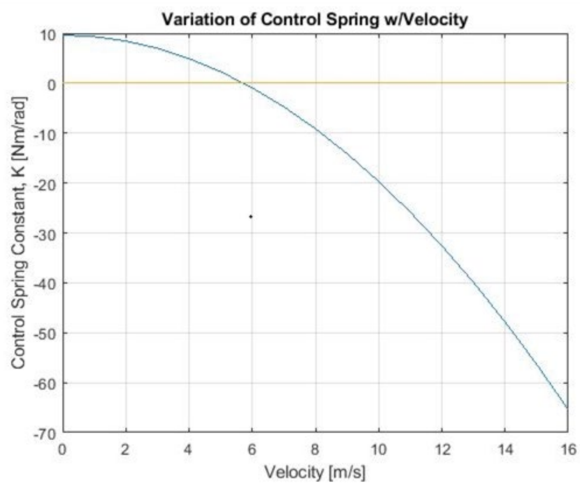


Figure 4.1: Patterson Model Control Spring Plot

4.1.2 SIMSCAPE MODELS

The Incompressibles utilized MathWorks software to develop Simscape models with a main MATLAB script which may simulate the direct drive, accumulator recharge or accumulator discharge mode. Simscape is a simulation tool which represents physical systems with block diagrams in which the blocks represent the components in the system; for example, pumps, motors, valves and more.

Direct Drive

The direct drive model, presented in Figure 4.2, considered equivalent fluid resistance in the pipes, motor inertia, fluid properties, rolling resistance of the rear tire, and the total mass of the bike to determine hydraulics losses and leakage.

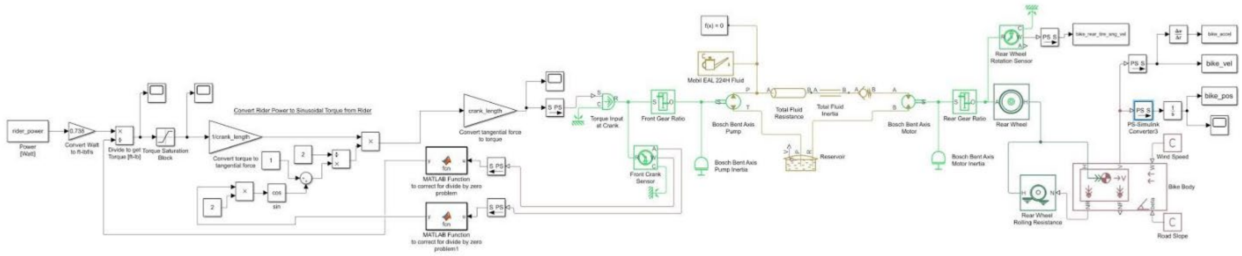


Figure 4.2: Direct Drive Simscape Model

The direct drive model, adopted from The Incompressibles, and unedited by Pump My Ride assisted in making design decisions through the CDR based on predicted endurance times. The accuracy was not yet determined with the testing completed by The Incompressibles or Pump My Ride. The differing physical capabilities and characteristics of the riders varied too largely to use one general power input profile to obtain representative results. Pump My Ride attempted to use power pedals to characterize the actual rider power input for incorporation and validation of the model. The team spoke with technical support from the manufacturers of the power pedals, used their help and were still unable to obtain reasonable results. The technical support was unwilling to help diagnose the pedals because their only claimed use was for typical road bicycles. This led us to continue with the use of a rider power input of 300 W, until validation testing was performed on the bike. Detailed reasoning for the use of a 300W power input is provided in Section 4.4 and further Simscape model development is provided in Section 5.4.2.

Accumulator Discharge

The accumulator discharge model, as presented in Figure 4.3, and described through this section, was used for decision making and predictions through the PDR. This model was meant to characterize the bike performance in the sprint challenge by considering the equivalent fluid resistance in the pipes, motor inertia, fluid properties, rolling resistance of the rear tire, and the total mass of the bike to determine the distance travelled over time. The model output was validated with competition results and testing by the Incompressibles.

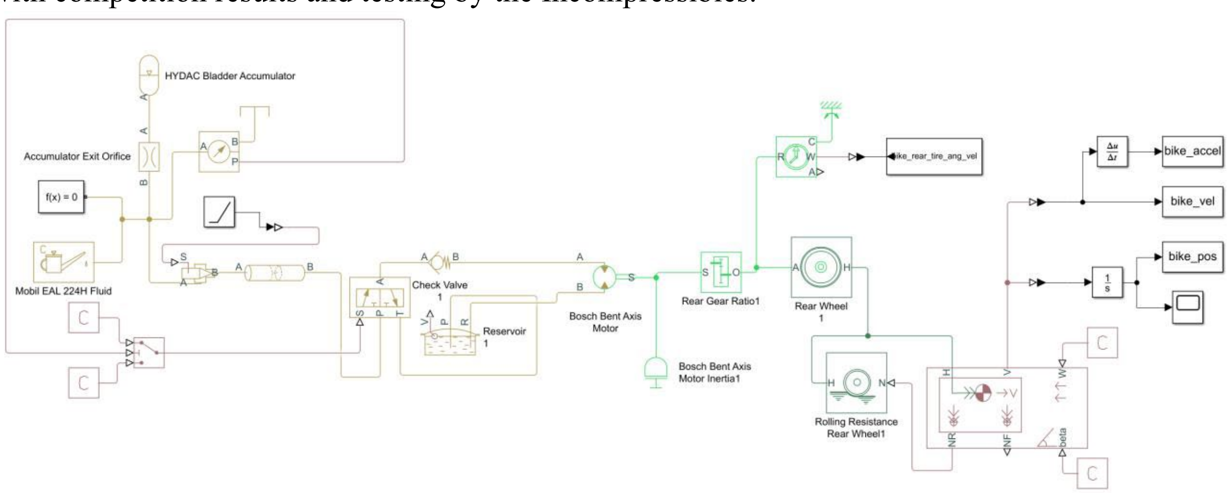


Figure 4.3: Accumulator Discharge Simscape Model

Pump My Ride increased the accuracy of the model adopted from The Incompressibles by including the ability to adjust rider weight and incorporating properties which better represented the hydraulic lines on the bike. The predicted sprint time was 22.36s with inputs which matched the conditions of the bike, rider and environment for The Incompressibles during the 2019 competition. The model had a 3.16% error from the actual sprint time of 23.09s. The model was run again with the properties of hard lines and all other inputs held constant to produce a predicted sprint time of 20.24s. Additional parameters were to be incorporated into the model for performance predictions after PDR. Specifically, the model as used through PDR only operated with a pre-charge pressure of 900 psi. Pump My Ride planned to make adjustments until the model was capable of incorporating a much larger range. These updates are provided in Section 5.4.2.

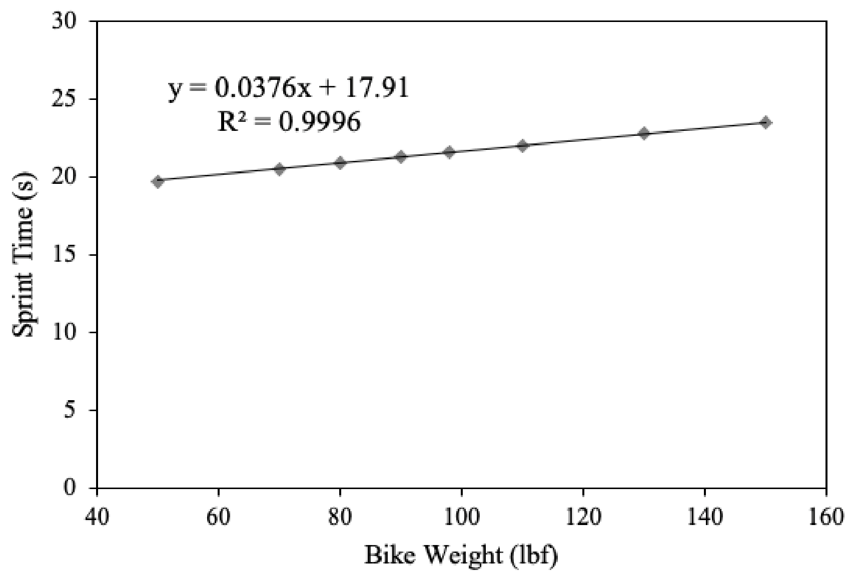


Figure 4.4: Relationship between Sprint Time and Weight

The time to complete the sprint challenge for various bike weights was determined by the Simscape accumulator discharge model and is represented in Figure 4.4. The slope of the graph indicates that each pound added to the bike weight increased the sprint time by 0.0376s. Also, the minimum sprint time achievable was predicted to be 17.91s unless additional changes, other than vehicle weight, were made to the bike.

4.2 FRAME

According to last year's rules, the NFPA specified that teams returning to competition are required to choose one of three options: (1) keep the hydraulic components and manufacture a new frame, (2) keep the frame and redesign the hydraulic system, or (3) build an entirely new vehicle. This year, however, the rules only dictate that "significant changes" must be made to the vehicle. The Incompressibles' goal was to design and build a lightweight frame with improved packaging efficiency. Their new design cut vehicle weight by 13 lbs. Moreover, the frame helped them achieve success at competition; judges noted their lightweight and packaging design distinguished them from other teams, contributing to their placement of 2nd overall.

4.2.1 FRAME SELECTION

Pump My Ride decided to keep the Incompressibles' hallmark frame for an upright standard bicycle. The implicit reward of designing and building a new frame does not offset the estimated 50-100 hours of work required. Therefore, Pump My Ride made modifications to the frame to accommodate packaging and integration of the improved subsystems.

Although we saw an advantage in keeping the Incompressibles' frame, Pump My Ride considered alternate frame concepts before making a final decision. We did not want to neglect innovative concepts that might help us place 1st overall. As a result, we investigated four frame concepts: (1) upright standard bike, (2) prone bike, (3) velomobile, and (4) elliptical. We tabulated these frame concepts along eight weighted criteria in a decision matrix. Then, we assigned values according to each frame's strengths and weaknesses. Table 4.1 displays Pump My Ride's final scores for each frame type. A negative score dictates an inferior concept and a positive score dictates a superior score, in comparison to the datum.

Table 4.1: Frame Type Decision Matrix

Criteria	Weight (1-8)	Frame Concept			
		Upright Standard Bike	**Prone Bike**	**Velomobile**	**Elliptical**
Weight	7	Datum	-7	-7	-7
Cost	2		0	-2	-2
Reliability	5		0	0	0
Handling	6		0	-6	-6
Manufacturability	8		0	-8	-8
Packaging Flexibility	4		-4	-4	-4
Ergonomics	1		0	0	0
Aerodynamics	3		3	3	-3
Total			-8	-24	-30

The team agreed that manufacturability should have the greatest weight since it can be the most time consuming and labor-intensive part of this project. It also reflects our confidence in taking a frame concept into a practical, effective solution. Pump My Ride agreed that weight, handling, and reliability were the next most important criteria since it influences how easily and safely a rider can operate the vehicle. Ergonomics, cost, and aerodynamics were the least important criteria. The following sections summarize our research and conclusions for each frame type, which led to the scores shown in Table 4.1.

Upright Standard Bike

An upright standard bike has been commonly used by other teams in previous challenges. It is a frame type supported by decades of innovation, ease of manufacturability, flexibility for packaging, familiarity for rider handling, and lightweight materials. An upright standard bike was

also attractive since we had a good relationship with the SLO Bike Kitchen, who offered their expertise and help in acquiring parts. Figure 4.5 displays the Incompressibles frame design for the upright standard frame.

Figure 4.5: The Incompressibles final frame design for an upright standard bike

Figure 4.5 shows some of the advantages that an upright standard frame, including packaging flexibility and size. It also shows its greatest disadvantage: poor aerodynamic design compared to some other types of two-wheeled vehicles. The upright standard frame has large cross sectional-area by design. Ultimately, aerodynamic design was an important consideration since it would improve our teams score in all three challenges by reducing drag forces.

Prone Bike

On the theme of aerodynamic design, we considered a prone vehicle. A prone vehicle would be accomplished by elongating a standard upright bike, moving the pedals above the rear wheel, lowering the handlebars, and providing abdominal support. Figure 4.6 depicts the frame concept for a prone bike.

Figure 4.6: Prone Bike and Rider

Research shows that there is a substantial decrease in drag from an upright position to a prone position at high speeds. However, our sources tell us that speed for the endurance is not high enough to justify changing the current frame we have. Additionally, the distance for the sprint is not far enough to make a significant decrease in time. Ultimately, we did not want to sacrifice the advantages of other features, like packaging flexibility and weight, for costly design decisions that provide insignificant gains.

Velomobile

During a brainstorming session, a team member proposed the idea of creating a composite faring for Pump My Ride's vehicle to sharply decrease drag forces. A velomobile, or human powered vehicle, most accurately represents this idea, where a carbon-fiber composite faring encases a tricycle or bicycle skeleton. Cal Poly has a team that design, builds, and races their original human powered vehicle. Every year the team places well at competition, so we thought it was worth exploring this material technology using it to our advantage. Figure 4.7 displays Cal Poly's human powered vehicle, Lazarus, form several years ago.

Figure 4.7: Cal Poly Velomobile (Human Powered Vehicle)

For similar reasons to the prone bike, Pump My Ride decided not to pursue this concept design. The time and speed for which the composite faring would become useful is unattainable during the competition. Additionally, we learned that the velomobile can be very difficult to handle. Finally, the manufacturing process of a composite faring is another project in itself—which involves creating molds, and meticulously laying up plies of carbon fiber.

Elliptical

Most frame concepts we investigated favor pedaling motion for driver input. On the contrary, research shows that linear motion is a more biomechanically favorable mode of input. To maximize drive train power, Pump My Ride investigated frame concepts that allow for a linear pumping motion. We found that an elliptical frame, as shown in Figure 4.8, can accommodate linear pumping and possibly greater power input.

Figure 4.8: Elliptical Bike Frame Concept

The elliptical bike frame can be designed to provide either a single or double mode of power input. For the single mode of input, the driver provides power at the handlebars, which connects to the driver's base and simulates a running motion. For the double mode, the handlebars and the base are unconnected, allowing power input at either location. In concept, this appear as a superior mode for maximizing power output. However, this design is very poor for packaging. Considering the amount of equipment included for a fluid powered vehicle, we believe this would negatively affect the vehicle size and weight. Without mentioning poor aerodynamics, manufacturing an elliptical frame would take the bulk of our design and manufacturing time. Since Pump My Ride's made a goal to develop a more effective hydraulic system, we decided not to pursue this frame concept.

4.2.2 HANDLEBAR SELECTION

After deciding on the upright standard bike frame, Pump My Ride explored different handlebar designs for an upright standard bike. Based on our research, we evaluated each handlebar against five criteria using the decision matrix shown in Table 4.2. Low-speed and high-speed handling were assigned the greatest weights because our team prioritized safety. Aerodynamics was assigned a greater weight than packaging because the mechatronics equipment is small. The aerodynamic drag coefficient and approximate frontal area for a bike rider using tri-bar handles are 0.88 in^2 and 528.3 in^2, respectively. In contrast, an upright biker has a drag coefficient of 1.1 and approximate frontal area of 620 in^2.

The Simscape accumulator discharge model predicted that incorporating tri-bars would decrease the sprint time by 0.3s. In addition, the power required to overcome the aerodynamic forces was calculated for a range of speeds as seen in Figure 4.9. The lesser power required by the tri-bars would allow more power to be transferred to bike movement in both the endurance and efficiency challenges.

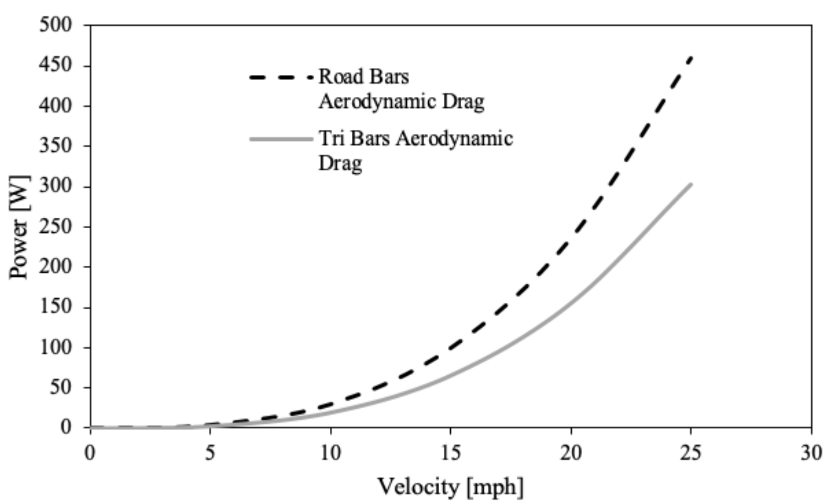


Figure 4.9: Power Losses with Tribars and Road Bars at Various Speeds

Table 4.2: Handlebar Decision Matrix

Criteria	**Weight (1-5)**	**Handlebar**			
		Cross-Country	Road	Tri	Hybrid Road x Tri
Low-Speed Handling	5	Datum	-5	-5	-5
High-Speed Handling	4		4	4	4
Aerodynamics	3		3	3	3
Ergonomics	1		-1	-1	-1
Packaging	2		-3	-3	2
Total			-1	-1	3

The total score showed that a hybrid handlebar (a combination of the road and tri bars) would improve on our current vehicle design. We planned to pursue this design overall because it would likely increase aerodynamics and improve times for the Spring and Endurance challenge while providing packaging flexibility. Figure 4.10 illustrates a preliminary design for hybrid handlebars to use on Pump My Ride's vehicle.

Figure 4.10: Concept for Hybrid Handlebars

4.2.3 WHEEL AND TIRE SELECTION

Pump My Ride also considered various wheel types for the upright standard bike. Wheel selection was based on research which led us to four criteria: (1) weight, (2) cost, (3) durability, and (4) rolling resistance, and (5) tire deflection. Table 4.3 displays the weight criteria and assigned values for each wheel type.

Table 4.3: Wheel Decision Matrix

Criteria	**Weight (1-4)**	**Wheel Concept**			
		Hybrid	Road	MTB	Beach
Weight	3	Datum	3	-3	-3
Cost	1		-1	-1	1
Durability	2		-2	2	0
Rolling Resistance	4		4	-4	-4
Total			4	-6	-6

Originally, we thought that using the smallest cross section tire would be the correct choice, but after further research it was determined that a larger cross section tire deflects more when rolling over an imperfect road allowing the tire to "roll over" imperfections rather than climb each little pebble. This is reflected in the recent trend of road racing tires growing in size (~25 mm whereas about ten years ago, 23 mm was more common) [5].

The Simscape accumulator discharge model was used to test the effects of tire rolling resistances on sprint time and distances travelled by the bike. The rolling distance (in feet) was used in the NFPA efficiency score algorithm to determine the effects. It was found that total rolling resistance and distance rolled (given a starting rolling speed) have a one to one linear relationship. Likewise, distance rolled also has a one to one linear relationship with efficiency score. That is to say that reducing the total rolling resistance by half, the distance rolled is doubled, and efficiency score is also doubled, given the same starting speed in both cases. Of course, not all rolling resistance comes from the tires, but the resistance from the wheel bearings is extremely small, and we proved in the clutch coast test that the rolling resistance of the motor is also small enough to be neglected (~5%). Therefore, we aimed to choose the tires with the smallest rolling resistance we can find as this analysis shows there should be marked improvement.

It should be noted that tire rolling resistance values do not directly match real world tire rolling resistances as they are measured on a test rig, not on the road. These values are, however, valuable for comparing tires to each other, as a tire with double the rolling resistance on the test rig should also have double the rolling resistance in real life.

4.3 HYDRAULICS

An important focal point of the team was to increase the efficiency of the hydraulic system, consequently reducing energy loss. The energy could then be used to propel the bike to result in higher competition scores for the endurance, sprint, and efficiency challenges.

4.3.1 HYDRAULIC CIRCUIT

Five capabilities were considered for inclusion in the hydraulic circuits: direct drive, accumulator discharge, regenerative braking, emergency release of accumulator pressure, and coast, as independent modes or in combination. The competition rules only required the inclusion of direct drive and regenerative braking. The additional modes were considered to help meet the team's objectives.

Direct Drive Mode

The direct drive mode supplied the power input of the rider to the pump which converted the energy to pressure in the system. The pressure was transferred through the hydraulic lines to the motor to propel the bike. This mode was meant to be engaged during the endurance challenge.

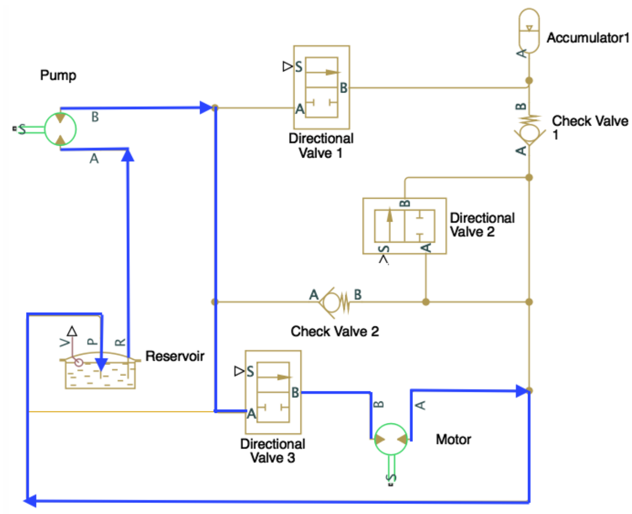


Figure 4.11: Direct Drive Circuit

Coast Mode

The Incompressibles used a coast mode to serve the function typically provided by a clutch in similar applications. The fluid flowed freely through hydraulic lines and the motor, disengaging the pump and allowing the motor to rotate freely. The inclusion of a check valve in the direct drive circuit incorporated the capabilities of a coast mode. When the rider is not pedaling the pressure was greater on the side of the check valve which forces it closed to enter coast mode.

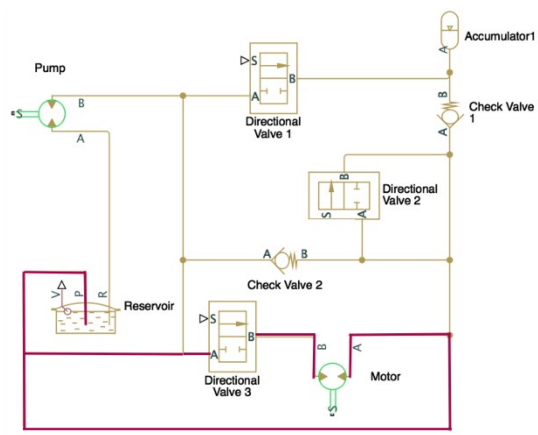


Figure 4.12: Coast Circuit.

Regenerative Braking Mode

The regenerative braking mode converted the kinetic energy of the bike to potential energy stored as pressure in the accumulator. Last year's competition rules required regenerative braking to be employed during the endurance challenge.

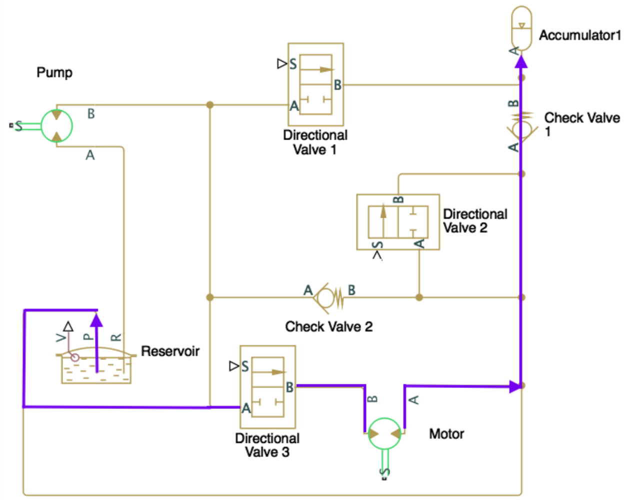


Figure 4.13: Regenerative Braking Hydraulic Circuit

Accumulator Discharge Mode

The accumulator discharge mode was fully engaged during the sprint challenge and modulated during the efficiency challenge. The pressure in the accumulator was released and fed into the motor to propel the bike.

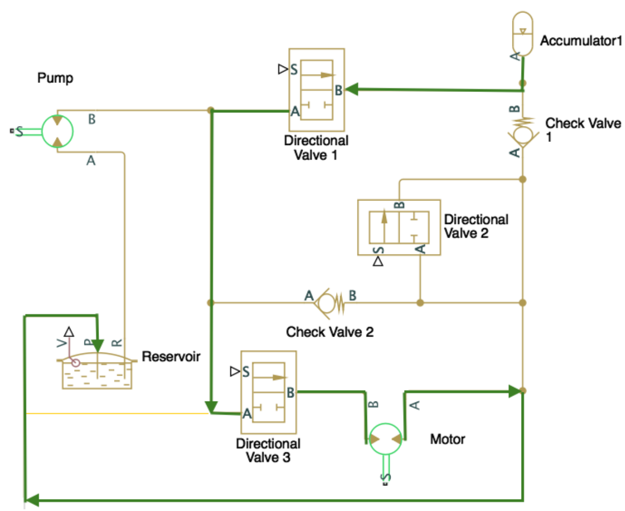


Figure 4.14: Accumulator Discharge Hydraulic Circuit

Emergency Pressure Release Mode

The emergency pressure release mode could have been used as a safety measure, in preparation of transporting the bike, and during testing.

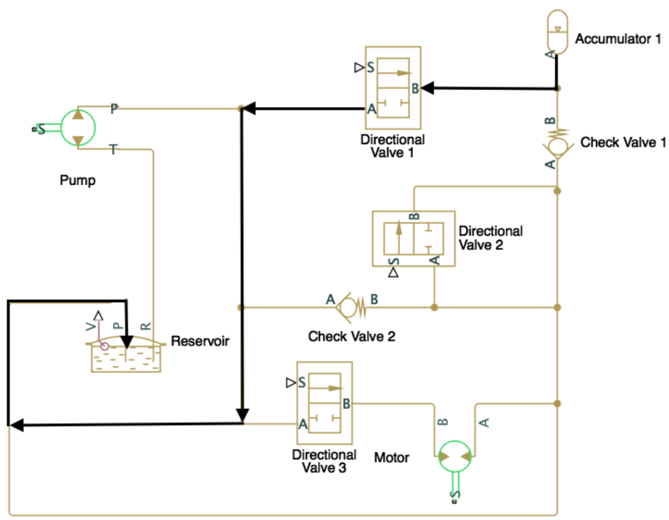


Figure 4.15: Emergency Pressure Release Hydraulic Circuit

The fundamental hydraulic circuits presented previously were finalized with respect to the final components chosen, as presented in the next chapter.

4.3.2 VALVES

The valves controlled the direction of fluid flow and enabled different modes to be engaged. The valve selection had the greatest impact on leakage and pressure losses which have been issues for the past two Cal Poly competition teams. The 805 Hub Masters used spool-type solenoid valves which caused a detrimental pressure drop of 1000 psi in 15 seconds. The Incompressibles were able to limit the pressure drop to 100 psi in 30 seconds using poppet-style solenoid valves. Also, a manual needle valve was used to connect the accumulator and motor to prevent motor blow out during accumulator discharge. The valve was able to prevent motor blow out but increased sprint time by adding a restriction to the system. Also, the motor and pump experienced cavitation which The Incompressibles attributed to the malfunction of a solenoid valve. Pump My Ride investigated three types of valve options which may be used in combination: spool- type, poppet-type, and manual valves. The most important criteria considered for valve selection included reducing the leakage and pressure loss to increase the efficiency of the system. Also considered were the response times, modulation and ease of assembly.

The team investigated the use of electric ball valves for zero leakage and variable opening. We assumed that fully open full-bore ball valves (in which the ball bore matches the line size) have no associated minor loss, but instead were modeled as contributing only to major loss. This is not completely true, as the fittings into and out of each valve have an associated pressure drop, but for the purposes of comparing valve to valve, this seemed like a reasonable assumption. Because of this distinction, there was almost no pressure loss through a fully open, full-bore ball valve. Our hydraulics advisor, Mark Decklar, recommended the use of solenoid poppet proportional valves for the application because they were designed for mobility unlike ball valves. Solenoid poppet valves also have the advantages of a faster response time (~30 ms Vs. ~5 s), lighter weight (.94 lb

Vs. 6 lb), increased compactness, and superior modulation compared to ball valves. There was no leakage and the solenoid poppet valves could be slow-opening. Ball valves and spool-type valves were compared against solenoid poppet valves, the valve type incorporated into the bike by The Incompressibles. The decision matrix in Table 4.4 indicated solenoid poppet valves were the best option for our criteria.

Table 4.4: Valves Decision Matrix

Criteria	**Weight (1-5)**	**Valves**		
		Solenoid Poppet Valve	Ball Valves	Spool- Type
Leakage	5	Datum	0	-5
Modulation	2		-2	-2
Pressure Loss	4		4	-4
Response Time	3		-3	0
Assembly	1		-1	0
Total			-2	-11

Mark offered to provide several versions of solenoid poppet valves from HydraForce: normally closed unidirectional flow, normally open unidirectional flow and normally closed bidirectional flow, all of which may have manual overrides and were interchangeable. We were initially hesitant to use poppet valves because they looked like they would restrict flow, whereas a full-bore ball valve is modeled as a length of tubing. To compare the two styles of valve, we gathered a maximum flowrate of the system during accumulator discharge of 1.3 gal/min. Next, we compared the pressure loss through the poppet valves, as seen in Figure 4.16, to a basically zero pressure loss through a fully open ball valve. The pressure loss through the poppet valve is ~10 psi when the system pressure is at 3000 psi, and since poppet valves were made for mobile applications, and therefore a lot more convenient to use, poppet valves were chosen.

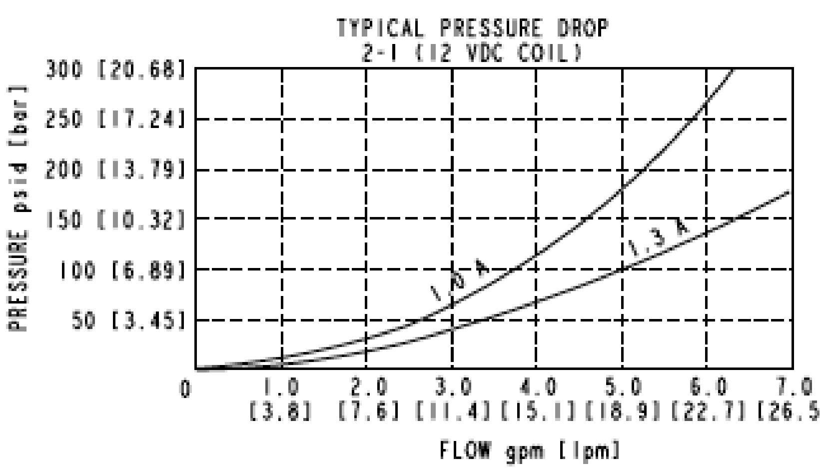


Figure 4.16: Typical Pressure Drop in a Solenoid Poppet Proportional Valve

4.3.3 MANIFOLD

Manifolds house hydraulic circuit passages and valves to control fluid flow of the system. The intent of a manifold is to reduce fittings and hydraulic lines, simplify assembly, and increase efficiency with reduced pressure drops and heat transfer. The Incompressibles outsourced an aluminum manifold, sponsored by the NFPA and provided by SunSource which housed five ports, the four solenoids, the check valve and accumulator pressure sensor as seen in Figure 4.17.

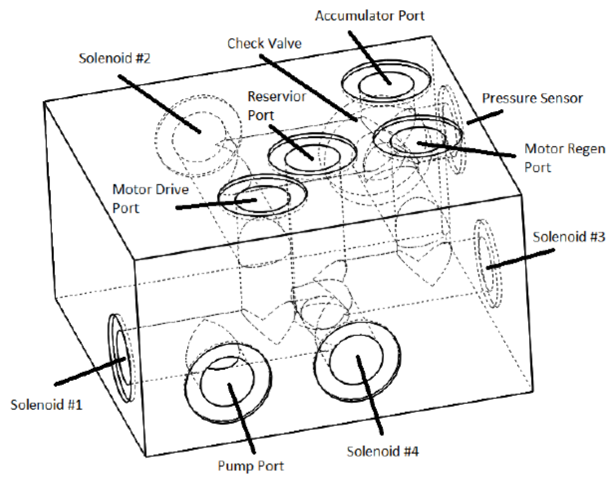


Figure 4.17: Manifold from Previous Bike

The incorporation of the manifold instead of individual solenoid blocks reduced line and fluid weight by 2.5lbs. Pump My Ride evaluated the options of including or eliminating the use of a manifold, as displayed in the decision matrix of Table 4.5.

Table 4.5: Manifold Decision Matrix

Criteria	**Weight (1-5)**	**Manifold**	
		Manifold	No Manifold
Leakage	5	Datum	0
Weight	3		-3
Line Length	2		2
Hydraulic Efficiency	4		-4
Assembly Time	1		1
Total			-4

The choice of incorporating a manifold was supported by a discussion with Mark and basic fluid dynamic analysis. Mark and Pump My Ride counted over 24 fittings to be required if the manifold was removed from the hydraulic system created by The Incompressibles. The manifold limits the fittings to six. The 90-degree bends within the manifold, which were of concern to Pump My Ride due to the associated efficiency losses are insignificant relative to the Tee bends required without a manifold. Specifically, the head loss through the fittings are proportional to the loss coefficient, which is 0.4 for 90-degree bends and 1 for the Tee bends. To further characterize the losses, there are three 90-degree bends, or four Tee bends required in direct drive mode, with and without the manifold, respectively. Therefore, a manifold is the best option for the hydraulic system.

Manifolds are extremely versatile and could be custom made by HydraForce for the vehicle. There were options to include one manifold to house all the components or multiple manifolds, each specialized to a location or function of the vehicle.

4.3.4 HYDRAULIC LINES

The implementation of hardlines in place of soft lines had an expected increase in efficiency and decrease in overall vehicle weight but required additional planning and manufacturing. The Simscape accumulator discharge model predicted a 2 second reduction in sprint time with all other parameters remaining constant. Therefore, the soft lines were to be exchanged for hard lines as the time scope allowed. Additionally, the amount of hydraulic lines could have been decreased with an alternate arrangement of components on the bike.

4.4 POWER TRANSFER

This section deals with the transfer of power through hydraulics supplied by the rider. As the final design was meant to be ridden by a typical human rider, the power output of a typical human being was accounted for. As can be seen in Figure 4.18, the amount of time a person is working has a huge impact on their output. In this competition, the most power output required by the rider would occur in the endurance challenge. The Incompressibles were able to complete the endurance challenge in around 4 minutes. If we benchmark this time, and using Figure 4.18 as a reference, we should not expect more than ~300W from our rider, who is a "healthy man", and not a world class cyclist. Also, the direct drive model used a 300W input provided by the rider. Therefore, the model predicted proper behavior of the components and an endurance time within our specification, so we expected the maximum output required by the rider to be 300W.

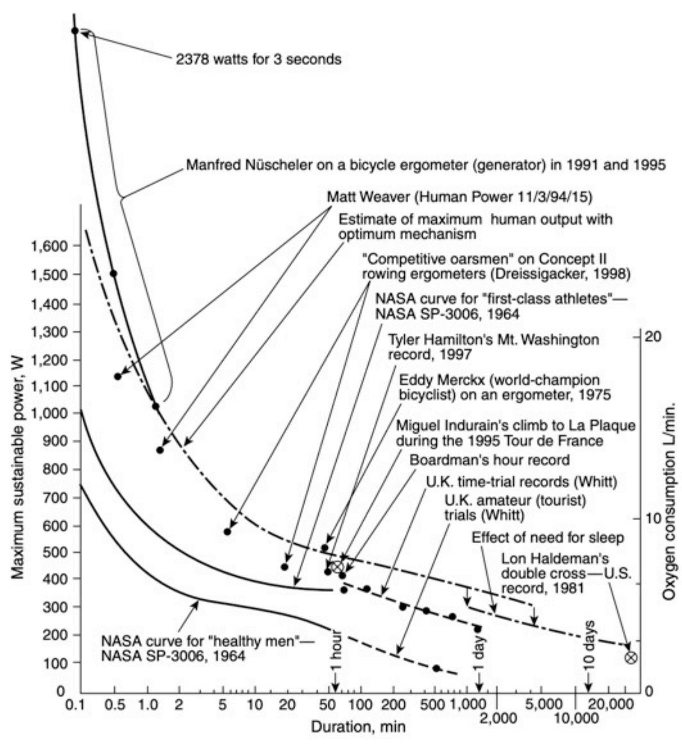


Figure 4.18: Max Human Power Output

4.4.1 MOTOR

The hydraulic pump on the bike converted human power into pressure that can then be used to drive the motor, while the hydraulic motor was used to convert hydraulic energy into motion of the vehicle. The pump was only used in direct-drive mode, and the motor was used in direct-drive, boost, and used for energy recovery in regeneration mode. The Bosch bent-axis pump that was used by The Incompressibles for both the pump and motor offers very good energy conversion per unit mass. It is virtually identical to the Parker F-11 pump used by most teams that are using a rotary pump, but instead of a cast iron body like the F-11, the Bosch bent-axis pump has an aluminum body. The change in materials brings the total pump mass from 12 lbs for the Parker unit down to 5 lbs for the Bosch, which results in a decrease of about 0.6 s in the Sprint Challenge when accounting for both motors. It is difficult to choose components for the Fluid Powered Vehicle Challenge, as the components are operating far outside their normal operating conditions. The pump and motor in particular are meant for an operating speed between 50 RPM and ~11,000 RPM continuously at a maximum flow rate of 13 gal/min. The Incompressibles' bike ran at approximately 300 RPM max and 1.3 gal/min max. Pump My Ride was unable to find another motor that operates better in this range than the Bosch bent-axis, and therefore opted to keep the same motor.

4.4.2 PUMPS

The pump selection made by The Incompressibles could be improved upon. Biomechanically, a bicycle crank is only advantageous when the end motion must be rotary. A typical bicycle crank delivers a sinusoidal power curve where the rider can only put peak power into the pedals through a very small range of motion. We investigated other methods of putting power into the system through the use of a linear pump in place of the Bosch bent-axis pump. Linear pump feasibility was slated for future testing and was not possible before the PDR was completed. The amount of force required for the linear pumps to reach an equivalent level of performance as the bent-axis pump could dictate the best method to operate the linear pumps. The methods considered were the "stair-stepper" fashion, a crank slider mechanism, or a large cam driven by the bicycle cranks.

Table 4.6: Pump Decision Matrix

Criteria	**Weight (1-5)**	**Hydraulic Pump**	
		Bosch Bent Axis	Linear
Integration	4	Datum	-4
Biomechanics	2		2
Operational speed range	3		3
Weight	1		1
Hydraulic Efficiency	5		5
Effectiveness			-
Rideability			-
Total			-

The final pump selection was planned to be decided with the decision matrix in Table 4.6 and the consideration of time at the time of PDR. After characterizing the linear pump and performing hydraulic analysis, Pump My Ride determined the Bosch bent axis was more advantageous, presented in Section 5.7.2.

4.4.3 ACCUMULATORS

The Incompressibles used a Steelhead Composites 1 gal composite accumulator, specification provided in Appendix G. Pump My Ride investigated other styles of accumulator, mainly comparing piston style to the currently used bladder style. Piston style accumulators have much higher discharge rates, which would likely result in better sprint times, but a 1-gal piston accumulator weighs roughly 35 pounds (roughly 1/3 the weight of the current bike). When compared to the ~10 lbs Steelhead Composites accumulator, the weight savings of about 25 lbs translates to an almost 1 second reduction in sprint time. In addition, multiple different accumulators were considered to change the configuration of the vehicle for different events. However, the 2020 competition rules changed from the 2019 rules so to specify that anything on the bike must stay on the bike for every event. Therefore, Pump My Ride decided that the composite bladder style accumulator is the correct choice. As the Steelhead accumulator has a very high specific energy storage, we have chosen to keep the existing accumulator. Once the hydraulic circuit was designed and built, various accumulator pre-charges were tested for each challenge so that the optimum performance level could be used during a live competition.

4.4.4 CLUTCH

One early idea Pump My Ride had to increase the efficiency of The Incompressibles' bike was to add a clutch to decouple the drive motor when coasting to decrease rolling resistance and increase coast distance. Most teams mentioned in their final reports that they had tried to add some way to decouple their motor for more efficient coasting, but none as far as we are aware have been able to get one to work. To get an idea of how much of an effect a clutch would have made on The Incompressibles' bike, we designed and executed a clutch-coast test. The bike was ridden down a very shallow incline to gain some speed and then allowed to coast to a stop. The first round of testing was done with the bike in coast mode, and in the second, the motor was decoupled by removing the final drive chain. Each mode was tested 5 times and the results have been tabulated in Table 4.7. It is important to note that wind was an issue during this test with gusts from 2-7 mph, and with significantly less wind during the chainless test. We decided beforehand that less that a 5% difference would make a clutch an unnecessary complication. The percent difference in the averages comes out to 7.4% which, when corrected for wind gusts, comes in under 5%. Therefore, the clutch was deemed to be too small of a gain for the amount of work it would take to implement.

Table 4.7: Clutch Coast Data

Coast Test		
	Distance (ft)	
Rank	**Chain**	**Chainless**
1	472	518
2	467	512
3	418	503
4	410	418
5	394	374
Average	432	465
STD DEV	31.5	58.2

4.3.5 DRIVETRAIN

In keeping with the theme of eliminating inefficiencies, the final drive on The Incompressibles' bike could have also used some work. When delivered to Pump My Ride, the bike had an ANSI 40 roller chain. This size of chain is often used in machinery, and in certain applications is rated upwards of 25 hp. As the peak torque is 12 ft-lb$_f$, and the peak horsepower of the bike is ~2 hp and taking into account that a 150 lb rider on 172.5 mm crank arms subjects a regular bike chain to 85 ft-lb$_f$, this chain is drastically oversized. Table 4.8 shows how the decision was made between the current final drive, a belt drive, and a typical 2.4 mm bicycle chain. All three choices have a theoretical peak efficiency around 98%, but both the belt drive (~2 lbs for all components) and the bicycle chain (~.5 lbs for all components) have much less rotating mass than the ANSI 40 chain (~5 lbs for all components). Rotating mass must be accelerated and decelerated any time vehicle speed is changed, therefore we believed it most advantageous to minimize rotating mass.

Table 4.8: Final Drive Decision Matrix

Criteria	**Weight (1-7)**	**System for comparison**		
		The Incomps final drive	Belt Drive	2.4 mm Rear Chain
Clutch Integration	1	Datum	1	-1
Tensioning	3		0	0
Manufacturing	4		4	4
Design Integration	7		0	7
Adding Shifting	2		2	-2
Durability	5		0	0
Efficiency	6		6	6
Total			13	14

In addition, Pump My Ride had to discard the rear hub because The Incompressibles welded their driven sprocket directly to the rear hub. Planning to use a screwed-on sprocket would allow for changing the final drive ratio. Lastly, there was the issue with final drive sprocket alignment, and no way to adjust final drive chain tension. This was dealt with by spacing the drive sprocket and slotting the motor mount to allow the drive and driven sprocket to be moved nearer to and farther

from each other. Bicycle chain seemed the most advantageous, and the associated weight savings translates to a .2 second decrease in sprint time according to our models.

4.4.6 BRAKES

The Incompressibles opted to use basic center-pull bicycle rim brakes for their simplicity and low cost. Pump My Ride confirmed this choice as is sufficient with calculations that are included in Appendix H. According to Oertel et al. in their paper "Construction of a Test Bench For Bicycle Rim and Disk Brakes", a typical braking force for a bicycle rim brake is 400 N, or ~90 lbf [6].Based on the assumption that bicycle rim brakes can supply 90 lbf of braking force at the wheel rim, the factor of safety for braking force overcoming torque supplied by the motor to the wheel is 2.79.

4.4.7 DERAILLEUR

The front drive train had multiple distinct issues. The tensioner was unable to supply enough chain tension, allowing the chain to slip. This was corrected last minute by The Incompressibles with a bungee cord. The tensioner also does not follow the chain as it is changed between the small and large chainring. This causes the chain to "bend" around the tensioner's idler, robbing rider power and decreasing chain life. Table 4.9 shows how the decision was made between the existing tensioner, and possibly adding a bicycle style rear derailleur with integrated tensioner, using a floating tensioner, or modifying the existing tensioner so that it can apply more chain tension and is able to follow the chain as it moves side to side. Although an improved tensioner had potential to be advantageous, Pump My Ride did not implement a new tensioner because we allotted time to complete more important design objectives.

Table 4.9 : Front Drivetrain Tensioner Decision Matrix

Criteria	Weight (1-4)	System for comparison		
		The Incomps Tensioner	Add Rear Derailleur	Improved Tensioner
Simplicity	1	Datum	-1	0
Integration	2		-2	2
Chain Following	3		3	3
Shifting	4		4	4
Total			4	9

4.5 MECHATRONICS

Table 4.10: Microcontroller Selection Decision Matrix

Criteria	Weight (1-4)	System for comparison		
		Arduino	Raspberry Pi	STM 32 Nucleo
Simplicity	1	Datum	-1	-1
Integration	2		-1	-1
Compatibility	3		0	0
Support	4		0	0
Total			-2	-2

Hardware

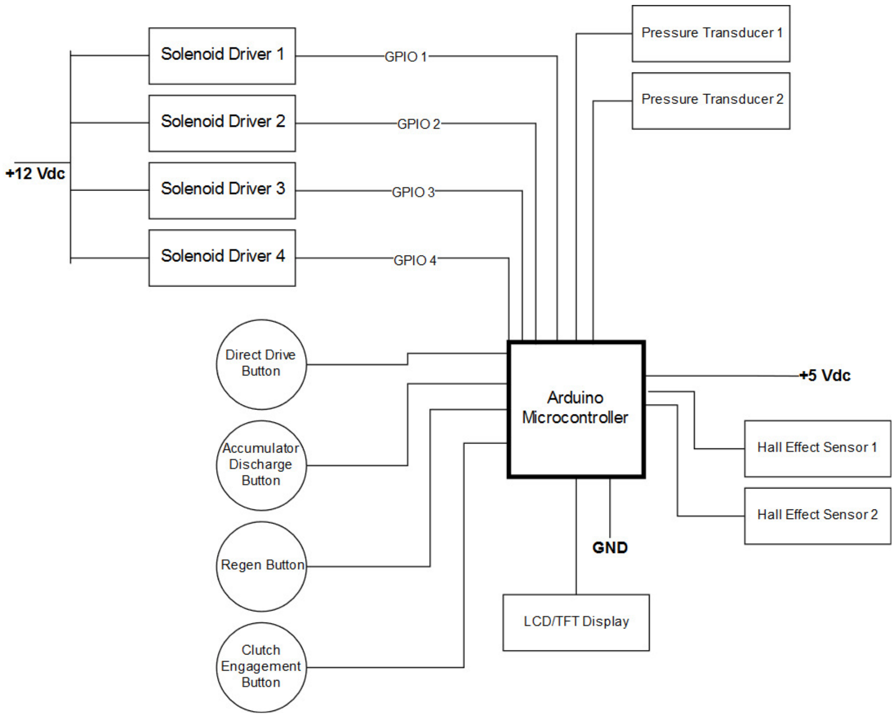


Figure 4.19: Previous Mechatronics Design

Figure 4.19 displays our preliminary design for the mechatronics layout. We initially decided to use the Arduino micro-controller. The decision matrix was used to confirm this decision due to the Arduino's simplicity and large access to drivers and libraries for coding.

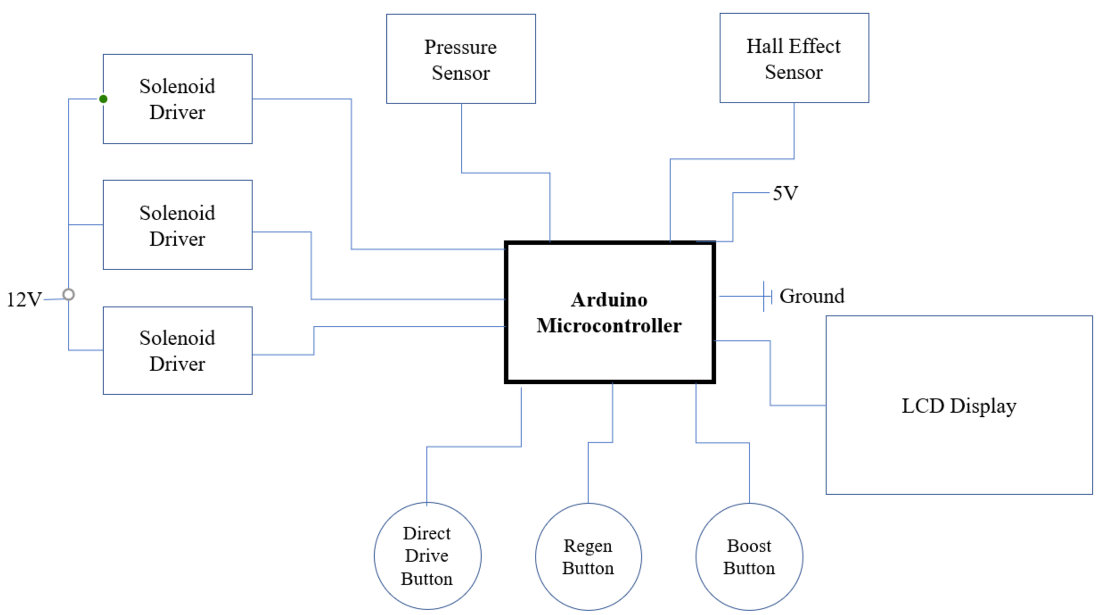


Figure 4.20: Mechatronics Layout

We were able to incorporate solenoid drivers, and buttons and were not able to include sensors and the LCD Display. We were able to remove coasting as a mode and instead have it integrated into the fluid circuitry. The buttons will now switch the solenoids to be in direct drive mode, regen mode and boost mode. The pressure sensor will give a reading of the pressure in the accumulator and the hall effect sensor can give data for distance traveled, velocity, and acceleration for the bike. A lithium polymer battery was selected for use because it is light weight, cheap, and powerful enough to last the entire competition. An initial component layout of the mechatronics can be seen in Figure 4.20. The basic components are comprised of:

1. 1x Arduino-Uno Microcontroller
2. 3x Solenoid Drivers – Solenoids will control and switch drive modes
3. 1x Pressure Sensor
4. 1x Hall effect sensor
5. 1x LCD Display
6. 3x Push Buttons
7. 1x 12V Lithium Polymer Battery

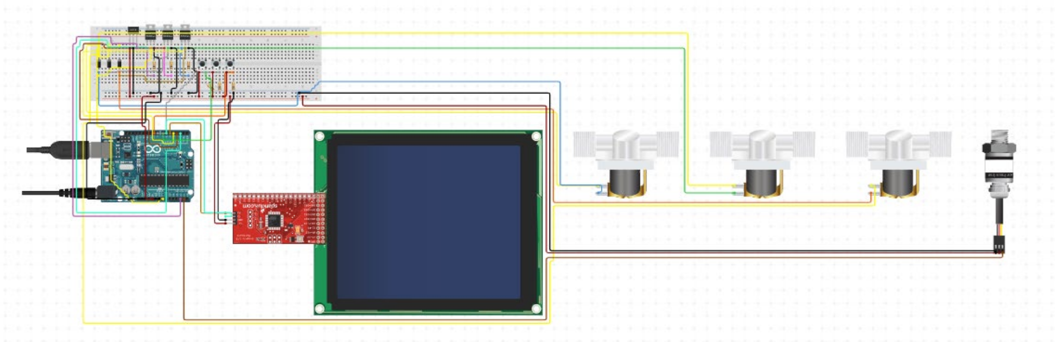


Figure 4.21: Basic Circuit Layout Designed on Arduino Circuit.IO

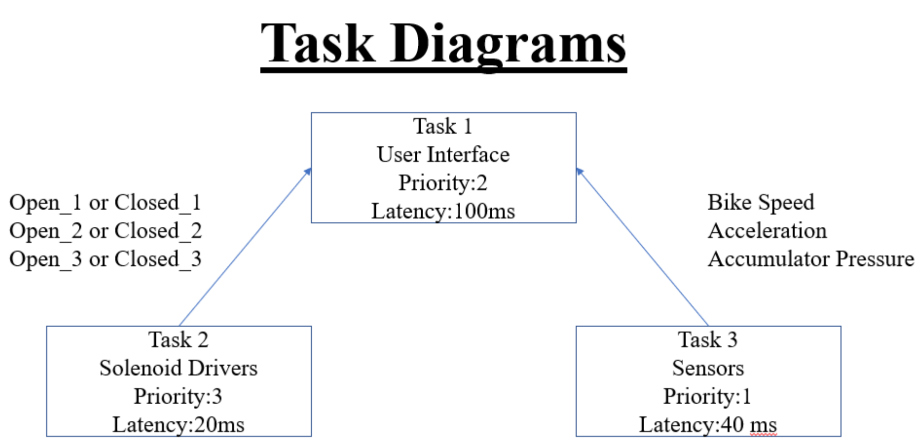


Figure 4.22: Preliminary Task Diagram

The coding for the mechatronics was done using Hydraforce's HF- Impulse software. Figure 4.22 displays the initial design for task diagrams for the code that will be implemented. Cooperative multitasking was used to run multiple tasks at once. The latency of the tasks was set to ensure that

correct data could be measured from each task, especially from the sensors. The solenoid drivers had the highest priority since they control the drive modes of the bike. The user interface was meant to be constantly checking the sensors for data and updating the LCD continuously, reading analog values and converting them to digital numbers.

State Diagrams User Interface

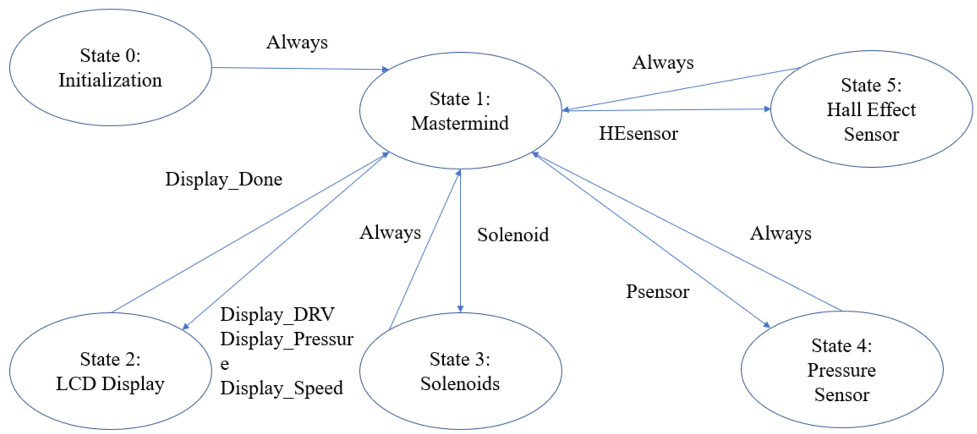


Figure 4.23: Preliminary State Diagram

Figure 4.23 displays the state diagram that controlled the operation of the vehicle. The controller was meant to wait for an input from the user or sensor and operate accordingly to update the display.

Developments after PDR

The hall effect sensor was in the plan for last year's vehicle however it was not able to be implemented. We planned to implement the hall effect sensor for data collection after CDR. Other sensors could be added by future teams. For example, a flow meter and other pressure sensors could provide better data throughout the bike to find deficiencies in the hydraulics, though these may hinder hydraulic efficiency.

4.6 DESIGN OVERVIEW

Figure 4.24: Isometric View of Preliminary Design

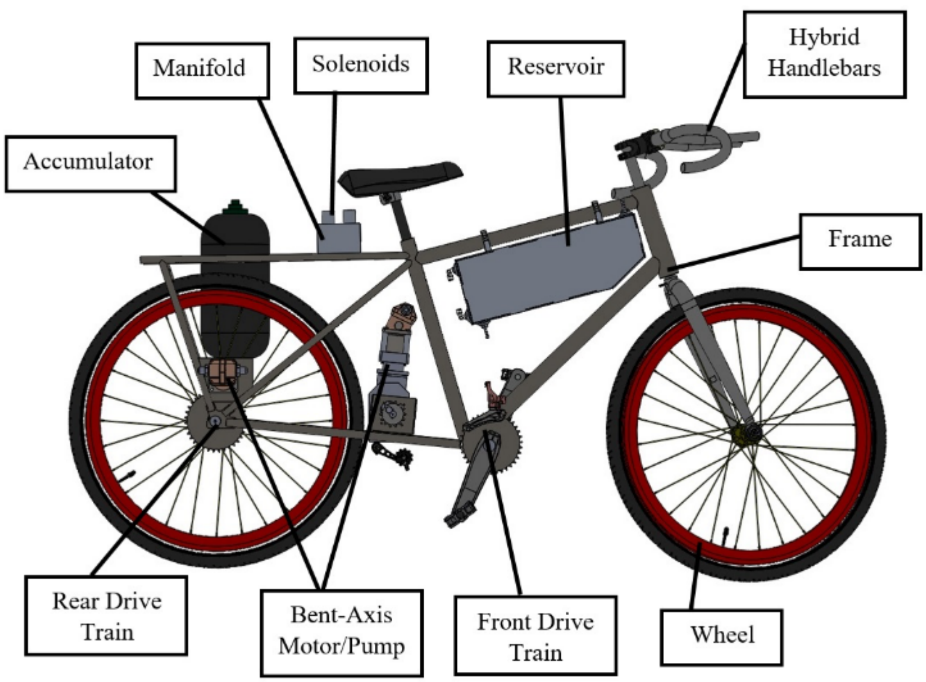


Figure 4.25: Component Layout as Planned at PDR

Figure 4.25 shows the component layout as it is planned at the conclusion of the PDR. It is largely similar to The Incompressibles' design with a few major differences. Pump My Ride chose to mount the accumulator with its inlet/outlet hose (not pictured) on top to keep air from getting trapped inside. The valves chosen were slow opening poppet valves to give greater control over flow rates. The bent-axis pump could have been replaced with linear pumps, which was decided at the point of CDR. Similarly, the amount of force needed to operate linear pumps, should they prove feasible, would have dictated the manner in which the pumps were actuated. The manifold was swapped with one that is less internally restrictive. The bent-axis motor remained the same and in the same orientation, though the final drive chain was changed for a more efficient bicycle

style chain and sprockets. Wheels were changed with lighter weight road bike style wheels and tires with an interchangeable rear driven sprocket. Handlebars were changed to road/tri style bars for a more aerodynamic rider posture. Mechatronics changed in the manner talked about in Section 4.5. The frame and fluid reservoir were to remain largely unchanged as The Incompressibles did a great job designing and building both.

4.7 DESIGN HAZARDS

Since we were studying to become ethical engineers, it was necessary for our team to design for potential hazards. Design hazards were prevalent in this project because Pump My Ride was building a vehicle with the capacity to store energy, operate at high pressure, and move a person on a heavy system more than 20 mph. We completed a design hazard checklist, located in Appendix H to help us sort through 20 general design hazards that project teams frequently encounter (e.g. handling flammable liquids and lifting heavy objects). Additionally, we found potential hazards with the Incompressibles' vehicle not mentioned in the checklist. Table 4.11 lists and elaborates on these critical design hazards for which Pump My Ride planned to take corrective action to improve safety.

Pump My Ride had strong motivations to follow-through on each item in Table 4.11. The first motivation was to protect ourselves. One team member suffered a minor injury from a hazard on the second test day. While he was removing the vehicle from the hangar, he pushed it in reverse with the vehicle mechatronics off. When he turned on the vehicle mechatronics, the pedals sprung forward, and a pedal collided with his knee.

The second motivation was to meet our project goal; achieve 1st place at the NFPA competition. We learned that safety features were a primary interest to the judges. Designing to avoid hazards and implement safety features had potential to impress judges and improve overall performance.

The third motivation was for the safety of others. We planned for the likelihood of another Cal Poly team after Pump My Ride and wanted to make sure they were well informed of the hazards of both the machine and the competition.

According to our review of Appendix H Design Hazard Checklist, Pump My Ride did not complete all items. Thus, we address the few incomplete items here. Foremost, we sought a safe mode to discharge the high pressure in the accumulator by adding an alternative mode or safety block. Instead, HydraForce installed a manual release valve on the new manifold. The manual valve is a lighter and cheaper option than installing a safety block. It also removes the bandwidth needed to code a new mode. One major disadvantage to this manual valve is that it is inaccessible form the rider's seat. Pump My Ride planned to test this valve prior to competition, however, our access to the vehicle was cut suddenly due to COVID-19. Therefore, the design is implemented but not confirmed by tests.

Table 4.11: Design Hazard Corrective Action Plan

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
High pressurized gas (≤3000 PSI) is stored in the system's accumulator. Discharge is only possible on system's "boost mode."	Add alternative mode of discharge through separate valve or subsystem (i.e. safety block).	TBD	*March 2020
Unintentional activation of vehicle "boost" may cause loss of vehicle control and injury.	Add shield over "boost" activation key. Code mechatronics system to default to "Direct Drive" or "Coast".	TBD	INC
Hydraulic fluid is flammable.	Identify and fix all system leaks.	March 2020	March 3, 2020
Hazardous revolving and rotating parts (e.g. chains, sprockets).	Implement chain guards to isolate moving parts.	TBD	INC
Vehicle instability, especially at high acceleration and top speed, creates risk of severe injury for rider.	Create and utilize Patterson Control to assess the vehicle stability and rideability.	October 2019	May 2019
Large moving object (approximately 105 lb.) has the potential to deliver dangerous force on impact.	The vehicle is equipped with front and rear and brakes that can provide enough force for rider to stop when desired.	Continuous Course of Action	N/A
Vehicle may be operated in unsafe manner.	Team members are knowledgeable on bike features and standard operating procedures. Vehicle is operated with at least one other team member present. Vehicle operator wears a helmet.	Continuous Course of Action	N/A
The vehicle may have burrs, sharp edges, or pinch points.	Burrs and sharp edges will be filed smooth. Pinch points may be encased to isolate them from other parts of the vehicle or rider.	March 2020	March 2020
*Design was implemented but untested.			

Second, we planned early to prevent an object or person from unintentionally activating the vehicle "boost mode", because this could cause serious damage to bike and/or person. Instead of adding a shield to the button, we pivoted with use of a hydraulic controller and compatible LCD for user interface. An LCD would have eliminated this hazard because access to the vehicle boost mode is less exposed than a button. Unfortunately, the software for the LCD could not be coded in time because of bugs with the controller unit and activating the correct valves on the manifold. The bug in the controller software created a new hazard where the vehicle defaults to "boost" when the

battery is initially connected. Pump My Ride addresses this significant hazard in the User Manual and Chapter 10 Conclusions and Recommendations. Additionally, we encourage next year's team to install the LCD and eliminate this hazard.

Another important item incomplete is the chain guards to minimize the hazard of rotating parts, like sprockets. Pump My Ride had a procurement plan for chain guards on the front and rear drivetrain. However, the rear drive train assembly took longer than expected, and we determined that custom manufacturing these chain guards could not be completed in time for vehicle testing. Fortunately, we did not encounter this hazard while testing. Nonetheless, we leave this recommendation for next year's team in Chapter 10.

5 FINAL DESIGN

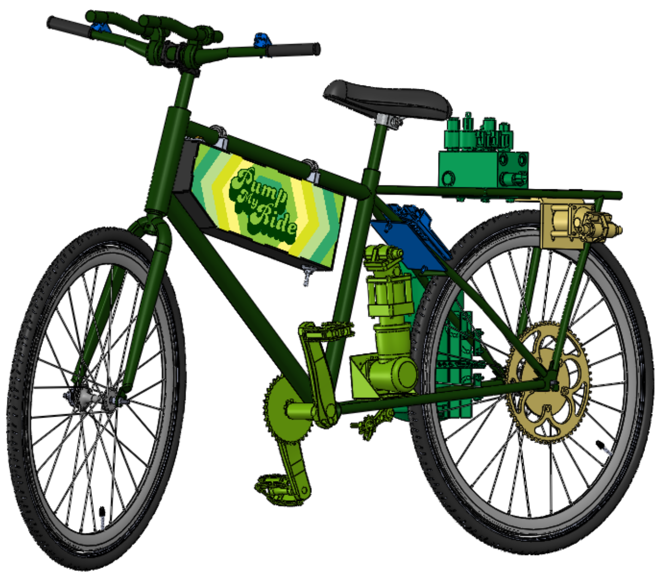


Figure 5.1: CAD of Final Vehicle Assembly (Isometric)

Cal Poly's 2019-2020 fluid powered vehicle included the hallmark features of the 2018-2019 vehicle with added features to improve the hydraulic design and overall performance. The vehicle has four operation modes—boost, coast, direct drive, and regenerative—triggered via buttons at the handlebars. An ECDR hydraulic controller activated the solenoid valves for various modes. The hydraulic pump and motor delivered power from the front drivetrain and from energy stored in the accumulator. Furthermore, hybrid handlebars gave the rider the option to reduce drag and reach higher speeds or use flat bars for better stability at low speeds. Figures 5.1 and 5.2 showcase the CAD of the overall vehicle design with highlighted improvements. Not pictured in the CAD are the new hydraulic lines and electrical connections. The drawing package, provided in Appendix J, contains assembly drawings, and detailed part drawings for all manufactured parts.

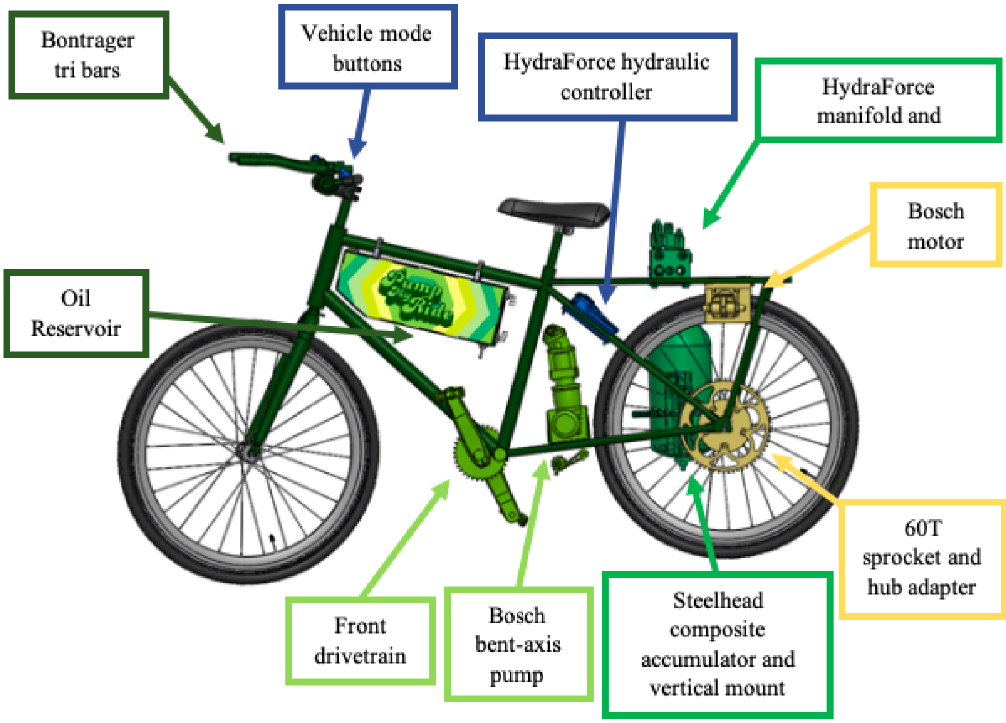


Figure 5.2: CAD of Final Vehicle Assembly and Component Layout

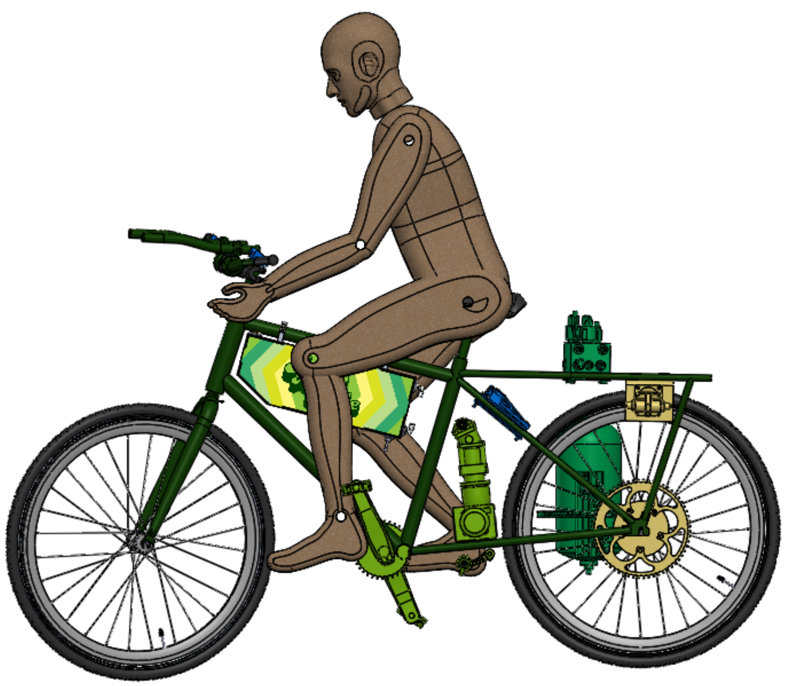


Figure 5.3: CAD of Vehicle with Rider

5.1 FINDINGS AFTER PRELIMINARY DESIGN

Bike Damage in Hanger Reorganization

Over summer, The Hangar was reorganized, and our workspace was moved into a storage container. We were not informed that this would be taking place, so none of our equipment was packed to move. It took us until the end of the first week to find where the bike, our tools, and equipment had been moved. When we did find our stuff, it was shoved in the back of a club's storage space. The bike was stored vertically with the oil drained out and the power pedals, that had been on the bike, missing. Additionally, there were paint scrapes and an out of position brake lever on the right side that indicated that the bike was tipped over. All of our spare batteries were missing, as well as our spare pedals, so we lost even more time before we could even see if the bike still worked.

We finally found that our pedals had been taken by the HPV team without our knowledge and were able to start our baseline testing. Unfortunately, it was at this time we realized the bike was broken. The entire mechatronics system was inoperable, and we were only able to energize one solenoid, even though the screen was indicating that the mode was being changed. As the bike sat, the only mode we had was coast (which is the failsafe of the system – all solenoids deenergized). We were hoping this was a simple problem such as buttons getting broken, or a dislodged wire, but after further testing (jumpers to replace buttons, and testing for solenoid signals at the computer), we determined that all of the ancillary equipment on the bike was functional, and the custom PCB that The Incompressibles had made for their machine was damaged beyond repair.

Contingency Plan

We still needed to complete baseline testing to validate our current Simscape models, and as we did not have a way to control the bike, we decided to build a box of three switches, dubbed the "Juicebox", to control each solenoid, and allow us to control the mode the bike was in so that we could complete preliminary testing. The construction and use of the Juicebox is detailed in Section 5.5.2. It should be noted that the Juicebox was initially meant to only be used for preliminary testing, so simplicity and assembly time were more important than being user friendly.

Baseline Testing

Pump My Ride conducted testing during the Fall 2019 quarter to establish a baseline of the vehicle performance and identify possible system issues due to vehicle damage. The testing methods paralleled with the three vehicle challenges outlined in the 2020 NFPA Fluid Powered Vehicle Challenge Rules. We chose these methods because they were concurrent with our objective and engineering specifications. Additionally, it provided training prior to the competition in April.

Baseline Testing – Endurance

The baseline endurance test was conducted on October 5, 2019 in the H-1 parking lot at Cal Poly (see Figure 5.3). Per the NFPA Endurance challenge rules, the course length is 1 mile and "may contain laps in a slalom fashion." Thus, Pump My Ride established a loop where 5.5 laps was equivalent to 1 mile.

Figure 5.4: Endurance Testing Location. 5.5 laps = 1 mile

Following the 2020 NFPA FPVC Rules, all teams were to be required to start their vehicle from a standing start with an empty accumulator. Prior to completing the course, all teams were meant to stop and charge their accumulator with their vehicle's regenerative mode. Vehicles would then have needed boost out of their stop using only the energy in the accumulator and travel one full vehicle length before resuming human power. Pump My Ride implemented the stop and boost into the procedure to test the effectiveness of the vehicle's regenerative mode. The NFPA did not specify when the stop and boost must occur, therefore we performed the "stop and boost" in the middle of our mock endurance course.

Pump My Ride completed two trials of the endurance challenge during the Fall 2020 quarter. Using the Juicebox to switch from the vehicle's direct drive to regenerative to boost was straightforward. However, design changes to the layout may have made switching modes more intuitive and user-friendly. Ultimately, the number of trials completed was limited by the endurance of the riders. Their finishing times are displayed in Table 5.1.

Table 5.1: Baseline Endurance Test Results

Date: October 5, 2019		
Course Distance: 1 Mile		
Trial	**Rider**	**Finishing Time [mm: ss.ds]**
1	Jacob	05:23.8
2	Bryson	05:32.0

Table 5.2: 2019 Competition Endurance Challenge Results

Place	**University Name**	**Time**
1st	Cal Poly	4:50:45
2nd	Cleveland State	5:40:00
3rd	Montana State	5:45:48
4th	West Virginia University Inst. Of Tech.	6:40:00
5th	Purdue Northwest	10:42:00

Our specifications required we complete the endurance challenge in 4:30:00 or less. At the time of CDR, our testing results showed that we were outside this specification. However, our baseline

results did not show the design changes to improve the vehicle. Moreover, they reflected the Incompressibles vehicle performance. Nonetheless, our baseline tests were competitive in comparison to the 2019 endurance challenge results, displayed in Table 5.2.

While testing, we noticed several system errors including leaks around the hydraulic fittings and air in the system. Leaks were planned to be resolved with new hydraulic lines and fittings. We observed air in the system by watching air bubbles move through the clear low-pressure lines. The effects were felt during testing as the pedaling felt discontinuous. Air was removed by bleeding the system and mounting the accumulator vertically. Resolving these deficiencies while implementing new design changes were expected to significantly improve the endurance performance. It was predicted we would perform under the engineering specification at 3 minutes and 37 seconds. However, human conditioning is always a major factor into the real endurance performance of the vehicle.

Baseline Testing – Sprint

The baseline sprint test was conducted on October 5, 2019 on Mt. Bishop Road at Cal Poly. Per the NFPA, the sprint challenge was meant to "demonstrate the vehicle to move a distance where the vehicle weight is proportional to human propulsion." The course length was meant to be a distance of 400-600 ft, unspecified prior to competition. All vehicles were required to start from a stand (no pushing) and allowed two attempts using the same rider. Following these rules, Pump My Ride marked a 500 ft, straight course. Prior to each trial, we used the vehicle's regenerative mode to charge the accumulator. The sprint challenge rules stated that all teams would be given 10 minutes to charge their accumulator. During the race, time was planned to be recorded from the moment the rider lifts his foot off the ground to the moment the rider crosses the 500-foot marker. We recorded the accumulator charge, rider, and finishing time in Table 5.3.

Table 5.3: Baseline Sprint Test Results.

Date: October 5, 2019			
Course Distance: 500 ft.			
Trial	**Charge Pressure [psi]**	**Rider**	**Finishing Time [mm: ss.ds]**
1	2450	Jacob	00:20.0
2	2450	Jacob	00:18.9
3	1750	Jacob	00:21.7

Trials 1 and 2 used a charge pressure of 2450 psi, while trial 3 used a charge pressure of 1750 psi. All three trials did not utilize the maximum accumulator pressure, 3000 psi, due to human limits and regenerative mode issues. Charging the accumulator from 1000 psi to 2450 psi took approximately 20 minutes and required strenuous physical labor of winding the pedals, pushing the bike forward, and repeat. During trial 3, Pump My Ride practiced charging the accumulator in a 10-minute period, which concluded with a charge pressure of 1750 psi. The difference in time between 2450 psi and 1750 psi was significant, approximately 2-3 seconds. Considering the 10-minute limit and test results, the time and activity to charge to 3000 psi was an obvious system

failure from bike damage and corrective action was necessary to successfully complete this challenge.

According to Table 5.3, there was a significant improvement in time from trial 1 to trial 2. During trial 2, the rider "tucked" to reduce the drag force on his body. The results verified that reducing drag on the rider improved the final sprint time.

Baseline Testing – Efficiency

The initial baseline tests for the endurance challenge revealed system deficiencies, such as leaks and air. Considering these deficiencies from the vehicle damage, Pump My Ride decided to not conduct an efficiency test because it would not provide helpful, reliable data.

5.2 Changes from Critical Design

After critical design, Pump My Ride followed the procurement, manufacturing, and design verification plans as best as the team could. Nonetheless, there were necessary design changes due to delays, time constraints, newfound system errors, and unprecedented changes with the COVID-19 pandemic. The most significant changes from the critical design that were not included in the final design were the hydraulic hard lines, chain guards, and LCD. In summary, these components were not included because of delays with other components that had higher priority in order of completion. You can read about these changes in more detail in Section 5.2.3 for hydraulic lines, Section 5.7.4 for chain guards, and Section 5.6.3 for the LCD. Additionally, we updated a few designs for improved packaging, manufacturability, and system performance. These include the hydraulic controller, manifold, motor, and accumulator. More elaborate explanations for the updates and changes from the CDR can be found in their respective sections below.

5.2 HYDRAULICS

The team's hydraulics were centralized through a custom-built manifold donated by HydraForce. The manifold is a convenient place to locate the valves so that the controls section of the hydraulic circuit is centralized in one location. The vehicle used soft hydraulic lines to distribute energy, in the form of pressurized hydraulic oil throughout the system. The soft lines were planned to be replaced with stainless steel hardlines in order to decrease hydraulic losses throughout the hydraulic system.

5.2.1 MANIFOLD

The manifold was created and designed with the assistance of Mark Decklar from HydraForce. The schematic layout is provided in Figure 5.4 and the CAD model is presented in Figure 5.5. The manifold centralized the hydraulics of the vehicle to a hub and improved the overall fluid system by decreasing the length of flow paths and in doing so reducing pressure drops. The manifold also reduced installation costs, the possibility of oil leaks due to less connections, and centralized maintenance by allowing the system to be bled from one point. The manifold design matched our engineering specification to reduce internal leakages in the hydraulic system. In addition, the manifold improved the overall organization and layout of the hydraulic lines due to less hoses and connections. The manifold itself was compact and the dimensions are measured to be 3.93" x 6.00"

x 2.93”. All valves for the vehicle came preassembled, threaded into the manifold. Details about each specific valve can be found in Section 5.2.2. Minor tweaks to the fluid schematic and manifold layout were made before ordering and procuring the manifold. The lead time to create the manifold was 8 – 9 weeks, however we received the manifold 16 weeks later. Because the accumulator was to be mounted on the side of the vehicle, the manifold had ample space to be mounted with a clearer path for hose connections and maintenance.

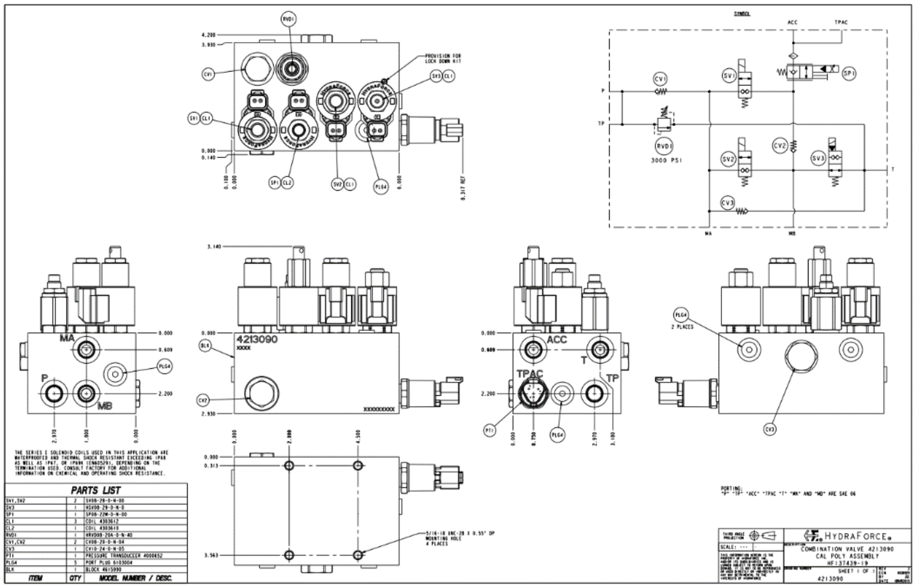


Figure 5.5: Schematic Layout of the Manifold

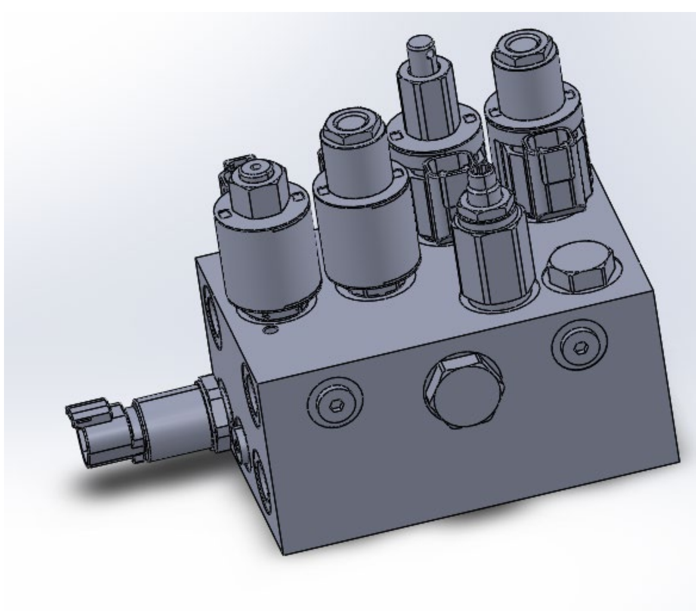


Figure 5.6: CAD Model for Manifold Design

5.2.2 VALVES

The valves that are directly attached to the manifold are sponsored and supplied by HydraForce, a major distributer of hydraulic components. The solenoid valves on the current vehicle were also supplied by HydraForce. The solenoid valves control fluid flow distribution and the switching between driving modes. The solenoid valves are controlled using the ECDR-0506A controller unit. Below are the different types of valves used on our vehicle. Each valve is explained thoroughly detailing function and performance.

CV-08

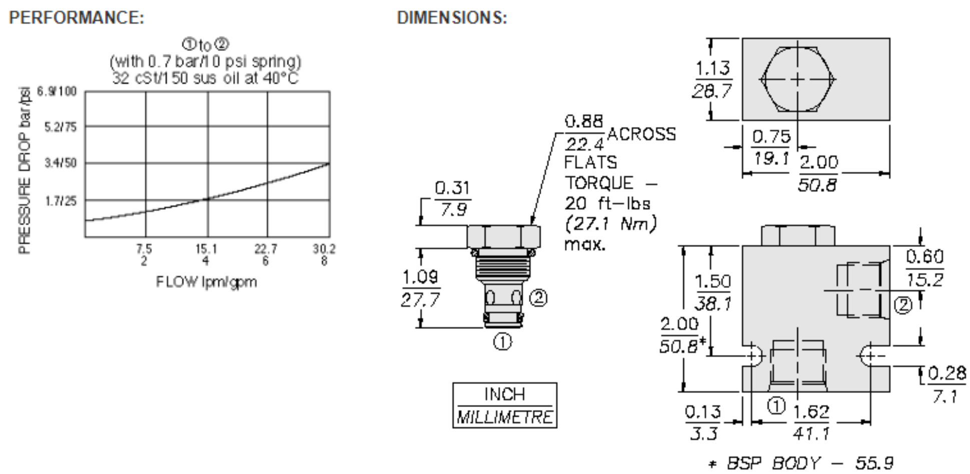


Figure 5.7: CV-08 Check Valve Dimensions and Performance Curve

The CV08-Check Valve is a hydraulic check valve used for blocking fluid flow or load-holding. The valve is rated to allow a flow of up to 8 GPM. Referencing Figure 5.6, the check valve allows flow from ports 1 to 2 while blocking flow from ports 2 to 1. The valve does not allow flow from ports 1 to 2 until a biased pressure is achieved by the system. The biased pressure could be adjusted with spring selection. The spring selections are rated for pressure ranges from 4 psi to 363 psi. The performance curve verifies that the check valve has low leakage levels with a pressure drop of 17 psi at 2 GPM, which is our max rated fluid flowrate for the vehicle. The internal leakage of the check valve is stated to be 2 drops per minute at max 3500 psi. At lower pressures the leakage is negligible. The weight of the cartridge is 0.17 lbs and is made of steel with hardened work surfaces.

CV-10

The CV-10 check valve is used for blocking fluid flow or load-holding. The valve allows fluid flow from port 1 to 2 while blocking flow from ports 2 to 1. The valve is rated to allow a flow up to 20 GPM. The valve features a hardened seat for long life and lower leakages and an adjustable bias spring to change starting pressures for fluid flow. The internal leakage of the valve is rated for 2 drops/minute at 3500 psi. At lower pressure the leakage is negligible. The performance curve shows that the pressure drops at a flow of 2 GPM is determined to be around 12.5 psi using a 5-psi bias spring and 27 psi using a 30-psi bias spring.

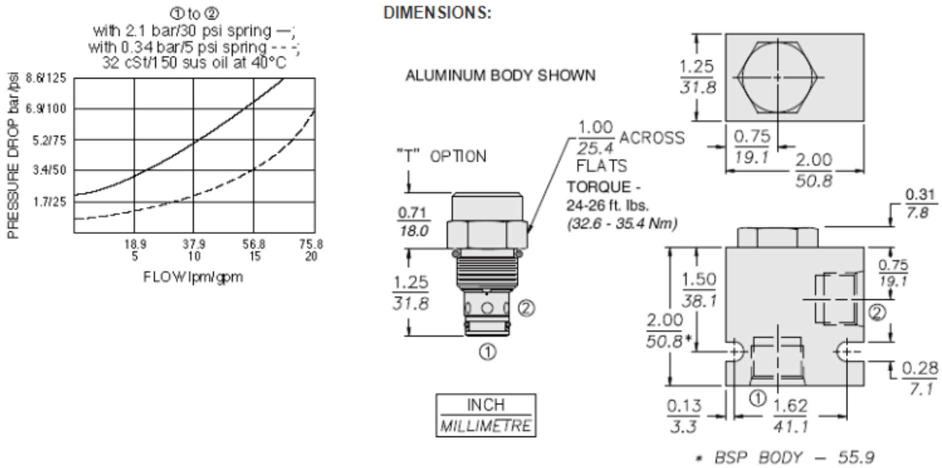


Figure 5.8: **CV-10 Check Valve Dimensions and Performance Curve**

SP – 08

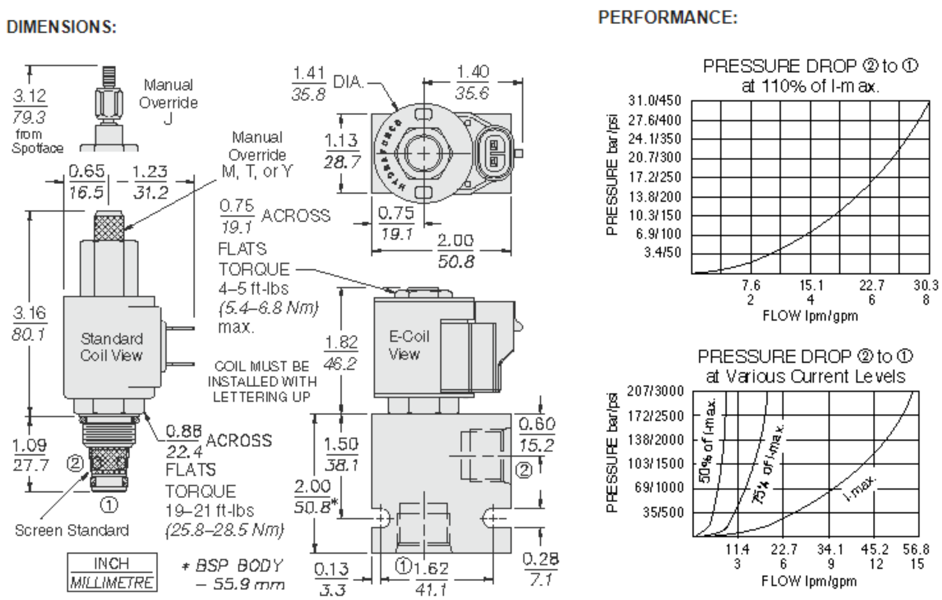


Figure 5.9: SP-08 Poppet Valve Dimensions and Performance Curve

The SP08 – 20 is a 2-way, normally closed, proportional, poppet, screw-in hydraulic cartridge valve for blocking and holding applications. When de-energized the valve acts as a check valve and allows flow from ports 1 to 2 while blocking flow from 2 to 1. When energized the cartridge lifts the coil to allow flow to go from port 2 to 1. The coil lift can be controlled using a ramp input. Flow is controlled by the ECDR – 0506A and the opening of the valve is proportional to the current applied to the coil. The internal leakage is 5 drops per minute at 3625 psi. At low pressures leakage is negligible. As we can see from the performance curves current affects the pressure drop of the system especially at higher flow rates. At low flows the pressure drop is consistent at around 25 psi regardless of current. The valve is rated for flows up to 5.8 GPM which is greater than our maximum flowrate in the hydraulic system.

SV – 08

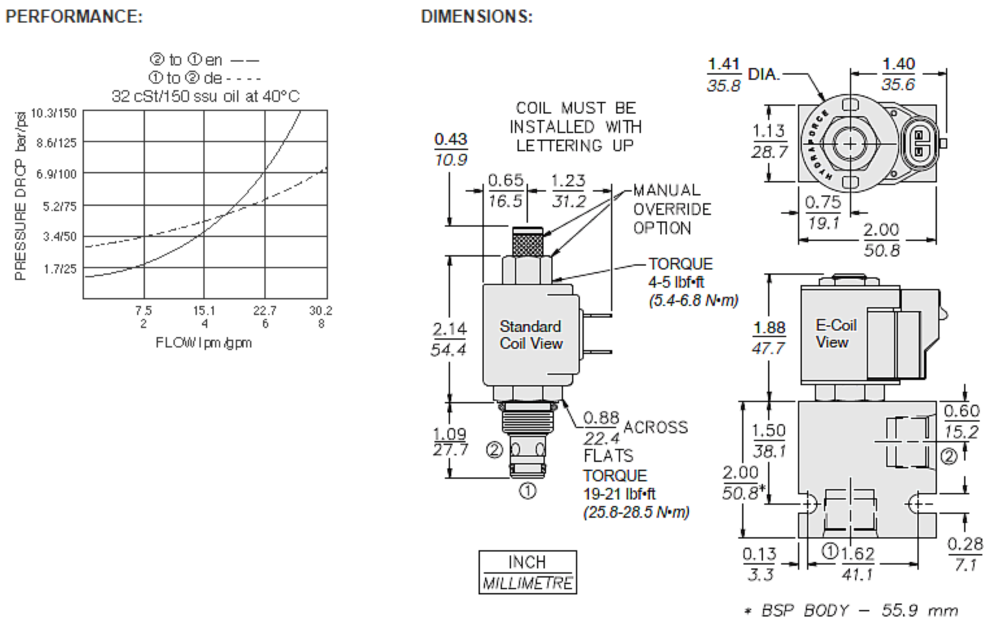


Figure 5.10: SV-08 Solenoid Valve Dimensions and Performance Curve

The SV-08 Solenoid valve is a 2-way, piloted poppet type, screw-in hydraulic cartridge valve intended to act as a blocking or load holding device for low flow circuitry. The valve is rated for flows up to 6 GPM. When de-energized the valve acts as a check valve allowing flow from port 1 to port 2. When energized the poppet lifts to allow flow from port 2 to port 1. Also, when the solenoid valve is energized the flow from port 1 to port 2 is severely restricted. The internal leakage of the valve is 3 drops per minute at 3000 psi. At lower pressure leakage is negligible. The performance curves show that there is a pressure drop of about 27 psi for a flow rate of 2 GPM from port 2 to 1 and a pressure drop of 50 psi from port 1 to 2 at a flow rate of 2 GPM.

HRVD08 - 20

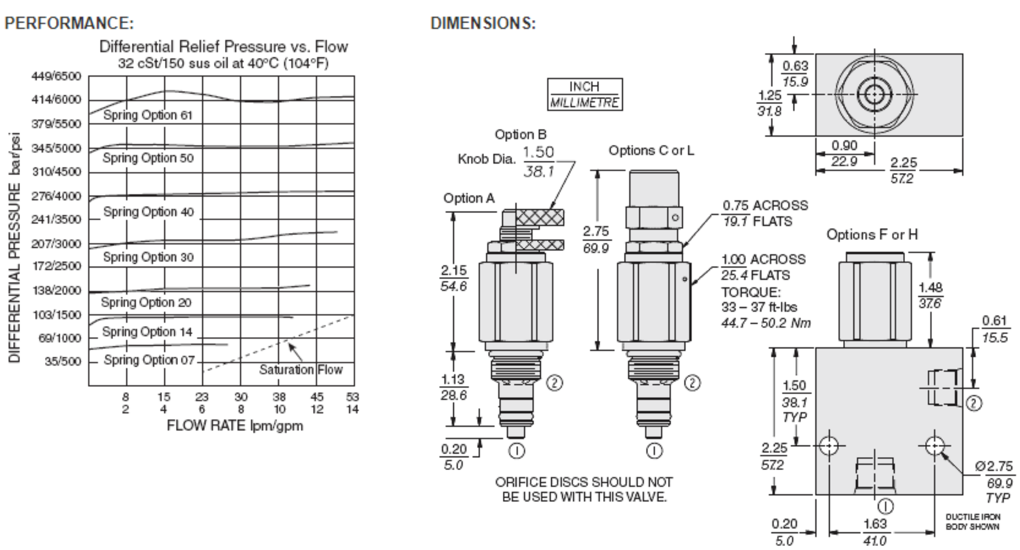


Figure 5.11: HRVD08-20 Pressure Relief Valve Dimensions and Performance Curve

The HRVD08 – 20 Pressure Relief Valve is a poppet-type, hydraulic relief valve with dampening for use as a pressure limiting device for common hydraulic circuit protection. The valve blocks flow from port 1 to 2 until enough pressure is present at port 1 to force the poppet from its seat. The cartridge has a fast response to load changes which result in low hysteresis, low pressure rise and low internal leakage. The valve is rated for flows up to 14 gpm. The valve has an internal leakage of 5 drops per minute at 75% of the nominal settings. The performance curves detail differential pressures versus flow rates. The flowrate of our bike is capped at 2 GPM and an allowable pressure of 3000 psi is allowed for the vehicle for safe operating conditions of the rider. Spring option 30 would be the best selection for our team based on the performance curve.

Heavy-Duty Pressure Sensor

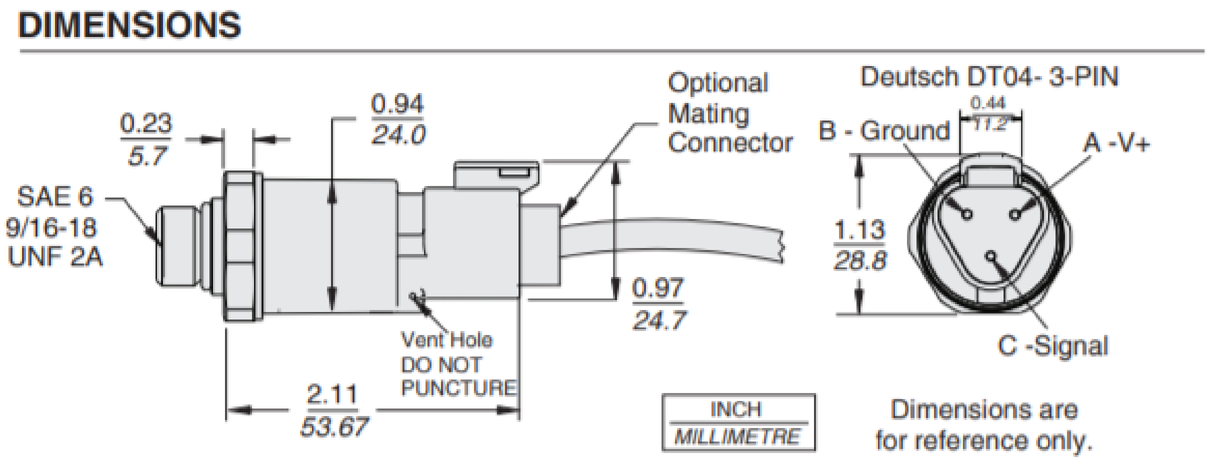


Figure 5.12: Pressure Sensor Details

The high-accuracy heavy-duty pressure sensors has a 1% total error band accuracy accomplished by combining a high-performance ASIC to a very stable, field-proven polysilicon, thin-film pressure sensor. These sensors are intended for use in demanding industrial and off-highway equipment. The pressure sensor was not able to be implemented this year.

5.2.3 HYRDAULIC CIRCUIT

The hydraulic models below were created using HydraForce's I-design software. The models took the parameters of the bike (including wheel size, wheel thickness, weight of the rider, gear ratios, etc.) and output the predicted fluid flow and pressure in the system for different drive modes across the fluid system. There were 3 driving modes the rider could select from which include boost mode, direct drive mode, and regenerative braking mode. An accumulator charging mode that used the pedaling from a rider was considered, but hand calculations found it to be impractical. Each mode uses different combinations of valve control, to direct the flow from the reservoir to the hydraulic components. The models visually show the direction and the valves that were energized for each specific drive mode.

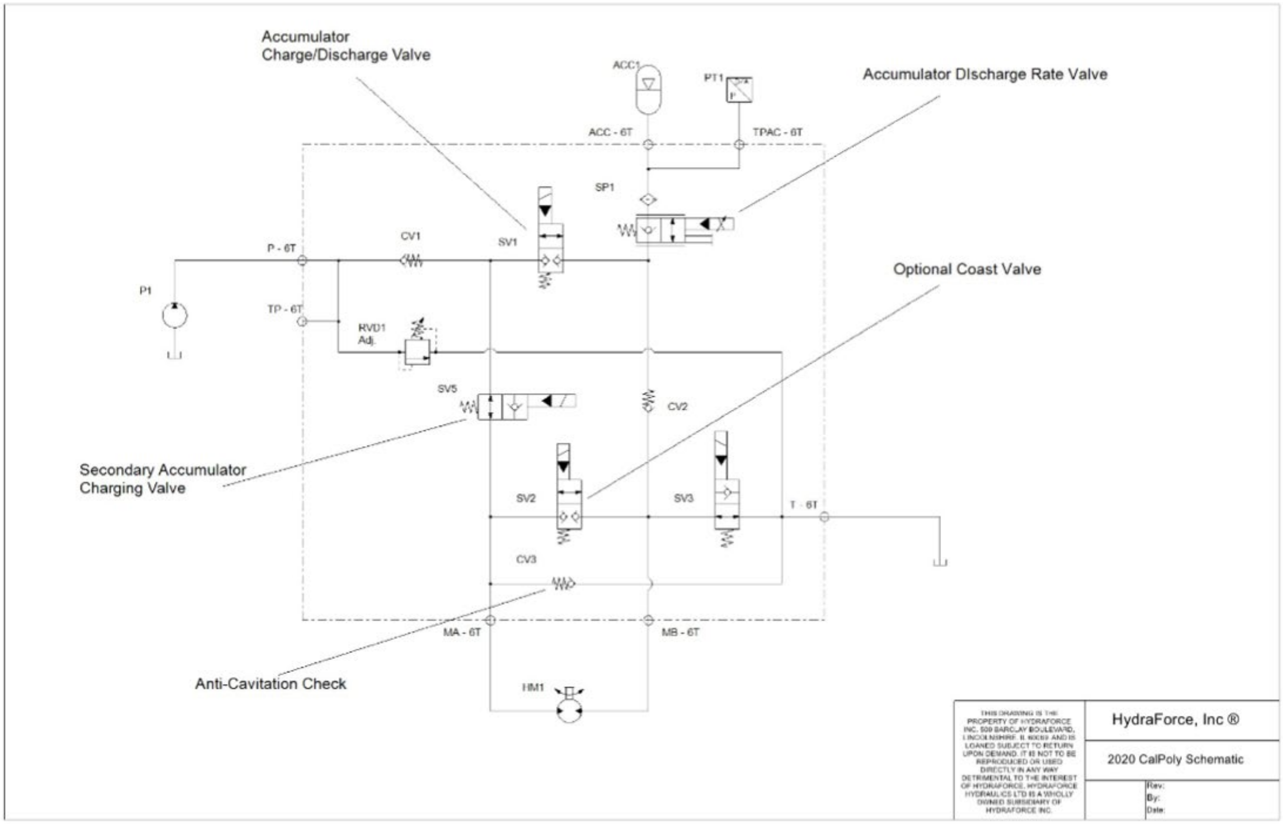


Figure 5.13: Annotated Fluid Schematic

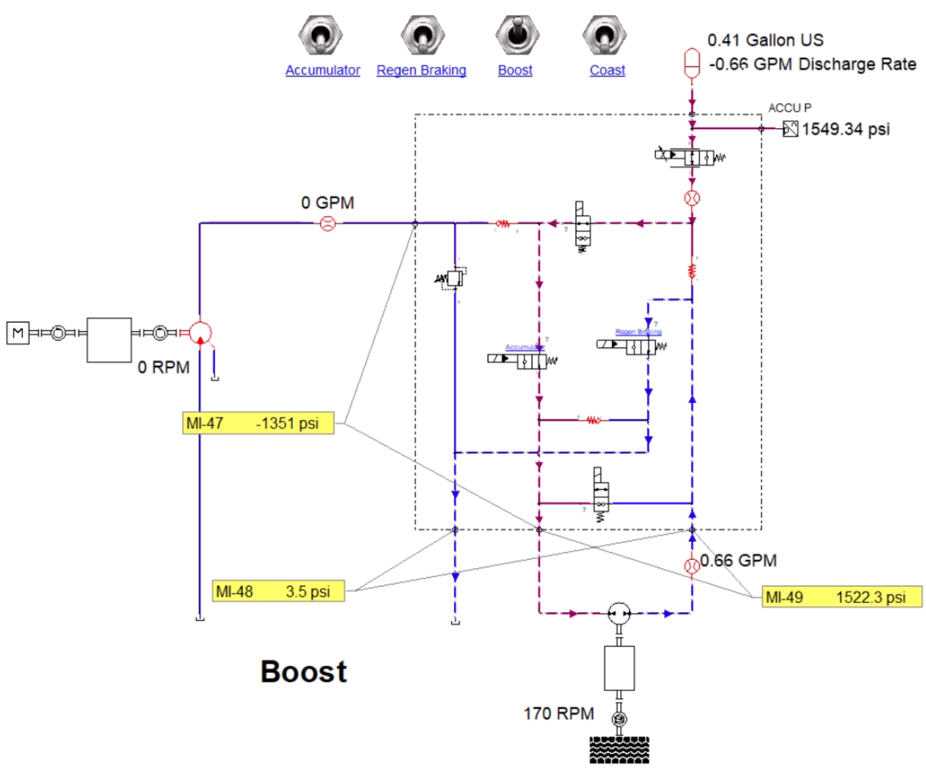


Figure 5.14: Boost Mode

In boost mode, the accumulator discharges stored compressed liquids to propel the bike. The accumulator ramps fluids through a proportional solenoid valve that travels through a bi-directional and one-way solenoid valve before reaching the driving motor (flow dashed in maroon). After the flow passes through the motor the flow exits back into the reservoir through a one-way solenoid valve (flow dashed in blue). A proportional solenoid valve was added to the circuit to avoid motor blow out. The flow directly powers the motor that transfers power to the rear drivetrain. This mode was used for the sprint challenge, efficiency challenge, and endurance challenge. A pre-charge pressure test was conducted to verify the impact that different pre-charges had on the performance for each challenge.

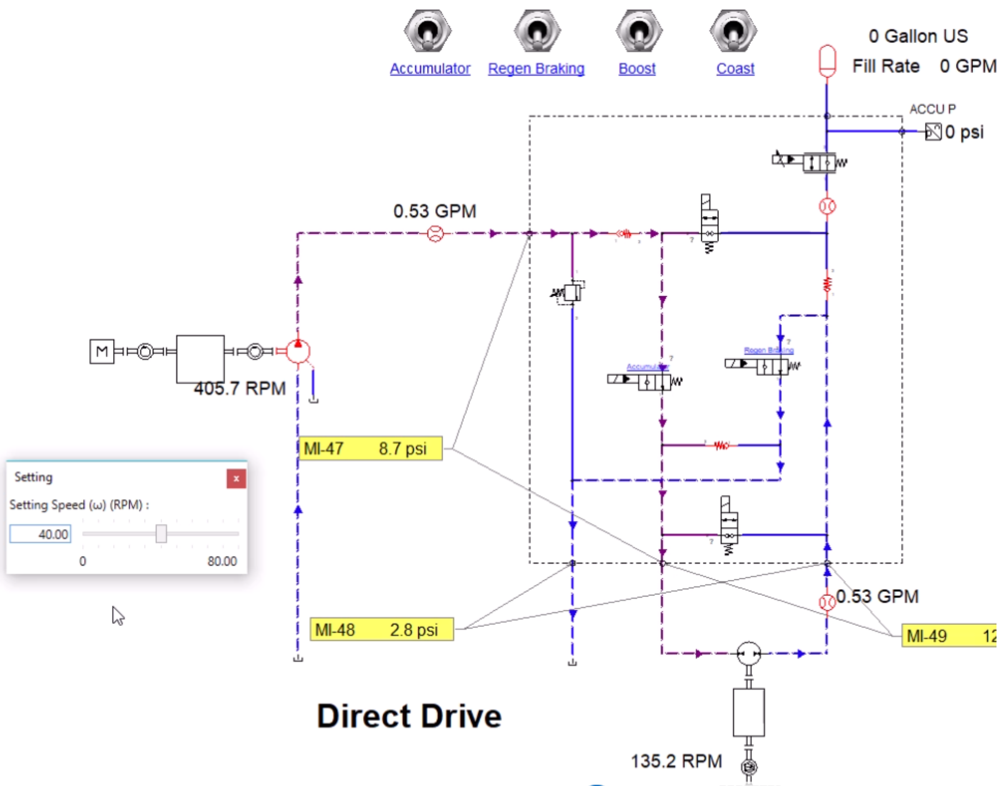


Figure 5.15: Direct Drive Mode

In direct drive mode the rider directly propels the vehicle by pedaling. The pump driven by the rider pushes fluid through a one-way solenoid valve to provide power to the second motor which drives the vehicle forward (flow dashed in maroon). The fluid is diverted through an energized solenoid valve in the circuit and is blocked to the accumulator by a check valve. The fluid to flow into the reservoir and the cycle repeats itself as the fluids are pulled from the reservoir back to the first motor thus completing the circulation of flow (flow dashed in blue). Direct drive mode closely resembles the operation of a normal bicycle and is primarily used in the endurance challenge.

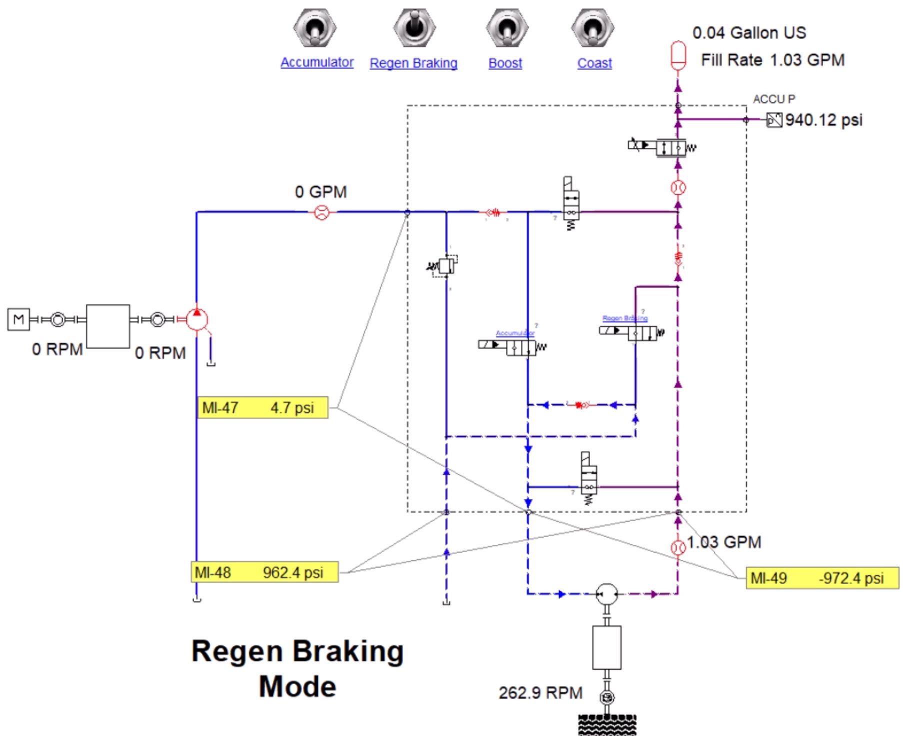


Figure 5.16: Regenerative Braking Mode

In regenerative braking mode, power is taken from the motor to recharge the accumulator. The flow goes from the driving motor directly into the accumulator through the proportional valve (flow dashed in maroon). The flow is allowed through the proportional valve because the valve acts as a check valve when de-energized. The motor pulls liquid from the reservoir, and the liquid from the reservoir travels through a check valve before reaching the motor (flow dashed in blue). The rider can either use the hand brakes or use the regenerative braking mode to slow the vehicle down while in motion. Using the regenerative braking mode to slow the vehicle down will charge the accumulator at the same time. The regenerative braking mode is the only way presently to charge the accumulator. The regenerative braking system is also a requirement by the competition rules for each team. In the endurance challenge the rider must be able to charge the accumulator with a regenerative brake and restart movement by discharging the stored energy using boost mode to travel a full vehicle's length.

There was also a coast mode that allowed the wheel to rotate freely with minimal resistance which did not need to be activated. The vehicle mode defaulted to a coasting method when the rider was not pedaling, and the bike was moving. The fluid was allowed to travel through two paths either through a solenoid bi-directional solenoid valve or a one-way solenoid valve and a check valve in series (flow dashed in blue). The flow infinitely cycled through the motor while coasting. This was useful when traveling down a slope or on a flat surface in order to roll freely. Without the coasting, there would have been increased resistance from the hydraulic system.

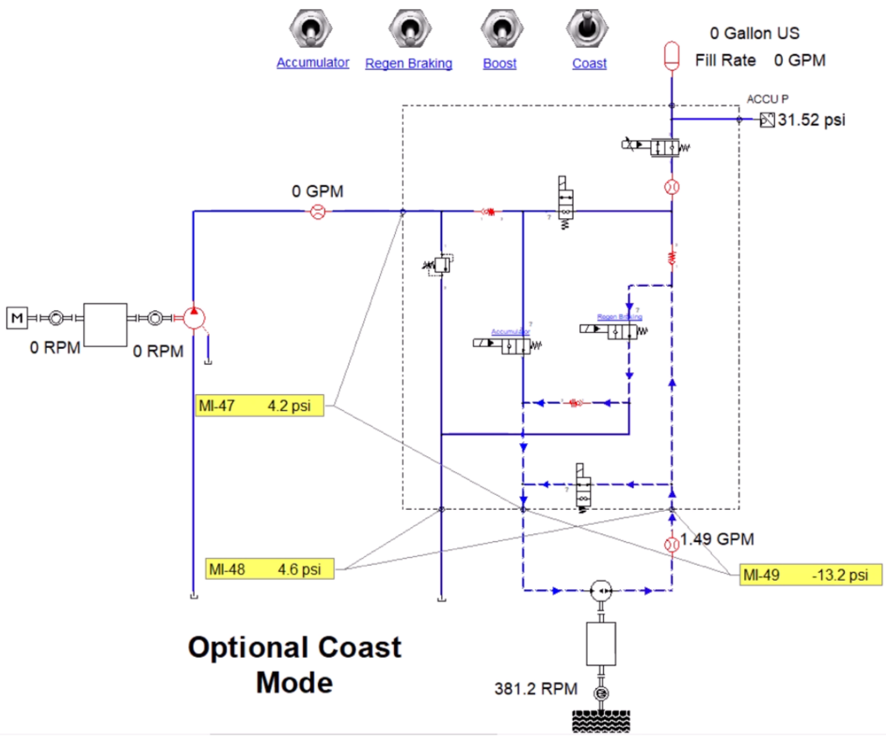


Figure 5.17: Preliminary Coast Mode

5.3.4 HYDRAULIC LINES

We planned to replace the current soft hydraulic lines on the bike with custom made hard lines. Soft lines are much more convenient as they allow for changes in positioning on the bike. Unfortunately, soft lines expand slightly when under pressure, contributing to hydraulic losses. They also require 90° fittings for certain components, except for being marginally lighter than bent steel hard lines. We had weighed the pros and cons of both soft and hard lines and had determined that hard lines are likely to be worth the cost and time to produce.

Update from CDR – Soft lines

Pump My Ride was unable to manufacture hard hydraulic lines because of a 4-week delay from HydraForce with the new manifold. Without a manifold, we could not accurately measure the distances and correct fittings for the hard lines. To leave enough time for testing, we decided to use the soft lines on the previous bike and move forward. Fortunately, the fittings for the soft lines and new manifold were compatible.

5.4 MODELS

5.4.1 PATTERSON MODEL

There have been no major structural changes to the Patterson model created for the PDR, and as such, the analysis was carried over.

5.4.2 SIMSCAPE MODELS

The Simscape models were used to predict the effects of various design changes on the bike performance. Each of the models consider fluid properties, pipe resistance, motor inertia, motor and pump profiles, accumulator properties, tire rolling resistance, aerodynamic drag and total weight of the rider and bike. A summary of the usage for the Simscape models is provided in Table 5.4 for reference.

Table 5.4: Simscape Models

Challenge (Model)	**Specifications Investigated**	**Primary Effected Design Decisions**
Endurance (Direct Drive)	Endurance Time Required Rider Power	Front gear ratio Rear gear ratio
Sprint (Accumulator Discharge)	Sprint Time Top Speed	Accumulator Size Rear gear ratio Handle-bars Tires
Efficiency (Pulsed Accumulator Discharge)	Efficiency Score	-
Between Challenges (Recharge)	Turn Around Time	-

The ability of the models to predict the actual bike performance was limited by the hydraulic and mechanical blocks. For example, the accumulator block used was meant to represent a gas charged accumulator but did not have different modelling functions to distinguish between bladder, piston or any other diaphragm type accumulator. However, many parameters for the accumulator could be adjusted for a better representation of the real system. Through model development the team realized the need to adjust Simscape settings for models to solve. Depending on the values set for input parameters the models would only commute within a range of values for the relative tolerance, which were determined with trial and error. Information on the accuracy of each model is further detailed in this section. Also, the MATLAB scripts and a detailed summary of model comparisons with testing data post CDR are provided in Appendix K.

Accumulator Discharge

The accumulator discharge model predicted the sprint time and maximum velocity of the bike. The Incompressibles' model was altered by Pump My Ride to increase inputs but was still limited in the number of variables which could be changed for one run and by the range that they could be altered. Therefore, a new model, presented in Figure 5.17 was created to better represent the hydraulic system of the bike, reduce computation errors and allow more freedom in changing model inputs to represent different design considerations. The modelling blocks with major alterations included the switching of the needle valve block for a solenoid poppet valve and changing the threshold value for the PS switch signaling the three-way directional valve. Also, the addition of a unit delay in the Simulink output computation prevented the error of taking the time derivative of velocity at time zero which modelled the vehicle as moving backwards at the start.

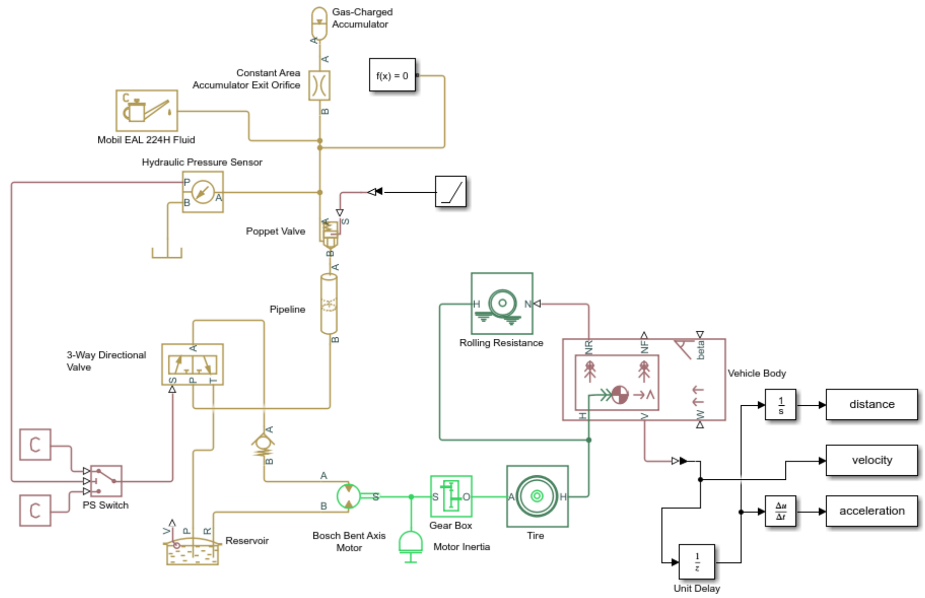


Figure 5.18: Accumulator Discharge Model

The model prediction error was increased for the sprint time of the current bike from 3.16% to 4.68%. However, the team was more confident in the results of the new model due to the additional verification completed with altered parameters. Specifically, during the baseline testing completed after CDR a 160lb rider completed the sprint challenge with an accumulator charge pressure of 2460 psi in 20.0 seconds. The new accumulator discharge model predicted a time of 19.75 seconds, a 1.25% error. In contrast, the previous model was not able to complete the computations and provide an estimate even after a significant time was spent attempting to address the errors outputted by MATLAB. The new model was able to account for various rider weights, vehicle weights and accumulator charges, all of which could not be altered previously. Additionally, the outputs of the model were expected to be correct based on the behavior of the components modelled. For example, the accumulator pressure was reduced in an expected manner, starting at 3000psi and never dropping below the specified pre-charge pressure, as can be seen in Figure 5.19.

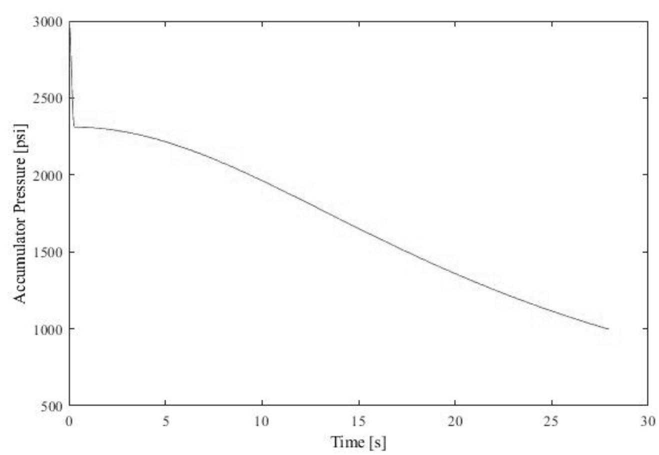


Figure 5.19: Accumulator Pressure Drop in the Accumulator Discharge Model

Originally, the model was run with a rider weight input which represented the average weight of three group members who have weights which vary within a ten-pound range. The team had not yet designated riders for the challenge events and reasoned to use this weight in the models to create consistency in the modelling used to aid design decisions. However, once the modelling for the CDR was expected to be complete the predicted sprint speed was determined to be well above our requirement, at 21.32 seconds. The team considered using the lightest weighing member of the group, providing a 45-pound weight reduction, as the designated rider in the sprint challenge. The rider weight input was adjusted with all possible design decisions incorporated into the model to reduce the sprint speed from 21.32 seconds to 18.10 seconds. This time still did not meet the requirement but was significantly closer. The specification may have been too large of a goal for Pump My Ride given the circumstances of time and inherent trade-offs in design for performance in the competition. Additional information on component specific trade-offs and the resulting decisions are provided within the following sections.

Efficiency Challenge

The efficiency challenge was modelled with a pulsed accumulator discharge based on the Accumulator Discharge Model used to predict the sprint performance. The accumulator was discharged only enough to keep the bike velocity within the critical range to preserve pressure and maximize distance while keeping the bike stable as presented in Figure 5.20.

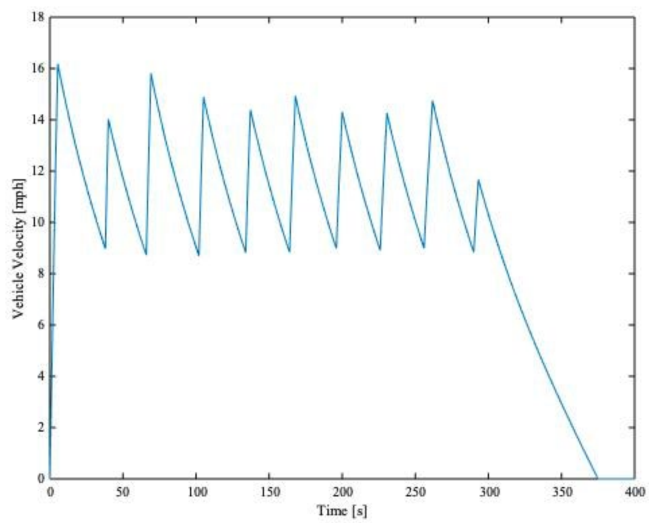


Figure 5.20: Pulsed Accumulator Model Results for Vehicle Velocity

The updated model, used through CDR, contained the same changes as was completed for the accumulator discharge model. The distance travelled by the bike is not accurately modelled at this time according to the competition results and testing completed by The Incompressibles, although the previous model and the new one produce similar results. Specific test and model results are shown in Table 5.5.

The efficiency model was not used to make any design decisions.

Table 5.5: Efficiency Model Accuracy

	Distance [ft]	Efficiency Score [%]	Percent error [%]
Test Results	3667	23	-
Previous Model	5195	34	47.8
New Model	5655	37	60.8

Update from CDR - Efficiency Challenge

Additional time dedicated to the improvement and adjustment of the efficiency model did not reduce the error to an acceptable value to be used in decision making. The efficiency score was overestimated by a range of 31%-64% for pre-charge pressures 200psi- 500psi.

Direct Drive

The structure of the Direct Drive Model was not altered since development by The Incompressibles. The model properly represented the behavior of the components in the system and consistently produced reasonable results based on engineering knowledge. Additionally, the Incompressibles used the model developed by the Cal Poly 2017-2018 competition team to verify the accountability of their model by its ability to produce similar results as displayed in Figure 5.21 taken from the Incompressibles' final design report [2].

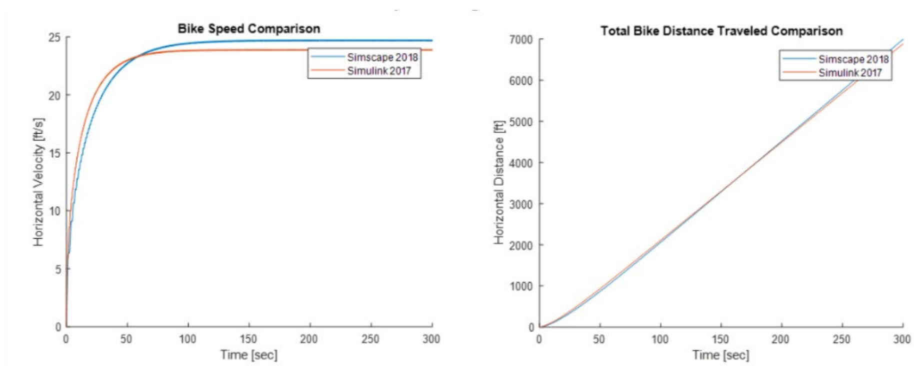


Figure 5.21: Endurance Challenge Model Comparison 2018 to 2017 [2]

Additionally, the Incompressibles were successful in achieving their goal for the endurance challenge time using the model to assist in design decisions. Therefore, Pump My Ride also used the model to observe the effects of different design considerations and to make decisions.

Update from CDR- Direct Drive

The accuracy of the model was difficult to determine due to the variations between rider abilities and characteristics. Pump My Ride attempted to obtain a rider power input profile with power pedals but were unsuccessful. The pedals were made for use with a typical bike and the manufacturer was unable and unwilling to assist us with our application.

Nevertheless, the constant input block was changed to a Repeating Sequence block which scales the constant rider power gain. The input waveform can be altered to represent the expected rider output for better accuracy and predictions.

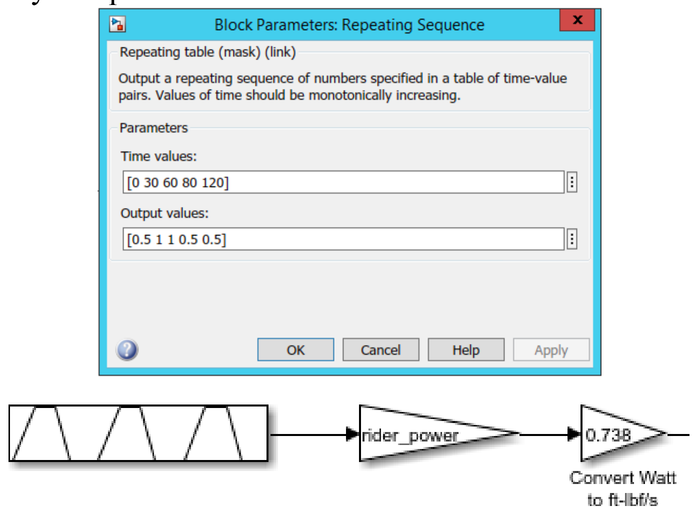


Figure 5.22: Endurance Model Input

The waveform in Figure 5.22. represents a situation where the rider starts with half effort as they warm up to full power. They continue to output full power for 30 seconds after which point, they become exhausted and their effort is reduced to half their maximum power. The riders are switched after about 100 seconds and the waveform repeats. This model version predicated an endurance time of 4 minutes and 55 seconds, with 15% error compared with validation testing after manufacturing. Information on manufacturing and validation testing follow in later sections of the report. The endurance model may be used by future teams to compare results of design decisions. Users must be aware that the accuracy of the predicted endurance time will depend on the user's ability to predict power input.

Accumulator Recharge

The Accumulator Recharge model was developed by The Incompressibles to predict the turn-around time for charging the accumulator between competition events. The model inputs for the rear gear ratio, resistance of the tires, and vehicle weight were altered to represent the updates to the bike. The model simulated a person pushing the bike at a conservative 3mph speed.

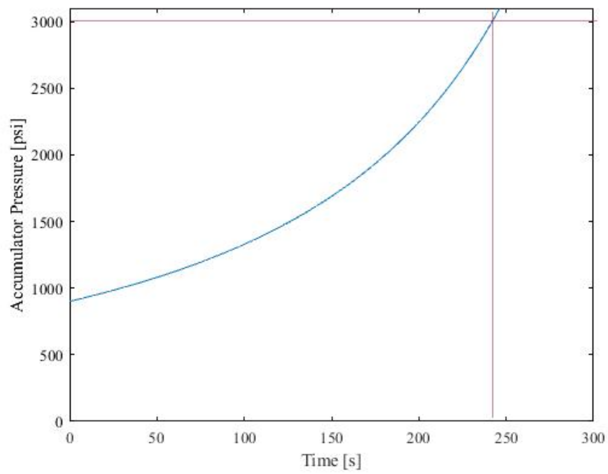


Figure 5.23: Accumulator Recharge Model Output

Figure 5.23 shows that the predicted time was 3.6 minutes, which satisfied our specified turn-around time.

Update from CDR- Accumulator Recharge

The model was inaccurate in estimating the actual time to recharge the bike. Additional time would be required to increase accuracy for use by future teams. Pump My Ride would suggest switching out the constant input to a downward sloping ramp to account for the exponential increase in difficulty of pushing the bike as the pressure reaches its maximum.

Hydraulic Analysis

The direct drive and accumulator discharge models provided hydraulic properties for the system and individual components. Most notably, the expected system flowrates ranged between 0.85 and 0.9 gpm in the direct drive mode, and at about 2.4 gpm during accumulator discharge. The flowrates aided in pump and motor selection, and in predicting pressure losses due to valves within each mode, as summarized in Table 5.6.

Table 5.6: Valve Pressure Losses

Mode	Pressure Loss at Flowrate 2*gpm*
Accumulator Charge	43 psi (1 solenoid, 1 check valve)
Regen Braking	35 psi (1 check valve, 1 solenoid)
Direct Drive	43 psi (1 solenoid, 1 check valve)
Coast	25 psi (1 solenoid)
Boost	75 psi (3 solenoids)

5.5 FRAME

In the PDR report, we considered multiple vehicle frame concepts including frames for a prone bike, elliptical, velomobile, and an upright standard bicycle. Ultimately, Pump My Ride decided on an upright standard bicycle. Considering the advantage of possessing last year's frame, built by the Incompressibles that was tested in the 2019 FPV challenge, Pump My Ride decided to reuse the frame shown in Figure 5.24.

Figure 5.24: Pump My Ride Vehicle Frame Inherited from the Incompressibles [2]

5.5.1 FRAME GEOMETRY

The vehicle frame was modelled after the Trek FX Sport 5. It was recognized as a hybrid frame, balancing the physical characteristics of mountain bike and road bike. Figure 5.25 displays the CAD of the frame inherited from the Incompressibles. Geometry is illustrated in Figure 5.26 with relevant dimensions displayed in Table 5.7.

Figure 5.25: Isometric View of Current Frame [2]

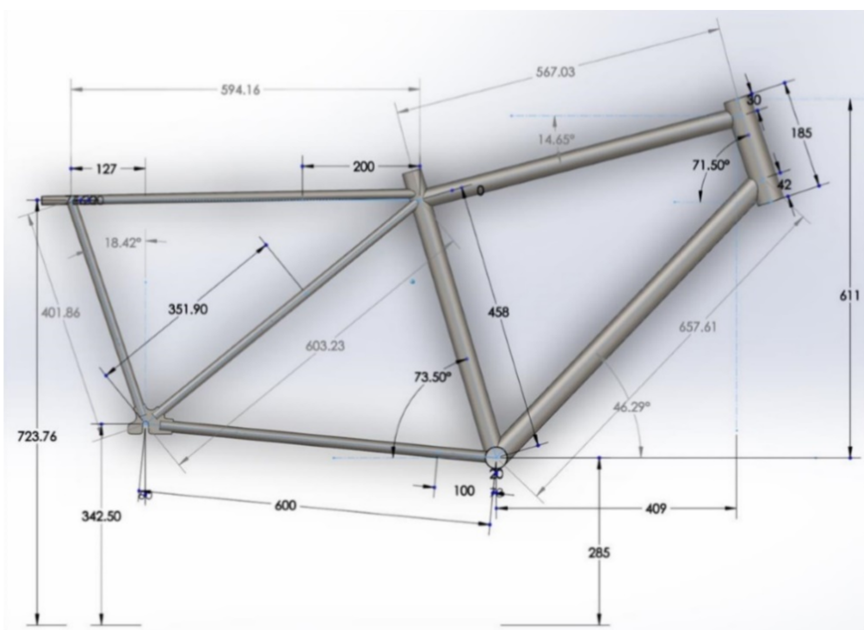


Figure 5.26: Frame Geometry [2]

Table 5.7: Relevant Frame Parameters and Dimensions [2]

Parameter	Length [mm]	Angle (degrees from horizontal plane)
Stack	409.0	-
Reach	611.0	-
Wheelbase	1238.9	-
Head Tube (t-t)	185.0	71.5
Top Tube (c-c)	567.0	14.6
Down Tube (c-c)	657.6	43.6
Seat Tube (c-c)	458.0	73.5
Chainstay Tube (c-c)	600.0	-
Seatstay Tube (c-c)	603.2	-

5.5.2 MATERIAL

The vehicle frame employs 4130 steel tube. The various tube diameter and wall thicknesses for selected components are summarized in Table 5.8 with references to Figure 5.27. Consistent with the current frame selection, Pump My Ride used 4130 steel tube for additions made to the frame, such as the vertical accumulator mount.

Table 5.8: Summary of Frame Tube Outer Diameter and Wall Thickness [2]

Name	Ref #	Outer Diameter	Wall Thickness
Top Tube	1	31.7 mm	0.8x0.5x0.8 mm
Head Tube	2	46.4 mm	1.25 mm
Down Tube	3	38.1 mm	0.9x0.6x0.9 mm
Seat Tube	4	32.7 - 33.5 mm	0.9x0.5x0.95 mm
Chainstay Tube	5	0.75 in	0.065 in
Seatstay Tube	6	0.625 in	0.065 in
Vertical Support Tube	7	0.625 in	0.065 in
Upper Support Tube	8	0.625 in	0.065 in
Chainstay Bridge	9	0.50 in	0.065 in
Seatstay Bridge	10	0.50 in	0.065 in
Upper Support Bridge	11	0.50 in	0.065 in

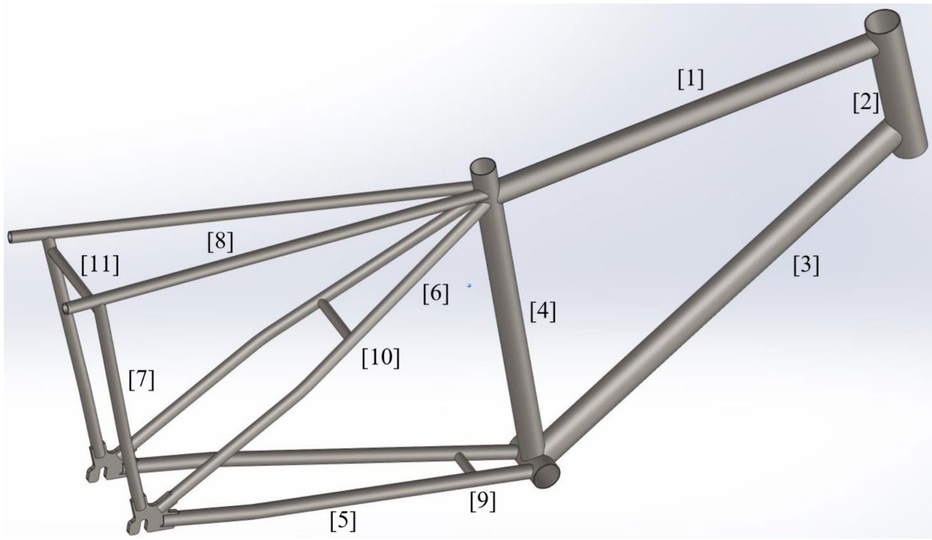


Figure 5.27: Final Frame with references for outer diameter and wall thickness [2]

5.5.3 FRAME STRUCTURAL ANALYSIS

Since there were no changes to the frame geometry, the structural analysis for the frame is carried over from the Incompressibles. Their analysis was designed to meet 2 G's of acceleration and simplified into a truss model. A bump load was applied at appropriate nodes, and the weight of the accumulator was placed at the farthest back node. Then the combined weight of the rider and bike was placed between the seat tube and the handlebars. The completed FBD with applied loads is displayed in Figure 5.28.

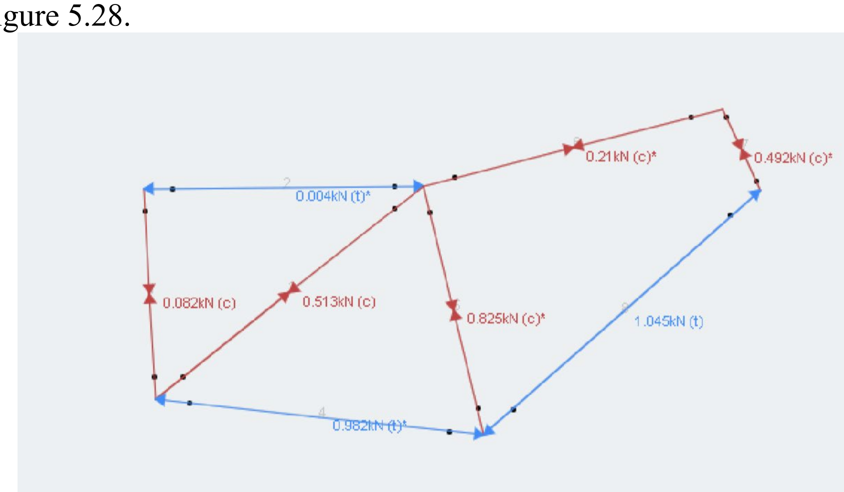


Figure 5.28: Truss Analysis of Final Vehicle Frame [2]

These forces were used to find normal stress in each section of piping, assuming all tubes had constant OD and wall thickness. The factor of safety per tube is summarized in Table 5.9.

Table 5.9: Tube factor safety from forces developed in truss analysis [2]

Tube	Factor of Safety
Chainstay	15.95
Down Tube	14.83
Head Tube	79.46
Horizontal Support	3900
Seat Tube	13.44
Seatstay	25.28
Top Tub	51.16
Vertical Support	191.11

5.5.4 HANDLEBAR SELECTION

In the PDR, Pump My Ride chose to implement hybrid handlebars: replacing the cross-country handlebars with aero drop bars and adding tri bar extensions. Model results and experience with the bike led us to reason that reducing air drag on the rider would improve scores in all three challenges. During the Fall 2019 quarter, we completed further investigation on this decision with the Simscape models. Tri bar extensions with the Simscape showed an improved sprint time by 2.08±.1% (.5±.02 s), and an improved endurance time by 8.64% (21s). However, aero drop bars did not reveal any significant improvement. Therefore, we determined that replacing the cross-country bars with aero drop bars was redundant. The evidence from the Simscape model supported the decision to purchase tri bars, so we compared various tri bar brands using a decision matrix, in Table 5.10.

Table 5.10: Tribar Selection Decision Matrix

Criteria	**Weight (1-5)**	**Tribars**				
		No Tribar	Bontrager	Lixada	Vision	Profile Design
Cost	1	Datum	2	5	2	3
Weight	3		9	6	12	9
Ergonomics	2		6	6	6	8
Adaptability	4		16	20	8	8
Aerodynamics	5		25	15	20	15
Total			**58**	**52**	**48**	**43**

Ultimately, Pump My Ride selected the Bontrager Race Lite Aero tri bars because they offer a great tuck for the rider, and they are easily attachable using clip-on brackets. Figure 5.29 displays a detailed image of our selection. A CAD model of our selection interfaced with the cross-country handlebars can be viewed in Figure 5.30.

Figure 5.29: Bontrager Race Lite Aero Tribars

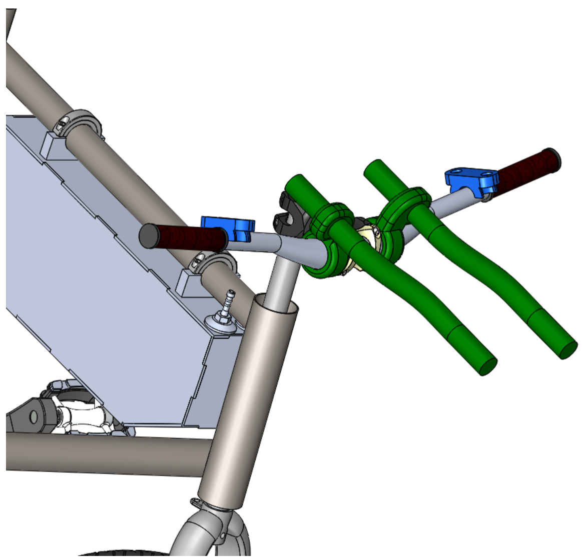


Figure 5.30: Hybrid Handlebar Design

5.5.5 VERTICAL ACCUMULATOR MOUNT

Steelhead Composites specify that accumulators should be mounted vertically in order to avoid inefficiencies from trapped air. According to another manufacturer—Wilkes and Mclean, Ltd.—it is estimated there is a 5% loss in efficiency when accumulators are mounted horizontally. By maintaining a horizontal accumulator, we could risk losing points on our final efficiency score during competition. Therefore, Pump My Ride removed the horizontal mount and constructed a vertical accumulator mount. We optimized the design for lightweight, manufacturability, and strength. Figure 5.31 displays a CAD of the accumulator mount assembly.

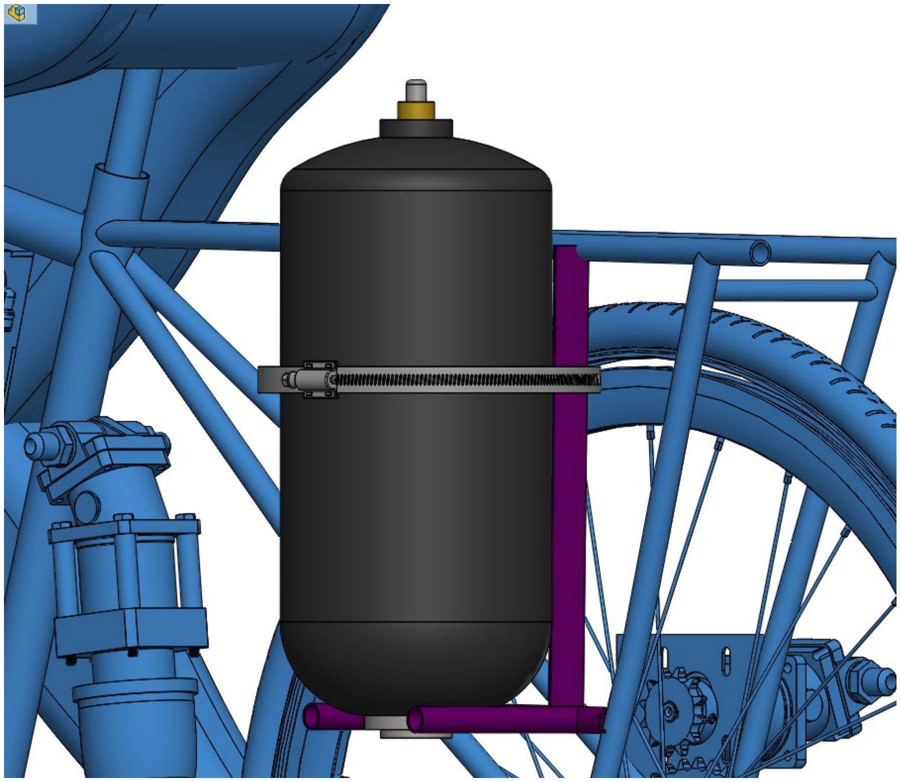


Figure 5.31: Vertical Accumulator Mount Assembly

As shown in the figure, the accumulator is supported at the base by two protruding steel tubes. A 4-inch gap is present to allow space for access to the Schrader valve. Steel angle-irons brazed to the mount's crossbar interface with the horizontal top tube of the frame. A vibration-resistant hose clamp secures the accumulator to the angle irons to prevent accumulator from tipping. The combined weight of a full accumulator and the mount is 11.8 lbs. The Patterson model verified that the new accumulator location does not disrupt the vehicle's stability. In theory, the added weight will help counterbalance the weight of the hydraulic motor.

The mount assembly interfaced with the frame at four sites: 2 at opposite nodes of the crossbar and 2 at the top of the angle irons with the horizontal top tube. Figure 32 and Figure 33 display the sites designated for brazing during manufacturing.

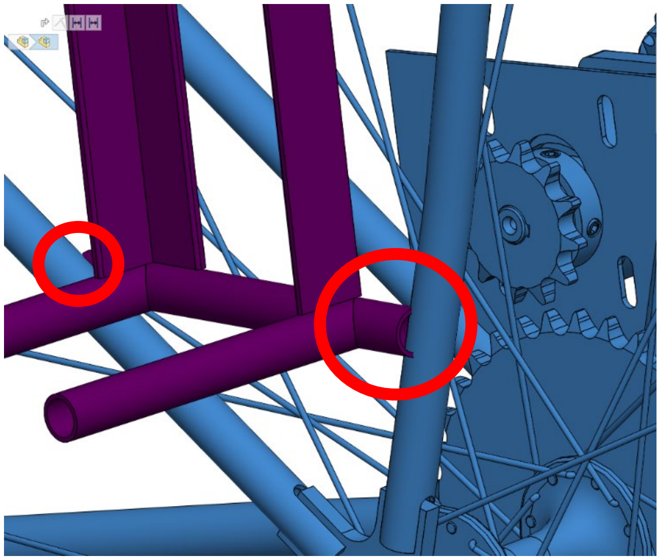


Figure 5.32: Accumulator Mount Detail with Brazing Sites

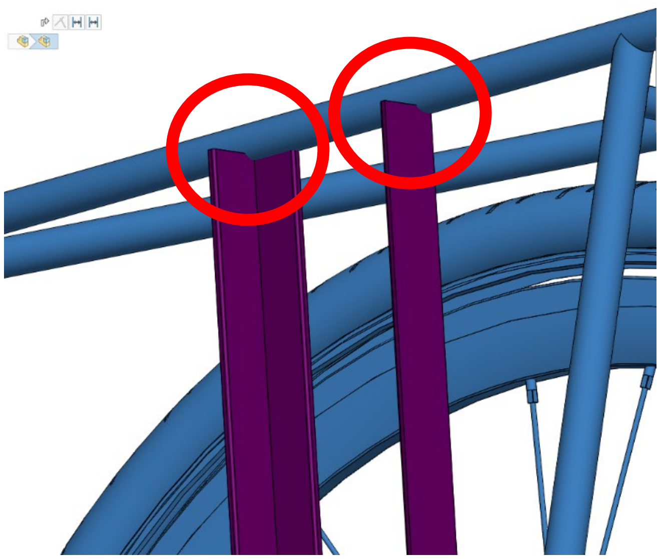


Figure 5.33: Accumulator Mount Upper Detail with Brazing Sites

Update from CDR – Accumulator Mount

The vertical accumulator mount design was updated to make the mount removable, accommodate more flexible packaging, and make assembly easier. We determined that a permanent fixture to the frame would have created issues for assembly of the rear drivetrain and fitting hydraulic lines to the accumulator. Therefore, we constructed the vertical accumulator mount with 1” x 1” steel angle irons conjoined via weld. Instead of brazing, the mount interfaced with the frame via U-bolts, brackets, and a hose clamp. More details on manufacturing are described in Chapter 8.

All design changes are reflected in Figure 5.34 and 5.35 below. Appendix J provides a 2D drawing of the subassembly for reference.

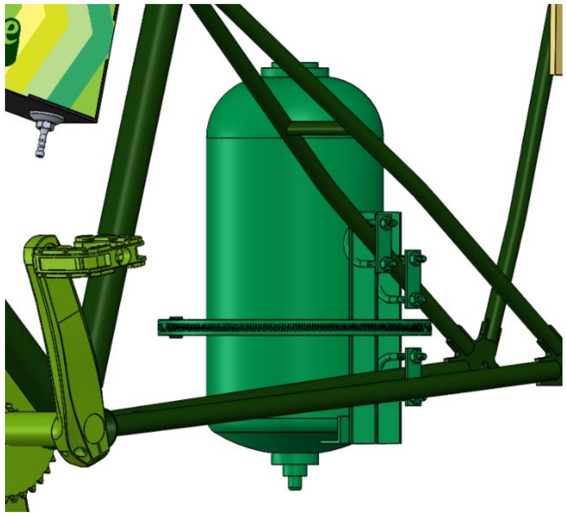


Figure 5.34: **Final Design of Accumulator Mount Assembly with Vehicle Frame**

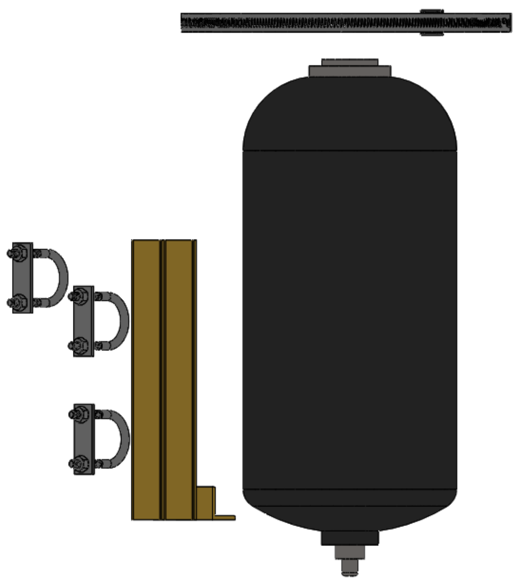


Figure 5.35: **Exploded View of Accumulator Mount Subassembly**

.

5.5.6 WHEEL SELECTION

According to the Simscape models, there was very little to be gained by reducing wheel mass. As such, we have decided to retain the standard 700 x 32c wheels used by The Incompressibles.

5.5.7 TIRE SELECTION

The tires on the previous bike were Schwalbe Marathon Supreme, with a rolling resistance of 19.1 Watts per tire as tested by BicycleRollingResistance.com, a consumer awareness group that tests and validates rolling resistance claims published by tire manufacturers. Using their tables of tire rolling resistances, while keeping the same 700c x 32c wheel size, we chose the Continental GP 5000 tires as they have the lowest rolling resistance in this size. The Continentals have a rolling

resistance of 8.3 Watts per tire as tested. This equates to a ~57% decrease in calculated tire rolling resistance, and according to calculations, should result is a markedly improved Efficiency Challenge score.

5.6 CONTROLS

The rider must be able to operate the controls in a safe manner and be able to switch modes without too much thought. These modes include boost mode, regeneration mode, direct drive, and coast mode. These modes are discussed in detail in Section 4.3.1. For our final design we have made the following component changes: 1) Addition of a new controller unit provided from HydraForce, 2) addition of a new LCD provided from HydraForce, and 3) user switch controls using the Juicebox. We reconstructed the decision matrix from the conceptual design to support the decision to switch to a new controller.

Table 5.11: Controller Decision Matrix

Criteria	**Weight (1-5)**	**Controller**			
		Arduino	Raspberry Pi	STM 32 Nucleo	ECDR-0506A
Simplicity	1	Datum	-1	-1	2
Integration	3		-1	-1	4
Compatibility	2		0	0	4
Support	4		0	0	4
Total			**58**	**-2**	**-2**

Due to the unexpected problems that occurred with the mechatronics, the decision to use a new controller was made. As we can see in the Table 5.11, the ECDR – 0506A proves to be the superior choice when considering integration, compatibility, and support. The team will be working closely with Mark Decklar, our HydraForce Advisor, to configure the controller to operate with the solenoid drivers, valves and pressure transducers on the vehicle.

5.6.1 HARDWARE

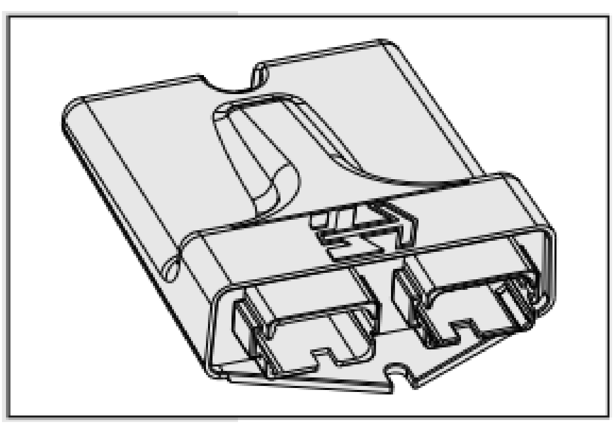


Figure 5.34: ECDR – 0506A Electronic Configurable Valve Driver

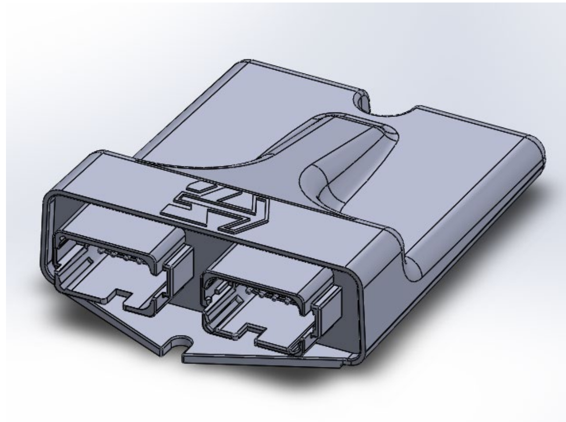


Figure 5.35: ECDR – 0506A CAD Model

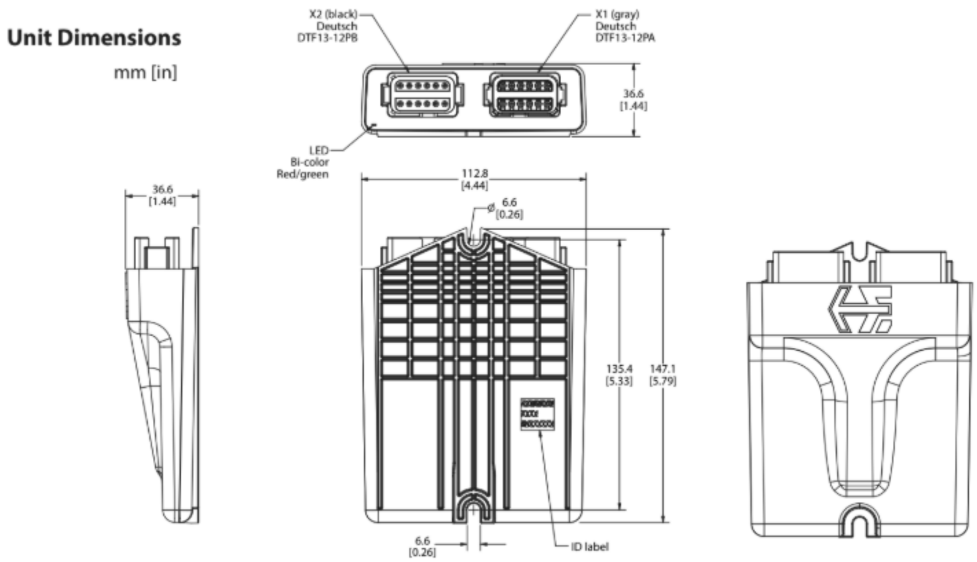


Figure 5.36: Controller Body Engineering Drawing

The ECDR – 0506A Electronic Configurable Valve Driver is a compact and robust multifunction controller with a 32-bit processor with powerful calculating capabilities. Below is a list of the unit's capabilities:

Mechanics and Hardware:

- Robust, light, sealed plastic housing tested in harsh environmental conditions
- Housing shape protects against mechanical wear
- Installed LEDs for quick status check

Versatile Input Capabilities:

- 6 inputs capable of different signal types
- Inputs equipped with overvoltage protection
- User Friendly Software
- Easy to use software for programming
- Internal diagnostics make it possible to detect overvoltage, undervoltage and coil failure in valves and drivers

The valve driver requires a nominal voltage supply of 10V and can operate up to a 24 V supply. It also has the capabilities for four analog inputs that can take input values in measurements of voltage, current, resistance or pull up/down resistance and two digital inputs that operate using pull up/down resistors as switches. The controller also has built in open loop and closed loop control. The closed loop output uses a PID controller to control the response of the current based on coil resistance and inductance. The single open-loop output estimates current regulation or duty-cycle output control. The open loop can be inaccurate because the coils resistance changes with temperature. Overall the ECDR-0506A is great choice with its capabilities and an easy decision to switch over from the previous mechatronics. The technical data sheet is included in Appendix L.

5.6.2 JUICEBOX

Figure 5.37: Juicebox

The Juicebox is a box of switches that distributes power to the solenoids on the manifold. The Juicebox was assembled in house by our team. The team was able to operate the vehicle using the Juicebox after the mechatronic components had been damaged. The rider can control all modes from the juice box on the handlebars based on the position of the switches.

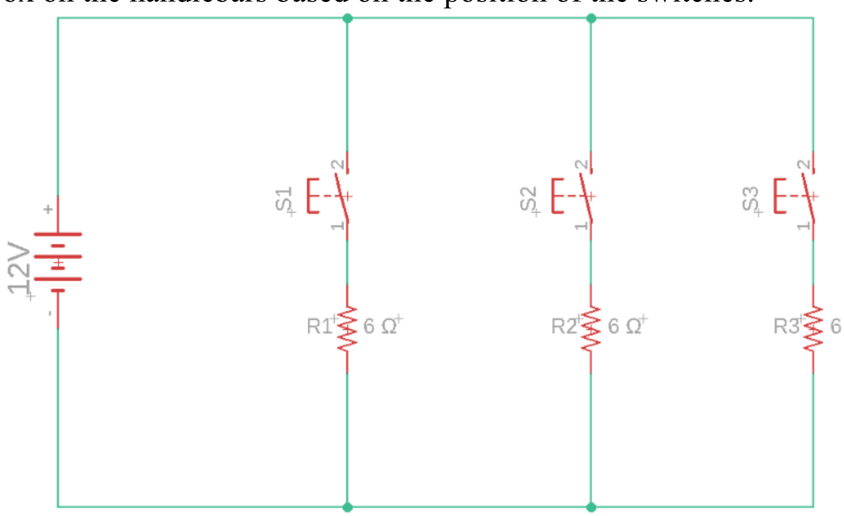


Figure 5.38: Electrical Schematic of the Juicebox

The Solenoid Valves are rated for current levels of 1.3 Amps to 3 Amps. Using Kirchhoff's Voltage Law;

Voltage [V, Volts] = Current [I, Amps] * Resistance [R, Ohms]

we were able to calculate a nominal current that was needed to energize each solenoid valve.

5.6.3 OPUS A3F WACHENDORFF DISPLAY UNITS

Figure 5.39: Opus A3F Wachendorff Display Units

Figure 5.40: Opus A3F Wachendorff Display Unit CAD Model

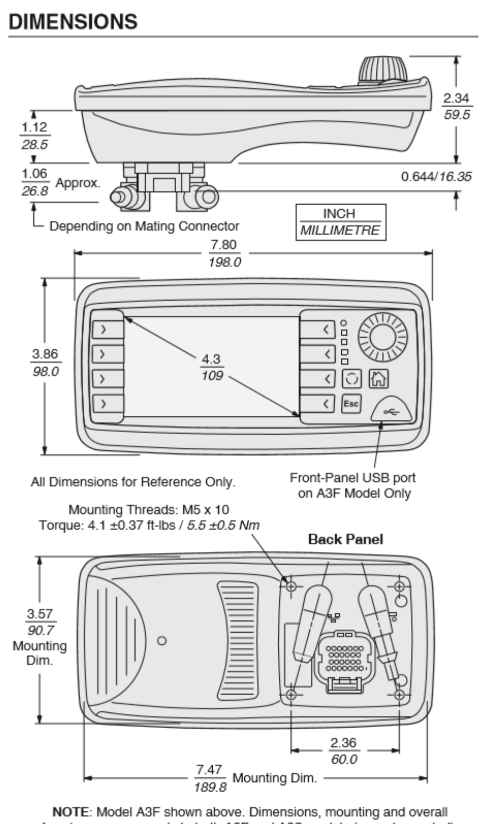


Figure 5.41: Opus A3F Drawing with Labeled Dimensions

The A3F Wachendorff display units are compatible with the ECDR – 0506A Electronic Controller Unit. The display is cost-efficient (especially because Mark Decklar donated it to us) compared to other equivalent units and is rated to operate on heavy duty vehicles and machines that must operate outdoors in harsh conditions. The LCD is equipped with an encoder, 11 keypad inputs, an RS232, and a USB port. The LCD has analog/digital inputs, digital outputs, ethernet and video connections for use with a camera. The screen has high visibility, even in sunny conditions. The operating system uses Embedded Linux and has a downloadable programming tool for windows called Wachendorff Projektor-Tool. The LCD is designed for a 12V to 24V input. This LCD screen is a major upgrade in aesthetics and user control from the previous team's bike.

5.6.4 SOFTWARE- HF IMPULSE

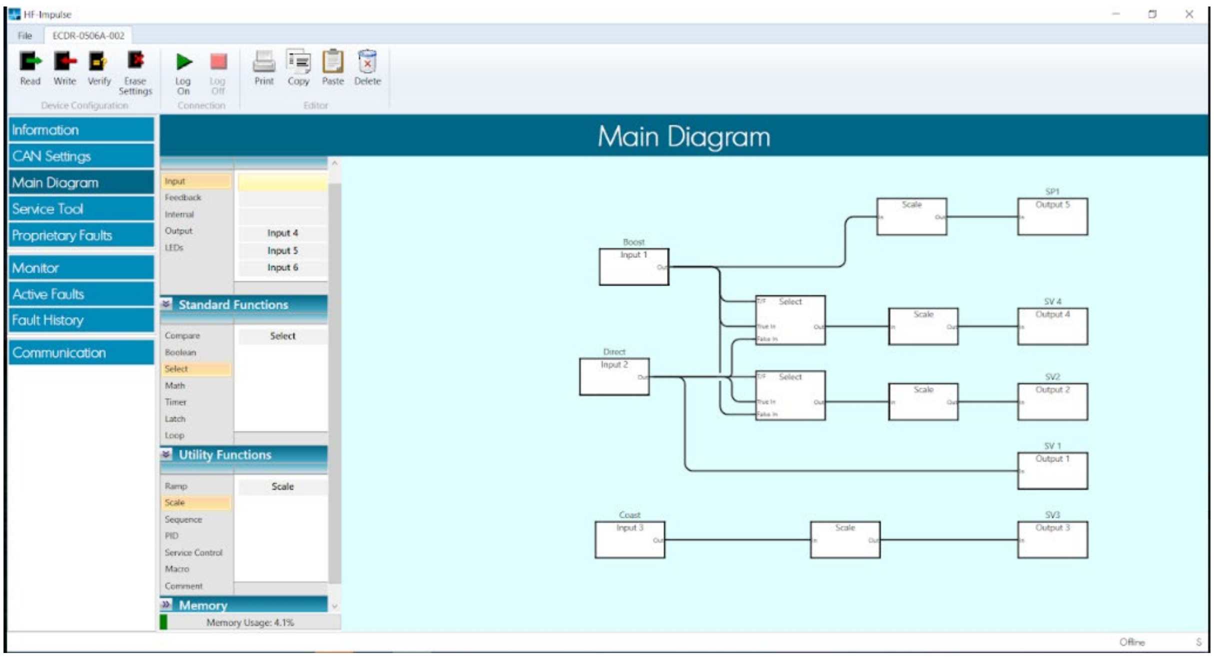


Figure 5.42: HF – Impulse Platform

HF – Impulse is the software used for the ECDR 0506A controller unit. The software was very simple to work with and uses block diagram and true/false logic to program the valves that control fluid flow. In Figure 5.43, there are three inputs and five outputs. The 3 inputs include boost, direct, and coast. A regen input block was not included because in regen mode the fluid flow only travels through a check valve. The coast mode input singly controls the energizing of SV3 (Solenoid Valve 3). SV3 is only activated and controlled by the coast mode and is not affected by any other inputs. The direct drive mode input controls the energization of SV2 (Solenoid Valve 2) and SV4 (Solenoid Valve 4). The boost mode input energizes SV2, SV4, and SP1 (Solenoid Proportional Valve). SV2 and SV4 are both controlled by the Direct input as well as the Boost input. The select block allows the checking for conditions to see which input was activated depending on True/False statements and activates outputs accordingly.

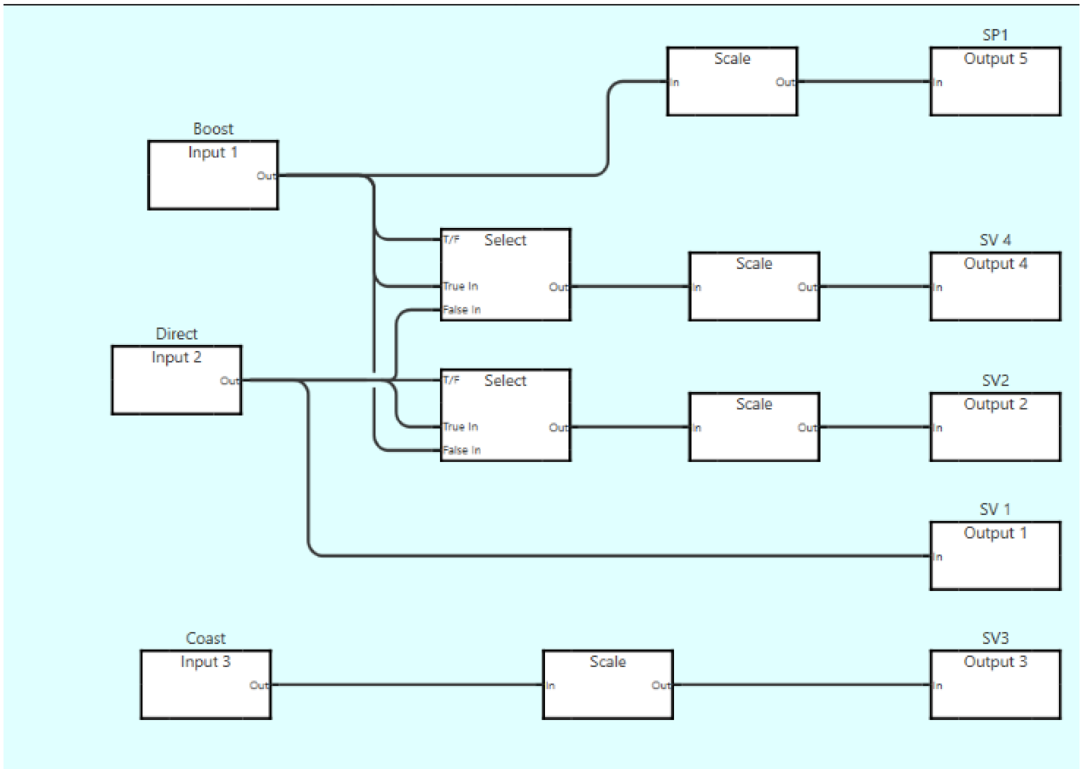


Figure 5.43: Block Diagram Pseudo Code

The above program was a prototype and is finished in part 9 of the report. The team worked with Mark Decklar to edit and debug the program. True/False select boxes needed to be configured to the right input and will be revised. Scaling blocks are used to control the input values. The scale block adjusts the inputs measurement to match the criteria for each valve. A ramping block also was added before the SP1 valve for proportional control.

5.7 POWER TRANSFER

This section discusses the final design decisions for the systems that transfer power from the rider to the hydraulic circuit, and then transfer power from the hydraulic circuit to the rear wheel. In keeping with our theme of optimizing efficiency, extensive modeling was conducted, and each decision was made to the best of our abilities, using engineering rigor and analysis where applicable.

5.7.1 MOTOR

The Simscape models predicted a 2.4 gpm flowrate through the motor during accumulator discharge. Therefore, we kept the Bosch unit for the motor, specifications are provided in Appendix M. We redesigned the motor mounts to account for the change to a smaller chain size.

Update from CDR – Motor Relocation.

After CDR, we found that the manufacturers specify the motor to turn clockwise. Previously, with the motor on the right side of the bike, it was spinning counterclockwise. We believed this was

causing issues with motor blowdown. Thus, we relocated the motor to the left side of the vehicle and manufactured an appropriate mount to interface with the frame (see Chapter 8 on manufacturing).

5.7.2 PUMP

The Simscape models predicted a flowrate range of 0.8 to 0.9 gpm through the pump during while in the direct drive mode. The pump is the same Bosch unit as the motor, so it remains true that we were unable to find a unit with a designed operating flowrate closer to the expected than the Bosch unit. Also, we found that the linear pumps provided by HydraForce had zero life expectancy for a system pressure of 3000psi. No other unit analyzed matched up to the Bosch unit, and as such, this pump was retained and used for this year's competition. This decision simplified the fabrication, as we were able to reuse the pump mounting points.

5.7.3 ACCUMULATORS

The Steelhead one-gallon composite bladder accumulator, used by The Incompressibles and rated for a pressure of 3000psi, was determined to be the best option for the bike. In addition to previously stated benefits, the 2020 competition rules were adjusted to limit the accumulator volume to one gallon. The team investigated bike performance with different accumulator sizes to ensure the one-gallon option would provide the best results through modeling. We found a trade-off in the sizing of the accumulator in terms of vehicle performance in the sprint and efficiency challenges. The efficiency score is inversely proportional to the accumulator volume and may be improved with a smaller accumulator. However, reducing the size of the accumulator significantly increases the predicted sprint time. Specifically, the sprint time increased by 10.14% when switching from a one-gallon accumulator to one-half gallon while the efficiency score was only improved by 8%.

5.7.4 DRIVE TRAIN

Cranks

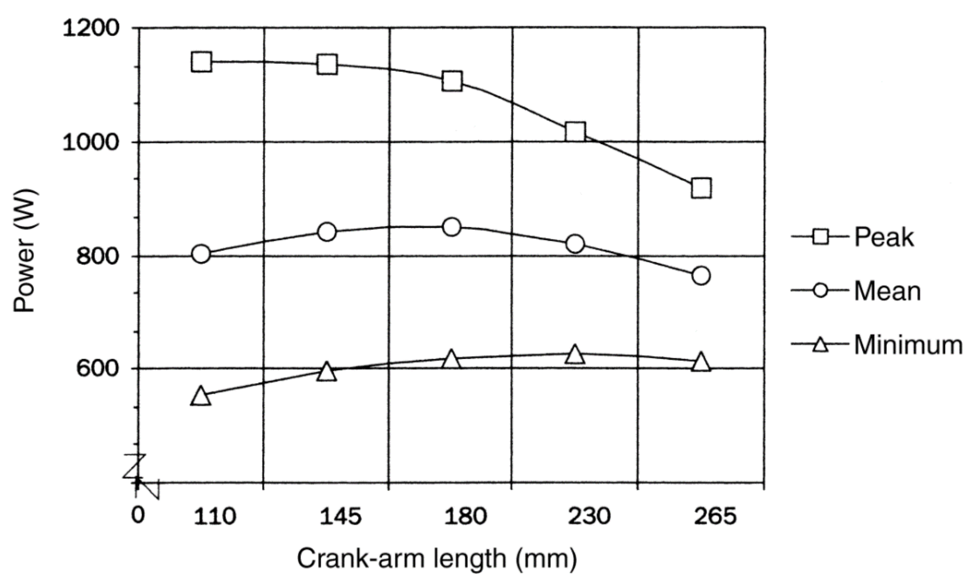


Figure 5.44: Effect of crank length on cyclist power output (From Too and Williams 2000)

Crank length, like most parameters on a bicycle, can only be optimized for a very narrow range of operating conditions. As can be seen in Figure 5.44, a very short crank (110 mm) enables the highest peak output but suffers in a scenario where anything other than peak power is desired. Likewise, a much longer crank (265 mm) is better for a minimum output (just cruising along) but has poor peak output characteristics. For this reason, 180 mm cranks were chosen because they have the best compromise through all ranges of power outputs required.

Pedals

We could find no conclusive engineering evidence of one pedal system being definitively better than any other. As clipless pedals would require each rider to use their own set of cycling shoes, and flat pedals can be difficult to locate the foot in the proper position. Therefore, we decided to use Fyxation pedals which have a strap that goes over the instep of the foot. These allow for an easy transition between riders, and proper positioning of the foot on each pedal.

Rear Drivetrain

The large 40 series chain was removed from the rear drivetrain as it was calculated to be serious overkill. The chain was replaced with an NJS 1/8" bicycle chain. NJS is a certification for Japanese Keirin racing, similar to Velodrome racing. These chains are made for riders that can put much more power into a bike than we can, giving us increase over our already very large factor of safety for this system.

The rear gear ratio presents a compromise between endurance and sprint performance due to their reliability on torque and speed. A larger gear ratio provides a larger torque to increase the initial acceleration as can be witnessed with the larger slope for velocity over time with the 5:1 gear ratio displayed in Figure 5.45. The graph was outputted from the accumulator discharge model with all other input parameters held constant. Furthermore, the bike reaches higher speeds with the higher gear ratio before the accumulator is completely discharged, as indicated with the sudden decline in velocity.

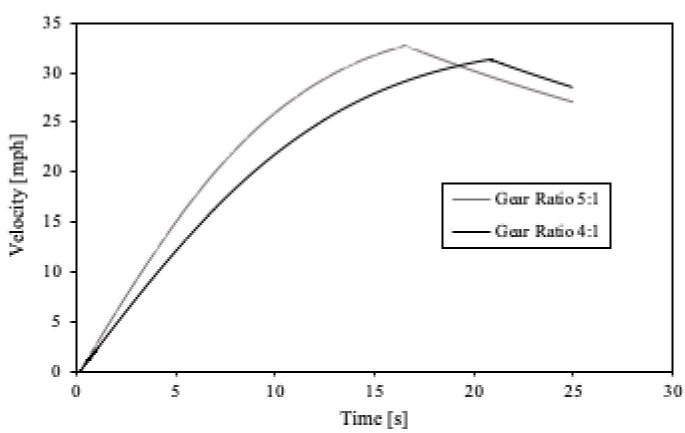


Figure 5.45: Comparison of maximum velocities with respect to rear gear ratios.

These characteristics are especially important in the sprint challenge where very short distances are travelled. The sprint challenge distance was changed in the 2020 competition rules to include a range of possible distances from 400 to 600 ft, with the specific distance undisclosed to the

competition teams. The distances of the bike travelled over a time period of 25 s with different gear ratios are presented in Figure 5.46, the horizontal lines distinguish the proposed race distances.

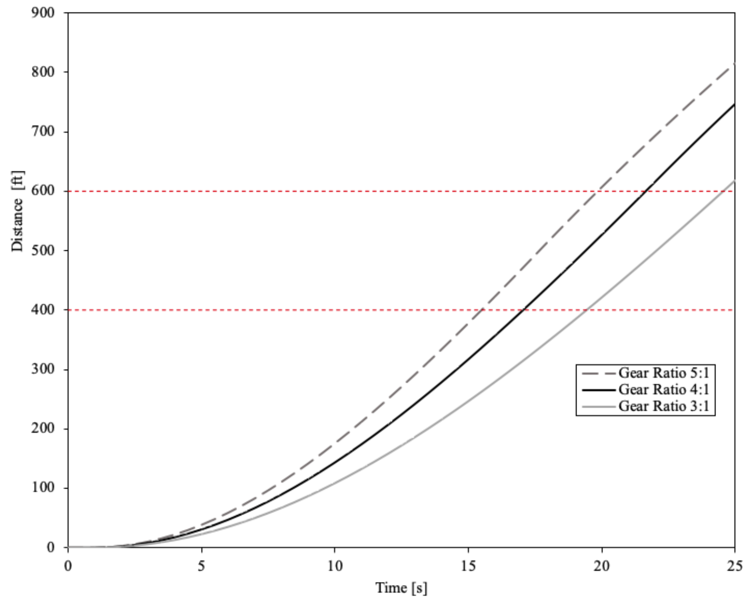


Figure 5.46: Gear ratio effect on distance travelled during accumulator discharge.

Another important aspect to note is the larger change in moving from the 3:1 to 4:1 ratio (12.5% reduction in time) than the 4:1 to 5:1 ratio (8.6% reduction in time). In addition, the change to a 6:1 gear ratio caused an even lesser reduction of 6.1%. The next consideration was the result of increasing torque on the possible speeds, particularly in relation to the predicted endurance time. The different rear gear ratios were modelled with the direct drive model which determined the optimal gear ratio to be 4:1 with a resulting endurance time of 3.895 minutes. It is important to note that the modelling was completed using various configuration considerations for the drivetrains including varying front drive train gear ratios and crank lengths to determine the best possibilities for design decisions. All other input parameters were kept the same to model the current bike and solely investigate the effects of an improved drive train. The use of a 3:1 ratio increases the predicted endurance time to 3.91 minutes, 5:1 predicts 3.92 minutes and 6:1 predicts 3.94 minutes. The further the gear ratio gets from the optimal 4:1, the more compromised the bike performance in the endurance challenge becomes and the more difficult manufacturing becomes. The team investigated driven sprockets to be used with our 13-tooth drive sprocket and were unable to find any which provided a gear ratio larger than 4.6:1. The process of manufacturing a custom sprocket would require a significant amount of time. Pump My Ride decided that the effort would not be worth our time when it could be used in other areas or worth the effect on endurance performance even though we would achieve better sprint times. Therefore, the team moved forward with the compromise of a 4.6:1 gear ratio with large 40 series sprockets to fit the new 1/8" chain. These are typical fixed-gear bicycle sprockets in 13T and 60T for the drive sprocket and driven sprocket, respectively.

To attach the 60T sprocket to the rear hub, an adapter needed to be machined which screws onto the hub and bolts to the sprocket.

Front Drive Train

The same gear ratio that The Incompressibles used, 1 to 10.3, is determined as the best compromise over all areas of operation. Pump My Ride investigated a range of values but did not find the effects on performance to be worthy of the time commitment necessary to implement a new gear ratio. Specifically, the front gear ratio is not a factor considered when predicting sprint time and the endurance times were only varied within one second when ranging gear ratios from 1:6.3 to 2:10. Therefore, the front drive train remained the same.

Gearbox

To keep the same packaging, the Neugart WPLPE 50 right angle gearbox was retained. The weight of the gearbox is well worth it for the 4:1 ratio it provides. Using this gearing on top of the 1:10.3 ratio of the rest of the front drivetrain keeps the pump in a more effective operating range.

Chain Guards

To make the bike safer, we were looking at adding chain covers for both the front and rear drivetrains. For the front drivetrain, a simple bicycle style chain cover, as shown in Figure 5.47 can be adapted to fit the bike. The front chain cover primarily keeps the rider's pants (and other loose clothing) from becoming entangled in the front drivetrain. For the rear drivetrain, a simple cover can be fabricated from sheet metal to keep anything from getting tangled in the rear drivetrain. It should be noted that the event of something being caught in the rear drivetrain is unlikely, but safety features are important design considerations according to the NFPA FPVC judges.

Figure 5.47: Front Chain Cover

Update from CDR – No Chain Guards

Pump My Ride did not acquire a guard for the front and rear drive train because we could not find an attachable guard to the existing sprockets. Therefore, we would have to machine guards from scrap metal. We determined that the time cost was not as important compared to manufacturing the parts that would impact the vehicle performance, such as the motor mount.

5.7.5 BRAKES

For the sake of simplicity, we decided on basic bicycle rim brakes. These brakes are capable of providing sufficient force to lock both wheels. The ability to lock the wheels is significant because this signifies that the maximum amount of usable braking force has been surpassed. Thus, the advantages of a more complicated braking system do not outweigh the drawbacks of its cost and

complexity. The calculations used to back up this decision were discussed in Section 4.4.6, and the hand calculations are shown in Appendix H.

5.7.6 TENSIONING

The tensioning on the front drive train had been a problem with the Incompressible's build. Improving the tensioning benefits the power transfer from sprocket to sprocket and therefore the overall power transfer through the system. There are various ways to improve chain tensioning in the system and we explored the use of a tensioner, adapting a rear derailleur, using a floating tensioner, and improving the chain wrap through analysis.

The chain wrap for the bike was found to be 72 links with a pitch of 3/8 in, chain stay of 6 in, front cog tooth count of 13, and back cog tooth count of 60. This was calculated using the following formula:

$$Chain\ Length = 1 + 0.25 * (F + R) + 2 * \sqrt{C^2 + (0.0796 * [F - R])^2}$$

C = Chain Stay (Sprocket to Sprocket Distance)
R = Number of Teeth on Rear Cog
F = Number of Teeth on Front Cog

Once the chain length was determined the number of links was calculated based on the pitch of the links and rounded down to the largest whole number.

With the correct chain wrap the tensioning in the front drive train should improve significantly with the addition of a tensioner. Our team was not able to implement new designs to the front tensioning due to the conditions at the time.

5.8 OVERALL SYSTEM

The expected system adherence to the engineering specifications based on design decisions through CDR are provided in Table 5.12. The actual results after manufacturing are provided at in Chapter 7.

Table 5.12: Engineering Specifications

Spec. #	Parameter Description	Requirement	Tolerance	Risk	Compliance	Predicted Performance
1	Sprint Time	18s	Max.	H	A, T	18.1 s
2	Endurance Time	4 min 30 s	Max.	M	A, T, I	3 min 37 s
3	Efficiency Score	18%	Min.	M	A, T	-
4	Weight	100 lbs.	Max.	H	A, T	95 lbs.
5	Top Speed	40 mph	Max.	M	A, T	32 mph
6	Braking Torque	FoS= 2 Compared to Motor Torque	Min.	M	A, T	FoS= 2.79
7	Turn Around Time	7 min	Max.	H	A, T	4 min
8	Power Required by Rider	300 W	Max.	H	A, T	300 W
9	Life of the Vehicle	2 years	Min.	M	A, T	-
10	Internal Leakage	2 psi/s	Max.	H	A, I	0 psi/s
11	External Leakage	0 drips	Max.	H	A, I	0 drip

5.8.1 SAFETY, MAINTENANCE, AND REPAIR CONSIDERATIONS

Maintenance

The way the bike was delivered to us, air entrapment was a huge problem with the hydraulic circuit. As the manifold is the highest point in the system, we have specified that our custom-made manifold have bleed points to allow for bleeding air out of the system without cracking fittings open. This would lead to less spilled oil and reduces the chance of a fitting being left loose and causing a disqualification during an event. We planned to take this into consideration when manufacturing hardlines. Finally, the accumulator mounting made it possible for air to get trapped inside with no way to get it back out. We have rectified this by repositioning the accumulator with its entry/exit hose pointing up. With this positioning, if air should enter the accumulator, it will be pushed out with the fluid leaving the next time the accumulator is discharged. It should be noted that this positioning is the opposite of the recommended positioning for a bladder style accumulator. Typically, an accumulator is mounted with its entry/exit hose pointing down such that any particulates or contamination will be pushed out upon discharge, therefore increasing the life of the accumulator by keeping the bladder from being damaged. As this system sees little use compared to an industrial accumulator, we have decided an increased amount of wear is an acceptable price to pay for increased efficiency.

Repair Considerations

Where possible, repair or replacement of parts has been considered so that turn-around times can be reduced, should anything need to be done to the bike at competition. In the mounting of our accumulator, we have used a quick disconnect strap that does not need tools to remove, while keeping the accumulator secure. Likewise, the chain guards have been designed so that they can be easily removed for chain maintenance or if the motor should need to be removed for any reason.

5.8.2 COST ANALYSIS

Table 5.13: Cost Analysis Per Subsystem

Sub System	Cost
Hydraulics	$499 ($399 sponsored)
Mechatronics	$ 353 ($303 sponsored)
Frame	$266.49
Front Drive Train	$106.03
Rear Drive train	$220.27
Total	$1,444.7 ($702 sponsored)

The cost breakdown for the major subsystems of the vehicle is listed in Table 5.13. As the table shows, most of the hydraulics and mechatronics is sponsored ($702). This amount accounts for half of our total costs. Our team is given a $1500 and $4000 stipend to fund project components. As we can see we are well below this stipend and we can afford the projected costs. Dr. Widmann asked that the team leaves at least $2000 in the account for the following team and our cost analysis at the time of CDR showed this was likely. The detailed budget can be found in the Appendix N.

6 MANUFACTURING

The manufacturing section outlines the steps followed to manufacture and assemble the final product. All manufacturing took place in the Cal Poly Machine Shops, the Hanger and Mustang 60, by our team, unless otherwise noted.

6.1 PROCUREMENT

The procured parts and components are detailed within this section. Additional information and links are provided in Appendix N.

Handlebars

The Bontrager Race Lite Aero clip-on bars were ordered online from Trek Bikes via www.trekbikes.com and shipped to Foothill Cyclery in San Luis Obispo.

Accumulator Mount

The accumulator mount material consisted of 1”x1” angle iron, a large hose clamp, and three U-bolts. The angle iron was purchased from a hardware store, while the U-bolts and hose clamp were obtained from McMaster.

Valves

All valves were ordered from HydraForce with advising from Mark Decklar before the end of Fall quarter. All valves were graciously donated by Mark Decklar.

Hard Lines

Hard line fittings were ordered from McMaster, but as the manifold was delayed, we did not have time to implement them.

Mechatronics

The controller unit, ECDR – 0506A, was received from HydraForce and was installed onto the vehicle.

Pneumatics

Pneumatics were always considered a “reach” goal, and as other projects were deemed more important, no serious consideration was given to them.

Twist throttle

The twist throttle was found to be too difficult to integrate and was abandoned.

Manifold

The manifold was provided by HydraForce, with advising from Mark Decklar. The Manifold arrived during week seven of the 2020 Winter Quarter. This arrival was much later than expected

which caused construction milestones to be pushed to later dates. The team adapted by abandoning hard lines to complete the bike manufacturing with time for sufficient testing.

Stock and Hardware

Any additional stock or hardware was ordered from McMaster-Carr, such as the U-bolts used to build the HydraForce controller mount, as well as the accumulator mount.

6.2 MANUFACTURING

Mechatronics

The main construction project for the mechatronics aspect of the project was the mounting of the ECDR. This was prototyped by printing a DXF of the CAD part. The paper prototype was used to determine proper integration into the bike. One iteration of this process is shown in Figure 6.1.

Figure 6.1. Rapid prototyping of one of the ECDR mount brackets.

Once we were happy with the design of the bracket, the prototype was replicated in 16-gauge mild steel plate using a band saw to cut the stock to shape and a press brake to bend up tabs. The turned-up edges help to locate the ECDR on the frame. The completed mounts can be found in Figure 6.2.

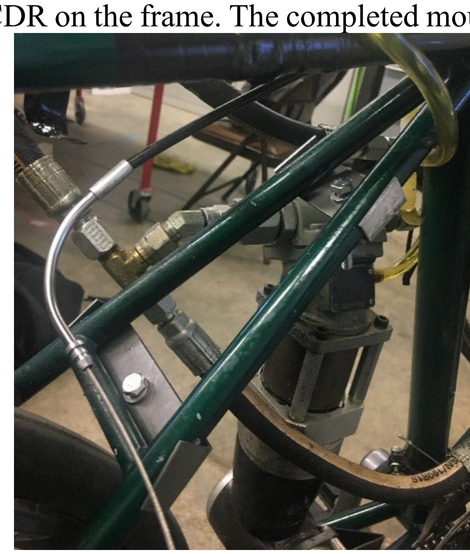


Figure 6.2: Front and Rear ECDR Mounting Clamps (ECDR not shown)

Controller – HF Impulse

The controller is programmed using HF Impulse for the ECDR controller unit provided by Hydra Force. The controller uses 4 inputs to control the different modes of drive which include Ludacris Mode (Formally boost mode), Direct Drve Mode, Coast Mode, and Regeneration Mode. Each input is controlled using a push button that is connected to the handle bars of the bike. Figures 6.3 and 6.4 display the block diagram code used to control the bike.

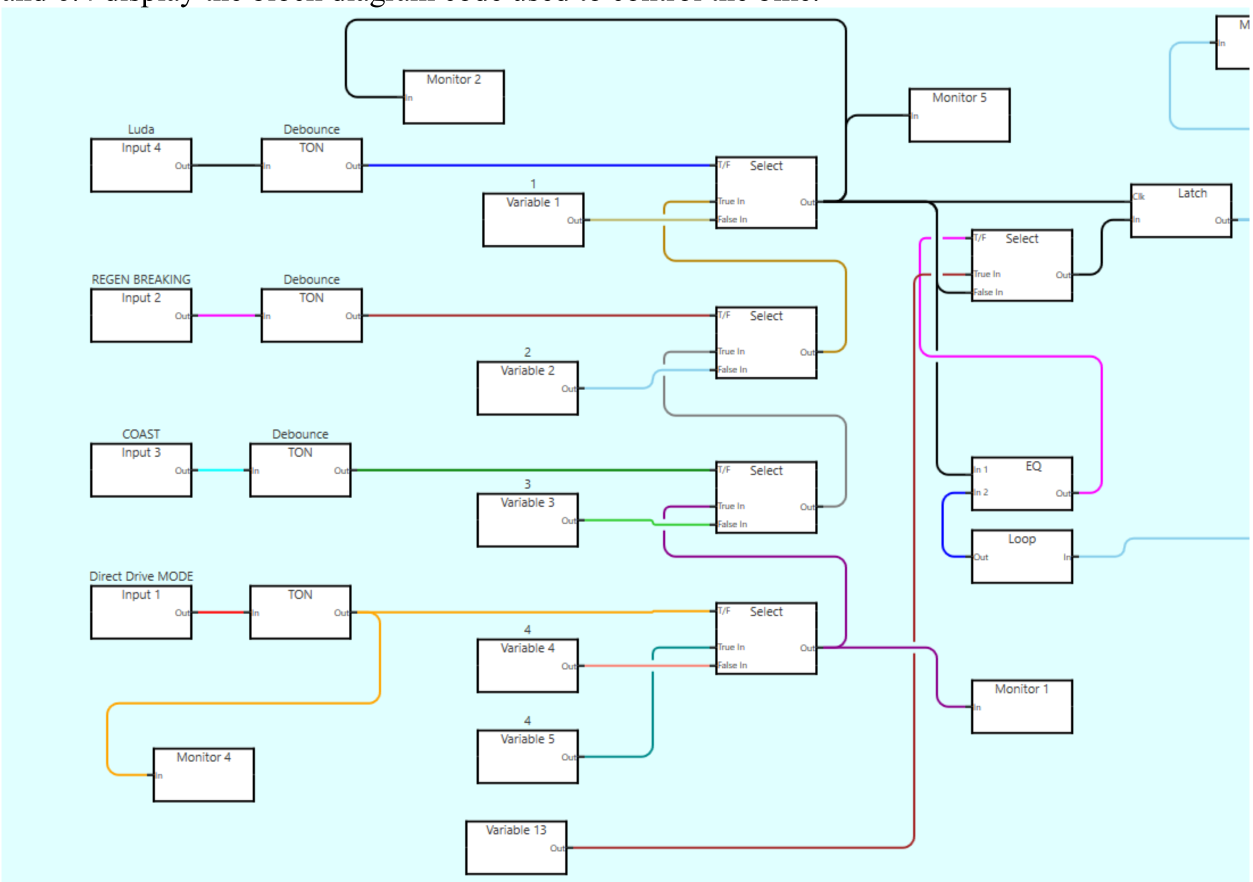


Figure 6.3: Input Side of HF Impulse Coding Scheme

Each input is connected to a debounce block that allows a short delay timer that prevents buttons from accidently activating when not pressed. When a button is pressed, the signal is grounded and proceeds to the select block. The select blocks execute commands based on the input signal received. When true, the select block will send a variable number for true or false. These variables will dictate which mode is activated. Each input block is activated when false because the signals are naturally energized and are pulled down to ground to activate a signal. When a signal is received and processed by the code for each mode, the signal moves to the latch section of the code. This latch section allows the buttons to act as on/off switches. For example, if the regen breaking mode was pressed, the regen mode will turn on. Then if the regen mode is pressed again the combination of equate, loop and select block will turn off the regen mode and put the bike back into direct drive mode. Direct drive mode is the default state.

Note: Monitor blocks are used to watch the signal of the controller when testing.

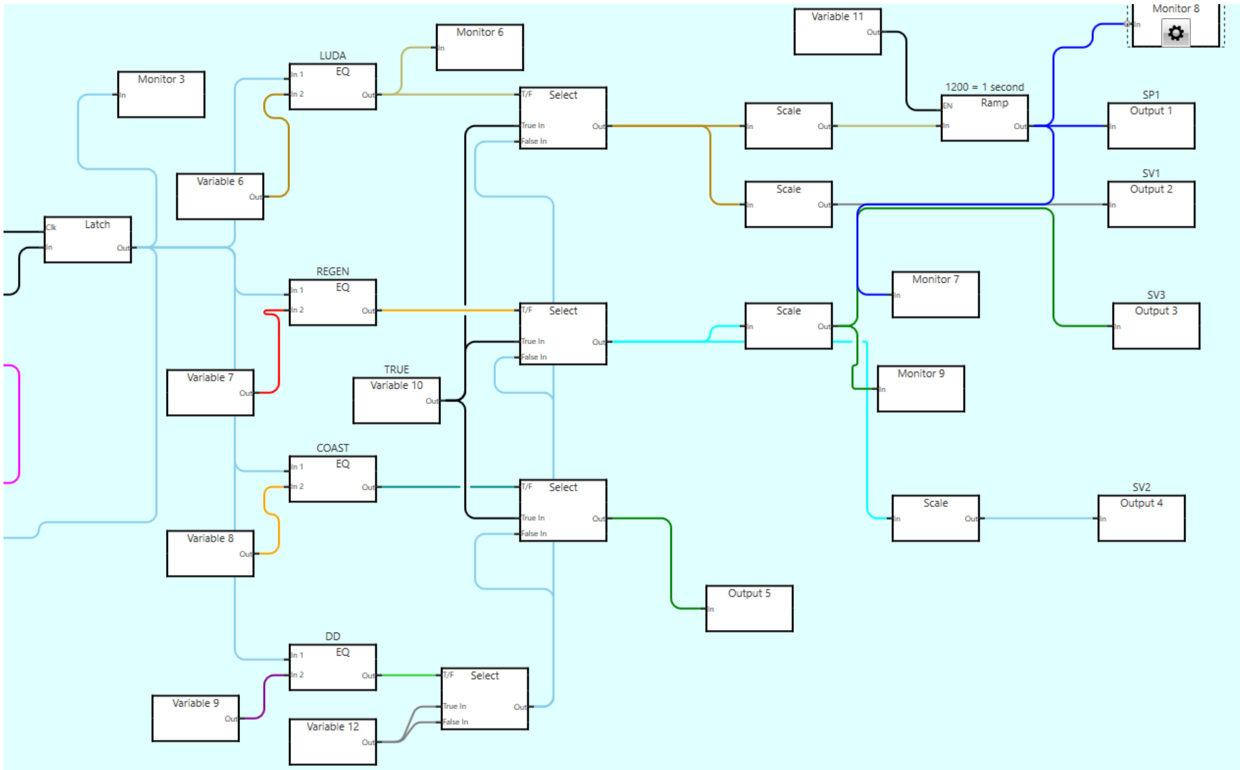


Figure 6.4: Output Side of HF Impulse Block Diagram Coding Scheme

After a variable input is received from the input side of the code. The output processes this information to activate certain outputs. The output from the latch will be compared to a number, using an equate block, to dictate which mode is activated. 4 is used for Ludacris mode, 3 is used for regen mode, 2 is used for coast mode, and 1 is used for direct drive mode. After each equate block, each mode transitions to a select block to transmit a signal to the outputs based on whether the signal is true/high or false/low. This is opposite from the input blocks. For the regen mode and Ludacris mode if the output reads true a scale block is used to activate the signal. An example of the scale block settings are presented in Figure 6.5.

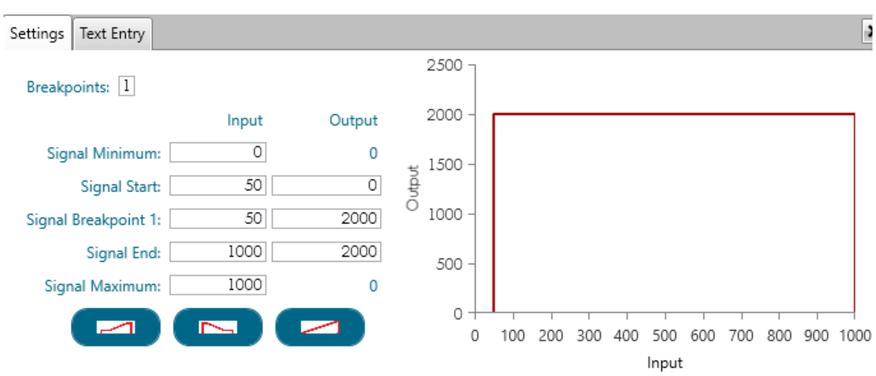


Figure 6.5: Scale Block Settings for HF Impulse Code

The scale block takes the input of 1 and ramps the signal up to the max output voltage for the solenoid devices. A slight delay is also used to match the activation of the solenoid specifications.

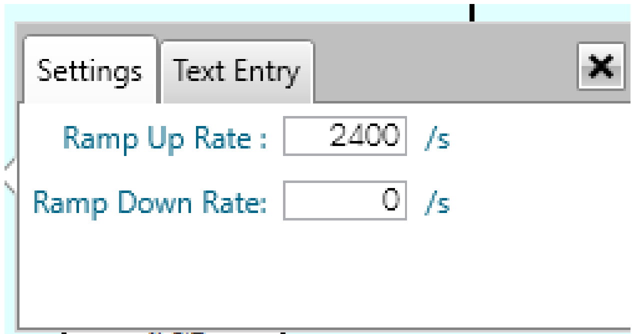


Figure 6.6: Ramp Block Settings for HF Impulse Code

To prevent potential motor problems, a ramp block is used to incline the released pressure from the accumulator storage. This block is set for a 2 second ramp up upon boosting the bike, where 1200 is equivalent to 1 second, as shown in Figure 6.6. There is also a variable block connected to the ramp block which is always true.

Ludacris mode uses 2 outputs, regen mode uses 2 outputs, coast mode uses one output, and direct drive mode de-energizes all the modes to its default position. Also coast mode was not used for the programming of the device and is just connected to a random output for future uses.

Hard Lines

Because the manifold was delayed, we were forced to abandon hard lines as there simply was not time to complete them. Components were ordered so that hard lines can be completed by next year's team, if they should choose to do so.

Accumulator Mount

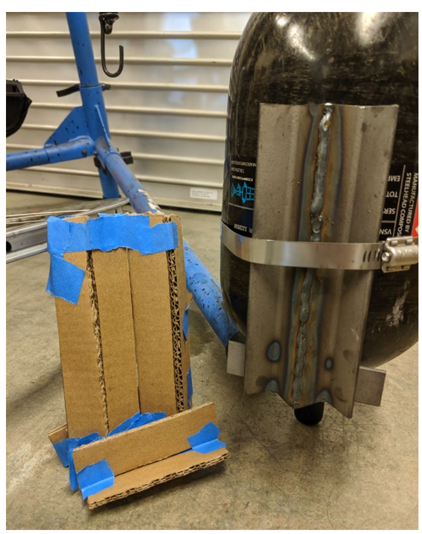


Figure 6.7: Accumulator Mounting Bracket

The design of the accumulator mount was changed during initial construction to reduce weight, complexity, and manufacturing time. The new design along with the cardboard prototype is show in Figure 6.7. The accumulator mount was constructed of 1”x1” angle iron. Three straight pieces were welded together to provide a cradle to hold the accumulator in place. Initially, this mount was meant to be welded to the frame, but the mounting system was changed to U-bolts to allow for more flexibility in the future. U-bolts were welded to the mount, and slot around the chainstay and seatstay to hold the accumulator vertically on the right side of the frame.

Accumulator Rebuild

During the construction frame, it was noticed that the system was equalizing to accumulator pre-charge pressure, even after being discharged. The only possible explanation for this was that the bladder inside the accumulator was punctured and allowing the nitrogen pre-charge to leak into the system. Because of this we were forced to rebuild the accumulator with a rebuild kit ordered from Steelhead Composites. As shown in Figure 6.8 the greatest difficulty was holding onto the cylindrical accumulator. This was accomplished by ratchet strapping the accumulator to a table while the end cap was removed (with a comically large crescent wrench). The team decided that it was best to limit pre-charge pressure to a maximum of 500psi moving forward to prevent the damage from reoccurring prior to or during competition.

Figure 6.8: Removing the endcap of the accumulator.

Rear Hub

The old rear wheel had its sprocket welded on, which did not allow for changing final drive ratios, and was also identified as a good place to reduce mass. We tried to salvage the rear wheel hoop and just replace the hub, but the welded in sprocket did not allow for the removal of spokes. Rather

than cut the spokes and remove the hub, we opted to take the opportunity to replace the steel wheel with an aluminum deep-vee wheel and further reduce weight. By using a front disk brake hub for the rear wheel, we were provided with a convenient flange for mounting the driven sprocket. The driven sprocket that provided the optimal final drive ratio was meant to be a front chainring for a track bike, and as such, an adapter plate had to be constructed. The adapter plate was made of ¼" plate steel and cut out on a water-jet cutter as seen in Figure 6.9. The completed adapter is shown in Figure 6.10.

Figure 6.9: Cutting out the rear sprocket adapter on the Mustang 60 water-jet machine.

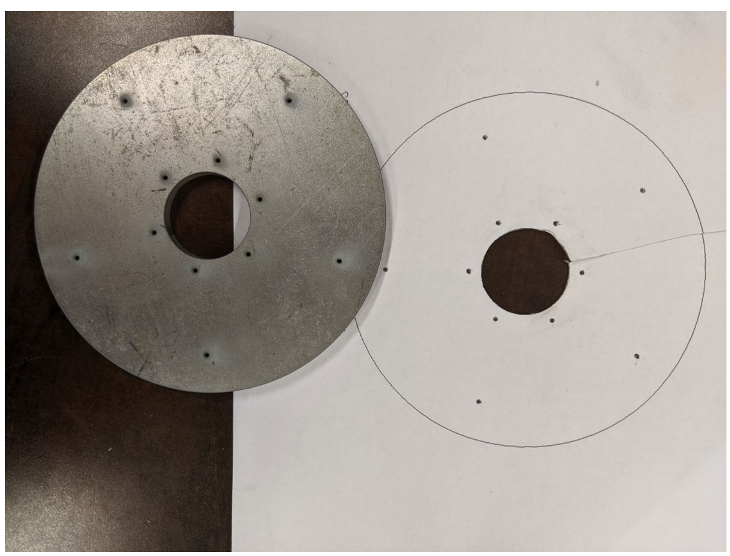


Figure 6.10: Completed Adapter Plate

The adapter plate bolts to the rear hub, and the driven sprocket then bolts to the adapter plate; the assembly is shown in Figure 6.11. Once the driven sprocket was mounted to the wheel, the 1/8" NJS bicycle chain could be cut to length, such that it could be tensioned. We initially had some concerns about sizing the chain down so drastically, but the reasoning is as follows. A 200 lb.

cyclist is able to put more than 116 ft-lbf on a 180 mm crank of a bicycle, which is much more than the calculated 12 ft-lbf that our Bosch bent-axis motor puts out in the sprint challenge.

Figure 6.11: Assembled Rear Hub

The choice of using a front disk brake hub on the rear of the bike was complicated by the frame hub spacing. The frame was designed around a 119 mm hub, which is a difficult size to find for a rear hub, and from our research, does not exist for a front disk brake hub. Because of this, a 100 mm front disk brake hub was used, and aluminum spacers were machined to take up the extra space. This hub spacing is used on motorcycles, and we could find no safety issue in spacer use here. The rear hub was also changed to a quick disconnect style to ease maintenance, but this required a new mounting skewer. The sourced skewer arrived at the wrong length, but a third spacer was machined to take up the extra length. The skewer with all three spacers is shown in Figure 6.12.

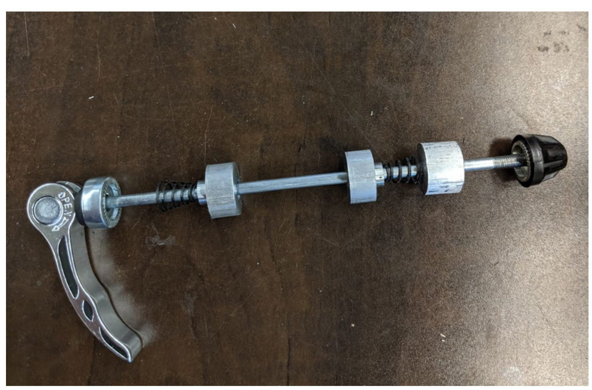


Figure 6.12: Rear Hub Mounting Skewer with Three Hub Spacers

Motor Mount

The motor mount needed to be relocated for two main reasons. First, the new driven sprocket is so large that the drive and driven sprocket would interfere. Second, The Incompressibles had mounted the motor on the right side of the bike, requiring the motor to spin counter-clockwise. The Bosch

unit that we are using is only meant to spin clockwise, and this may be the source of some of the problems we had encountered with the motor thus far (blowdown, problems self-bleeding, efficiency issues).

The motor mount was constructed of 16-gauge mild steel plate that was cut out on a water jet, and then welded to increase strength. The original plan, as shown in Figure 6.13 was to weld the motor mount directly into the frame, but this plan was abandoned when we realized how out of square the frame is, which left us with no good reference to align things to. We were initially concerned with using a bolted in mount because we felt that a welded in mount would prove stronger, but an FEA analysis on the bolted in mount showed a factor of safety of 3.5. The main added benefit of a bolted in mount provides for minor adjustments so that the drive sprocket can be properly aligned with the driven sprocket on the wheel.

Figure 6.13: Original Plan for the Motor Mount Tack Welded in Place

An extra crossbar was added to the frame to allow the new motor mount to be positioned farther to the rear of the bike to increase side to side adjustment of the motor. This would give us the most flexibility in mounting both the motor and the driven sprocket on the wheel. The new crossbar can be seen in Figure 6.14 and the new motor mount can be seen in Figure 6.15.

Figure 6.14: New Crossbar for Motor Mount

Figure 6.15: Final Motor Mount

The final issue in construction of the motor mount was interference between the end of the motor shaft and the tire. Because the frame is not square, the rear tire did not sit vertical in the frame and did not allow the rear tire to turn. To remedy this, we were forced to clearance the left side vertical dropout, bringing the left-hand side of the rear axle up and allowing the rear wheel to sit vertically

in the frame. The minimum safe frame clearance on a bicycle is stated by Cervelo as 4mm, and we now have a minimum clearance of 3/16”, or about 4.7 mm [7].

As for manufacturing on the motor to accommodate the new chain, a new drive sprocket was purchased in the proper width, but the shaft hole on the sprocket had to be resized to fit the existing motor shaft. This proved very difficult, but doable, as the sprocket was hardened throughout, and tooling for performing an interrupted cut (the sprocket came with a keyway in the shaft hole) on hardened steel was limited. A simple machined aluminum spacer had to be constructed to set the side to side position of the drive sprocket. Finally, the motor shaft key was resized to fit the keyway in the sprocket. The new assembled motor with spacer and sprocket can be seen in Figure 6.16.

Figure 6.16: Motor Assembly with Sprocket and Sprocket Spacer

6.3 OUTSOURCES

Manifold

Figure 6.17: Hydra Force Finished Manifold

The manifold made by HydraForce and sponsored by Mark Decklar is shown in Figure 6.17. The product was designed and procured in house by HydraForce. The lead time to make the part was supposed to be 8-9 weeks but ended up taking 15 weeks. The ports were easy to connect to and were designed based on last year's model. Once installed onto the bike, the process to connect the controller unit was simple as the solenoids were easy to access and attach to.

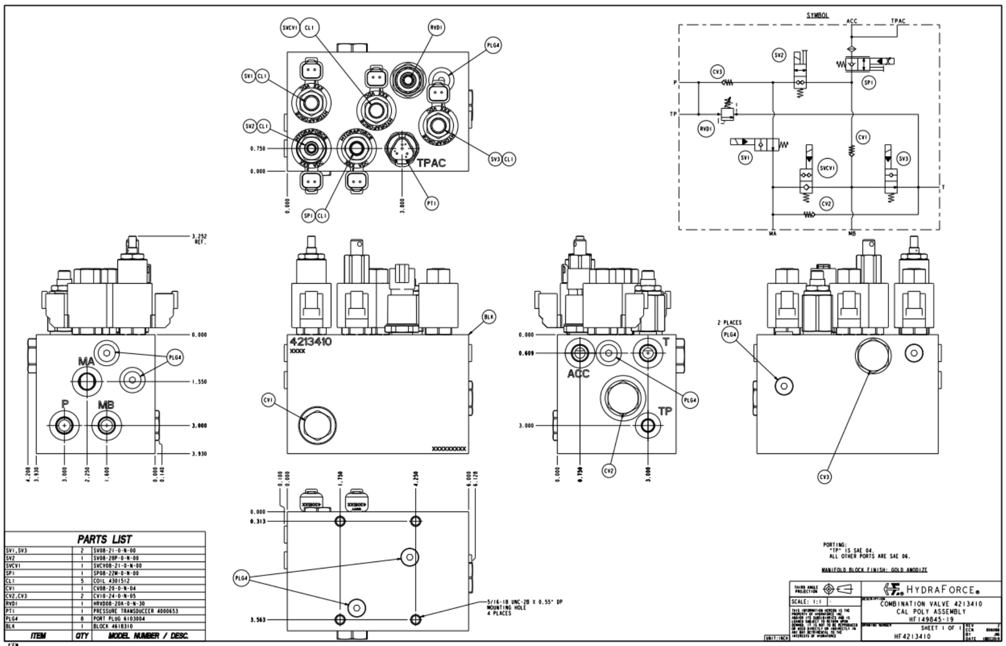


Figure 6.18: Modified/Final Manifold Schematic

Some modifications were made to the drawing before assembling the manifold, the final schematic is presented in Figure 6.18. An SCVC08 valve was added for the coast mode to allow the bike to coast when power from the rider is not present. This adjustment added changes to the software in which regen mode needs to energize two solenoids instead of one. This change eliminated a coast mode and the coast mode input was excluded from the program. This means three modes are used which improves the overall efficiency of the vehicle by improving the interface of the bike.

7 DESIGN VERIFICATION

Pump My Ride's design verification chapter describes the tests, their methods, materials, and facilities needed to qualify the final design according to our engineering specifications. The objective of the design verification is to evaluate the performance of the vehicle and system for the NFPA competition with only three team members.

7.1 PRE-CHARGE DETERMINATION

Based on the Incompressibles' results, Pump My Ride believed it was necessary to investigate the impact of accumulator pre-charge on the vehicle performance in three challenge categories: sprint, efficiency, and endurance. Therefore, we performed tests concurrent with the NFPA rules while varying the accumulator pre-charge pressure. The team limited the maximum pre-charge pressure to prevent damage to the accumulator bladder prior to or during competition. The accumulator charge is not meant to be discharged to a value lower than the pre-charge pressure, although this

is a requirement during the efficiency challenge. Thus, the team reasoned that damage is less likely to occur with limited maximum pre-charge.

Test Location

During baseline tests, Pump My Ride conducted tests at Mt. Bishop Road on Cal Poly's campus. However, our team determined that light traffic on this road interrupted tests and risked our team's safety. Therefore, we changed the testing location to Sports Complex Road next to Cal Poly's IM Sports Complex (see Figure 7.1). Riding from north to south, there is a positive grade which is considered during the discussion of our results.

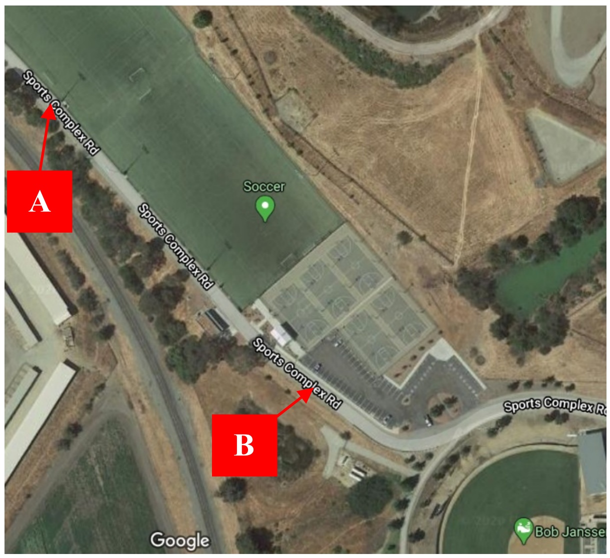


Figure 7.1: Satellite Image of Testing Location (Cal Poly IM Sports Complex)

Test Equipment

The required equipment for testing is listed:

- Fluid Powered Vehicle
- Cones (2)
- Stopwatch (2)
- Pen and paper

Test Method

The pre-charge determination tests were conducted on March 5 and 6, 2020. Prior to arriving at the test location, the accumulator pre-charge was pressurized to 500 psi. Then, at Sports Complex Road, we measured 600 ft and marked the distance with cones. For reference, these distances are marked as "A" and "B" on Figure 7.1. We performed six circuits for six pre-charge pressures between 500 psi and 125 psi. A single circuit involved measuring sprint time, distance for efficiency, and endurance time. The first circuit is explained in detail in the following paragraphs.

Starting at cone A, we used the vehicle regenerative mode to fill the accumulator with fluid until the pressure gage measured a charge of 3000 psi. Then, we recorded the pre-charge and charge. Next, the rider mounted the vehicle and aligned the front wheel with the cone. Initiating the vehicle boost mode, the rider moved along a straight path to cone B. Meanwhile, time was measured from the moment the vehicle boosted to the moment it crossed cone B. The time was recorded as the sprint time.

The rider continued travelling past cone B along Sports Complex Road until the vehicle rolled to a stop. Then, the rider returned to B from the stop point while counting the number of revolutions of the vehicle's front wheel. The number of revolutions was recorded under the efficiency distance.

In the last segment of the circuit, the rider mounted the vehicle at B. Using the vehicle direct drive mode, the rider pedaled quickly from B to A. We measured the time it took for the rider to pedal from B to A. This time was recorded as the endurance time. Finally, we discharged the pre-charge by 100 psi and restarted the circuit.

Results

The measured values are tabulated according to sprint time, efficiency, and endurance time for various pre-charge pressure. Table 7.1 displays the sprint time results of the pre-charge determination test. Similarly, Table 7.2 and 7.3 display the results of the efficiency and endurance time, respectively.

Table 7.1: Sprint Time Results for Pre-charge Determination

Friday, March 6, 2020						
Course Distance: 600 ft.						
No.	**Pre-charge [psi]**	**Charge [psi]**	**Rider**	**Time 1 [s]**	**Time 2 [s]**	**Average [s]**
1	500	2840	Jacob	25.00	25.33	25.17
2	400	2800	Jacob	24.00	24.57	24.29
3	300	2800	Jacob	25.00	25.73	25.37
4	200	2825	Jacob	28.00	27.83	27.92
5	200	2800	Kayla	25.88	25.70	25.79
6*	125	2900	Jacob	31.95	N/A	N/A
				Standard Deviation		2.14
*Thursday, March 5, 2020.						

According to Table 7.1, we observe the trend that sprint time decreases as the pre-charge pressure decreases—with an exception at test number 5 where we switch riders. We know that system pressure includes pre-charge pressure and accumulator charge pressure; therefore, our tests show that the highest system pressure translates to the greatest motor speed; thus, the fastest sprint time. The standard deviation of 2.14 seconds show there is significant difference in time for lowering pre-charge pressure. Additionally, switching riders confirmed that a rider weighing less will

improve the sprint time. In conclusion, we determined it was necessary to set the pre-charge to 500 psi for the sprint challenge and ride using the lightest team member.

Table 7.2: Efficiency Test Results for Pre-charge Determination

Friday, March 6, 2020						
No.	**Pre-charge [psi]**	**Charge [psi]**	**Rider**	**Revolutions**	**Total Distance [ft]**	**Efficiency [%]**
1	500	2840	Jacob	81.50	1192	8.12
2	400	2800	Jacob	102.50	1345	9.35
3	300	2800	Jacob	91.00	1261	8.99
4	200	2825	Jacob	76.00	1152	8.46
5	200	2800	Kayla	87.00	1232	7.36
6*	125	2900	Jacob	38.25	878	6.63
*Thursday, March 5, 2020.						

Table 7.3: Endurance Test Results for Pre-charge Determination

Friday, March 6, 2020					
Distance: 600 ft.					
No.	**Pre-charge [psi]**	**Rider**	**Time 1 [s]**	**Time 2 [s]**	**Average [s]**
1	500	Jacob	39.00	39.50	39.25
2	400	Jacob	34.26	35.45	34.86
3	300	Jacob	33.19	33.91	33.55
4	200	Jacob	31.07	34.00	32.54
5	200	Jacob	32.53	33.61	33.07
6*	125	Jacob	38.75	N/A	N/A
			Standard Deviation (#2-5)		1.21
*Thursday, March 5, 2020.					

Table 7.2 displays the predicted efficiency based on pre-charge pressure. According to the table, there is no obvious trend that pre-charge directly correlates to efficiency score. This makes sense because the efficiency formula factors system pressure, weight, distance travelled, and accumulator volume on individual scales. Looking at Table 7.2, we observe that the highest efficiency is connected to the greatest total distance. We know the efficiency challenge utilizes the vehicle "boost" and "coast" mode. Therefore, Pump My Ride believed we would score the greatest efficiency if we boosted the vehicle from the highest system pressure (highest pre-charge) and engaged the coast mode periodically to save energy and travel the farthest possible.

According to Table 7.3, tests 2-5, we observe the endurance time for 600 ft hovers around 33 and 34 seconds. We believe tests 1 and 6 are outliers because they were the first tests of the day and the rider was being cautious. The standard deviation of 1.21 seconds shows that the difference in

time is most likely human factors instead of system-related factors. In conclusion, pre-charge is unrelated to the endurance time.

The most significant discoveries from the pre-charge determination test results are summarized: (1) the fastest sprint time requires the highest pre-charge pressure, (2) the highest pre-charge pressure increases distance travelled and improves efficiency, and (3) there is no correlation between pre-charge pressure and endurance time. Ultimately, Pump My Ride determined a pre-charge of 500 psi should be used to obtain the best scores in sprint time and efficiency.

7.2 SPRINT TIME VERIFICATION

The engineering specification for Pump My Ride's sprint time is 18 seconds for a 600 ft track. This specification was written with the goal to place first in the sprint race during competition. The sprint time depends on weight, aerodynamic drag, and total energy available from the accumulator. Therefore, our testing plan for sprint time verification aimed to minimize weight, reduce drag, and increase vehicle system pressure.

Test Location

Pump My Ride conducted testing on Sports Complex Road, shown in Figure 7.1.

Test Equipment

The required equipment for testing is listed:

- Fluid Powered Vehicle
- Cones (2)
- Stopwatch (2)
- Pen and paper

Test Method

Final sprint time verification was conducted on Friday, March 13, 2020. Based on the pre-charge determination tests, we set the pre-charge to 500 psi. We measured 600 ft along Sports Complex Road and marked the distance with cones. Then, we used the vehicle regenerative mode, and charged the accumulator to 3000 psi. Pump My Ride selected Kayla as the rider to minimize weight. At cone marker A, Kayla mounted the vehicle with the front wheel aligned with the cone. Jacob, standing approximately halfway between the two cones, signaled Kayla to switch the vehicle to its "boost" mode. At this moment, Jacob and Bryson began recording time with their stopwatches. When the vehicle reached a comfortable speed, Kayla translated her position from "upright" to "tuck" with use of the tri bars. Bryson, standing at the 600 ft marker, signaled when Kayla met the cone. At this moment, Jacob and Bryson stopped time. Their measured values, including pre-charge pressure, charge pressure, and time are recorded.

Results

Table 7.4: Final Sprint Time Results

March 13, 2020			
Distance: 600 ft.			
Pre-charge [psi]	**Charge [psi]**	**Time 1 [s]**	**Time 2 [s]**
500	3000	21.95	21.96

Comparing the results to our engineering specification of 18s, we are approximately 3.95s over time. These results do not meet the engineering specification; however, more testing and practice could reduce the difference. Unfortunately, rapidly evolving circumstances with COVID-19 prohibited Pump My Ride from reconvening and conducting more tests.

Looking forward, this is the fastest recorded sprint time over a distance of 600 ft. Initially, the specifications were written to achieve a 20% improvement from the Incompressibles' vehicle performance during the spring 2019 fluid powered vehicle challenge. Instead, Pump My Ride proved a 5% improvement.

7.3 ENDURANCE TIME VERIFICATION

The engineering specification for Pump My Ride's endurance time is 4 minutes and 30 seconds. This specification was written according to the NFPA rules for the endurance challenge.

Test Location

Pump My Ride needed a large, empty, flat plot to ride the vehicle 1 mile. The H-1 parking lot, used in the baseline tests, was problematic due to vehicle traffic. For safety and convenience, Pump My Ride used the perimeter of the outdoor basketball courts next to Sports Complex Road (see Figure 7.2). We measured that 9.75 laps approximated to 1 mile which satisfies the course distance for the competition challenge.

Figure 7.2: Endurance Time Testing Location for Design Verification

Test Equipment

The required equipment for testing is listed:

- Fluid Powered Vehicle
- Stopwatch
- Pen and paper

Test Method

The endurance testing method is similar to the 2020 NFPA rules for the endurance challenge. Pump My Ride conducted a single test with two riders, Jacob and Aaron. At the start time, Jacob pedaled in direct drive around the course perimeter. After completing five laps, Jacob stopped, and Aaron took over the vehicle as the second rider. At about ¾ of the course perimeter on the ninth lap, we stopped time and recorded it.

Results

Pump My Ride recorded an endurance time of 5 minutes and 40 seconds. Compared to the engineering specification of 4 minutes and 30 seconds, Pump My Ride did not meet it by 1 minute and 10 seconds. The engineering specifications were originally written to achieve a 15% improvement from the Incompressibles competition time. However, we conducted the endurance test according to the 2020 NFPA FPVC Rules which declares the vehicles start with zero accumulator pressure. Compared to the previous year, vehicles could start with a full charge on the accumulator. We believe this discrepancy caused a stark difference in endurance times.

Upon reviewing this engineering specification, it would have been more correct to base it from our Simscape models. Looking at the endurance model, we predicted an endurance time of 4 minutes and 55 seconds with an uncertainty of $\pm$44 seconds (15%). The recorded final endurance time is one second outside the range of our model prediction. A specification written according to the models would have made the endurance goal achievable if time allowed for human conditioning. Ultimately, Pump My Ride believes the original endurance time specification was unattainable given rule change and demanding rider requirement.

7.4 EFFICIENCY SCORE

The engineering requirement for the efficiency score is 18%. Verifying this score required that we measure the following parameters prior to testing:

- Gas pre-charge pressure in pounds per square inch (Note: minimum 100 psi)
- Maximum system pressure that the accumulator is charged to
- Volume of the accumulator [maximum 231 in^3]
- Weight of the vehicle and rider [lbs.]

Test Location

Pump My Ride conducted efficiency tests on Sports Complex Road (refer to Figure 7.1).

Test Equipment

- Fluid Powered Vehicle
- Nitrogen high pressure tank
- High pressure hose (whip)
- Cones

Test Method

The test methods are concurrent with the NFPA rules for the efficiency challenge. Prior to testing, we pressurized the accumulator pre-charge to 500psi and recorded this value. Next, we used a large scale and measured the vehicle weight, 103 lbs. In addition, we weighed the heaviest team rider Jacob at 163 lbs. At cone A, we used the vehicle regenerative mode to charge the accumulator to 3000 psi. After, Jacob boosted from a standing start. At a stable speed, Jacob switched from "boost" to coast. When the vehicle slowed to an unstable speed, Jacob switched to the "boost" mode again to return to a stable speed. For the duration of the ride, Jacob switched between "boost" and "coast" until the accumulator completely discharged, and Jacob arrived at a forced stop from coasting. Jacob returned to the 600 ft marker, cone B, while counting the number of revolutions of the front wheel. The number of revolutions were recorded.

Results

We obtained the distance from cone marker B in feet from the revolutions using a conversion factor of 7.76, which is approximately the wheel circumference in feet per revolution. The total distance was the calculated value plus the distance from marker A to B, 600 ft. The resulting efficiency with the remaining efficiency parameter values are included in Table 7.5.

Table 7.5: Final Efficiency Score Results

March 13, 2020						
Pre-charge [psi]	**Charge [psi]**	**Accumulator Volume [in^3]**	**Weight [lbs]**	**Revolutions**	**Total Distance [ft]**	**Efficiency [%]**
500	3000	231	266	165¼	1800	12.17

Given our tested parameters, we calculated a vehicle system efficiency of 12.17%. The tested efficiency does not meet the engineering specification of 18%. Pump My Ride believes more testing could qualify our system efficiency closer to the engineering specifications. In addition, the positive road grade along Sports Complex Road significantly understates our efficiency. Unfortunately, Cal Poly does not have the necessary facilities for unbiased vehicle testing, and COVID-19 removed future opportunities for more tests.

7.5 WEIGHT

The vehicle weight according to the engineering specification is 100 lbs. Pump My Ride used an industrial scale available in the Bonderson Projects Center and measured a vehicle weight of 103 lbs. The actual weight does not meet the engineering specifications because of unplanned, but necessary, modifications to the system—including a rear hub adapter and keeping the hydraulic

soft lines. Compared to the Incompressibles, we added 3 lbs. to the vehicle weight which we believe is insignificant. Unfortunately, we are not able to see how this added weight affects the overall vehicle performance due to the cancellation of the NFPA competition.

7.6 TOP SPEED

The vehicle top speed should be less than or equal to 40 mph according to the engineering specifications. A laser tachometer test was planned to verify the top speed. However, a tachometer could not be obtained prior to campus closure consequently to COVID-19. Based on our recorded sprint times, Pump My Ride believes the vehicle boost at maximum system pressure did not exceed 40 mph.

7.7 BRAKING TORQUE

The engineering specifications state that the braking torque compared to the motor torque has a factor of safety of 2. While calculations can verify this requirement is met, real tests will only reveal a factor of safety of at least 1. With the accumulator is charged to 3000 psi, Jacob switched to the vehicle boost while pressing on the front and rear brakes. Aaron helped stabilize the vehicle so it would not tip on its side. Our test confirmed that the braking torque satisfies a factor of safety of at least 1.

7.8 TURN AROUND TIME

The turn-around time specification refers to the time it takes to charge the accumulator to maximum pressure. Currently, Pump My Ride requires a turn-around time of 7 minutes so that we are well under the allotted time of 10 minutes during competition. During sprint design verification, we recorded the time it takes to charge to 3000 psi is approximately 6 minutes. The tests satisfy our engineering specifications.

7.9 POWER REQUIRED BY RIDER

Pump My Ride expects a rider should input a maximum of 300 W to operate the vehicle. The equipment available to our team does not allow us to accurately measure human power during operation. Thus, our team relied on our observations during performance testing. Simply, we assumed that a rider operating the vehicle while using direct drive mode is not exceeding the 300 W maximum power requirement.

7.10 VEHCILE LIFE

Pump My Ride wrote the life of the vehicle engineering requirement of 2 years to ensure this project can be passed down to future Cal Poly students. Since most of our components, especially the hydraulic motor, are operating under their specified flow rate, we cannot test the expected life accurately. Thus, Pump My Ride does not have design verification plan for the life of the vehicle, but it is assumed that since each component is under stressed, and there should be no significant wear.

7.11 INTERNAL LEAKAGE

According to the engineering specifications, Pump My Ride requires a maximum internal leakage rate of 2 psi/s. We tested internal leakage by measuring the accumulator pressure before and after

storing the vehicle. If internal leakage were present, then we expect to observe a pressure drop over time. No pressure dropped was observed during stowage period; thus, no internal leakage is present.

7.12 EXTERNAL LEAKAGE

Per the NFPA competition rules, it's required that all vehicles have no external leakages. Thus, our engineering specifications are concurrent with the rules. External leakage was tested concurrently with performance testing by observation and we observed no external leakage

8 PROJECT MANAGEMENT

The project management section identifies the resources and process which will drive the project forward to meet the team objectives before the FPVC in April 2020.

8.1 ROLES AND RESPONSIBILITIES

Our team created and signed a contract which establishes guidelines to aid in the success of the project and promote an equitable and respectful team environment. The operating procedures for decision making, communication, meeting deadlines and conflict resolution are specified within the contract. Additionally, each team member has been assigned specific roles which align with the project logistics and responsibilities for specific technical aspects of the project, outlined in Table 8.1.

Table 8.1: Team Member Roles and Responsibilities

Team Member	Roles	Responsibilities
Kayla Londono	Project Planner, Secretary	Modelling, Hydraulic Circuit
Jacob Torrey	Testing Coordinator, Editor	Power Transfer, Frame
Bryson Chan	Sponsor Contact, Treasurer	Mechatronics, Hydraulics Circuit
Aaron Trujillo	Manufacturing Coordinator	Manufacturing, Power Transfer

8.2 PROJECT TIMELINE

A visual representation of the timeline for our project has been created using Gantt chart, provided in Appendix O. The main tasks are defined and assigned to the responsible team member to ensure the project progress aligns with deadlines. The main deliverables for the project include; the Preliminary Design Report (PDR), Critical Design Report (CDR) and the competition/Final Design Report (FDR). The PDR defined and supported the expected design direction with approval by our sponsor to be updated with the release of the competition rules. The CDR, completed by October 25th, included all the information necessary for the vehicle to be built as originally designed. The team presented the Design and Specification Midway Review to the Program Manager, Technical Liaison and Industry volunteers in early December. The final presentation was sent to the Program Manager before the deadline of April 8th to be presented during the virtual competition which takes place April 15th through 18th in 2020. The FDR summarizes all the work performed in developing the project, and the results from testing and virtual competitions. The Gantt Chart, provided in Appendix O, outlines the timeline and team member with main responsibility for each task.

8.3 PROJECT MANAGEMENT REFLECTION

The process of assigning specific responsibilities to each team member aided in the progression of the project. Each team member was aware of the specific details required to ensure their respective area was on track to meet time requirements. Periodic meetings with all team members present were important for determining critical tasks and potential issues within the scope of the entire project. Team members prioritized and contributed to tasks outside of their assigned responsibilities whenever necessary to equalize efforts and ensure the integrity of the project.

The team experienced difficulty in scheduling meetings due to variable schedules and dynamic project requirements. Increased communication between team members about expectations, availabilities and scheduling would be beneficial in future projects.

9 COMPETITION RESULTS 2020

The competition was transformed to a virtual event in response to the COVID-19 pandemic which began to affect the United States in January 2020. However, the pandemic did not halt our team's progress until March 19, 2020 when San Luis Obispo County ordered a shelter-in-place for all residents. Pump My Ride suspected interruptions when it was announced on March 11, 2020, that Cal Poly suspended non-essential travel, which included our travel to the NFPA FPVC competition. Shortly after, on March 18, the NFPA contacted Pump My Ride announcing the virtual event to take place of the live event.

Overview of Virtual Competition

The virtual event provided the opportunity for teams to host their final presentations via webinar. The planned live events—including the sprint race, efficiency challenge, and endurance challenge—were not included in the judging criteria and overall final score. The NFPA also announced that it would not require a proof of a working vehicle. Therefore, points for 1st, 2nd, and 3rd depended on advisor meeting summaries, the Midway Review Presentation and Final Presentation. Additionally, all teams were able to get points for viewing six presentations:

1. Welcome Ceremony
2. Bimba & IMI PE: How Things Work
3. Bimba & IMI PE Careers
4. Danfoss Power Solutions Careers
5. International Fluid Power Society - Certification
6. Iowa Fluid Power Careers

An updated rubric based on the virtual competition is provided in Appendix B.

Since the virtual competition depended on the final presentation, Pump My Ride focused on presentation and communication of everything we completed—including the final design, manufacturing, and design verification. For the presentation, we followed an outline provided by the NFPA, which involved a summary of the midway review design, the vehicle construction, the final design, and the lessons learned. The presentation was a challenge because of time limits: 15-minutes for the presentation and 10-minutes for Q&A from the judges.

Virtual Competition Results

Pump My Ride gave the final presentation on Thursday, March 16, 2020, via webinar. The following Friday, the judges presented the awards during a live ceremony webinar. The awards and winners a summarized in Table 8.2.

Pump My Ride was awarded Judges Choice for best teamwork. The judges remarked on our ability to communicate effectively with one another, achieve total participation in mentor meetings, tradeoff answers to questions, and give presentations cohesively.

Table 8.2: NFPA FPVC 2020 Virtual Competition Awards and Teams

Award	Team
Overall Champion-First Place	Cleveland State University
Second Place	University of Cincinnati
Third Place	Purdue University
Best Presentations	Milwaukee School of Engineering
Judges Choice: Use of Components	Murray State University
Judges Choice: Design	Purdue University Northwest
Judges Choice: Teamwork	Cal-Poly SLO
Rookie of the Year	Arizona State University
Best Use of Pneumatics, Sponsored by Bimba	Western Michigan University

10 CONCLUSION & RECOMMENDATIONS

10.1 LESSONS LEARNED

The original written objective of this project was to design and build a fluid powered vehicle that would place Cal Poly as overall winner at the NFPA FPVC competition in Little, CO. Since a live competition did not take place as planned, we cannot accurately report if this objective was met. According to the virtual competition results, Cleveland State University was awarded first place. However, the virtual competition severely impacted Pump My Ride's overall performance because it eliminated the challenge events, which we relied on to provide an objective measurement against the other teams' vehicles.

Nonetheless, the virtual competition results helped us draw conclusions about the competition and reflect on our team's final design. First, it confirmed that hydraulic design is a significant factor towards the judges' scoring. The judges remarked on Cleveland State University's efforts to begin with benchmark tests of various hydraulic components. They used these benchmark tests to select key components and hardware for their vehicle, which impressed the judges. Pump My Ride used online research and models to select key components. We found that this was a time-effective method to select components. However, more thorough research on various hydraulic components may have improved our score. More importantly, our team did not follow through on hydraulic hard lines. We speculate that the hard lines would have made a more impressive hydraulic vehicle.

Second, the virtual competition results confirm that safety and ergonomics are another concern of the judges. All top 3 teams implemented a new safety feature, such as pneumatic brakes. One judged commented on Cleveland State University's addition of a more comfortable seat for rider

ergonomics. Reflecting on these comments, Pump My Ride should have communicated about the safety of the vehicle, such as writing a user manual. Additionally, we could have communicated that we moved hydraulic components to allow seat adjustment for accommodating riders of different heights.

While we can reflect on our design choices and guess how that contributed to our standing in the virtual competition, we must also recognize that our design decisions were motivated prior to knowledge of a virtual competition. In this way, Pump My Ride believes we made the best design decisions for a live competition. Therefore, we have our engineering specifications to reflect upon.

Appendix P contains the Design Verification Plan and Report (DVPR) which quantitively and qualitatively summarizes our findings from the final design verification and compares it to the engineering specifications. Out of the 11 list specifications, we did not meet 4; sprint time, endurance time, efficiency, and weight. However, these results were based on limited test results, a consequence of COIVD-19. It was evident we needed to conduct more tests to obtain results that accurately reflect the vehicle's performance, or to pinpoint system failures and inefficiencies. Thus, one lesson learned is that human training for the vehicle is important for best vehicle performance.

10.2 RECOMMENDATIONS

Cal Poly has assembled a team to compete in the 2021 NFPA FPVC. This section outlines Pump My Ride's future recommendations based on our discoveries during the final design review.

10.2.1 VEHICLE OPERATION RECOMMENDATIONS

First, we strongly recommend all future team members read the User Manual, in Appendix Q, prior to operating the vehicle. As the bike is set up right now, when the battery is connected, the bike automatically engages boost mode. Damage or injury may occur if care is not taken when connecting the battery. We suspect this is a software issue, and should be resolved for team safety.

Second, it is known that a fluid powered vehicle is an atypical application for a bladder accumulator. Therefore, routinely check pressure in the system for any unexpected changes. In addition, order a second accumulator for back-up, if affordable. During construction, it was noticed that the accumulator bladder had ruptured. After the system had been fully discharged, it was noticed that system pressure was, after some time, equalizing with the accumulator pre-charge pressure. We believe the root-cause of this issue was a ruptured bladder. Thus, we recommend the bike should not be stored for extended periods with the system pressure below pre-charge pressure, because it causes the bladder to overinflate, and limit the pre-charge pressure. The use case for this project is far outside the operation range for this bladder, and care must be taken if the accumulator bladder is to last any length of time.

Last, we encourage teams to build upon and revise our user manual. Following teams could benefit greatly if the frustrations and learning curves of previous teams are well documented with their subsequent actions. This could save teams time, improve their safety, and would provide practice in building a valuable engineering skill- documentation.

10.2.2 HYDRAULIC AND PNEUMATIC RECOMMENDATIONS

Pneumatic Brakes

This year, a new pneumatics category was added. Our plan, if time had permitted, was to add a safety brake, like those used on semi-trucks and trains. This type of brake's normal state is fully engaged and is only released when air pressure is applied. This type of brake should be feasible with the $500 allotment of parts from Sun Source.

Hydraulic Hard Lines

We suspected an increase in efficiency from switching to hydraulic hard line instead of hoses. Originally, the plan was to do this, but we were delayed by the manifold, and made the decision to focus on testing a working bike rather than using our time to further modify the bike. Fittings and collars were ordered, so that the next team can just order the hard line and construct hard lines as they see fit.

10.2.3 MECHATRONICS RECOMMENDATIONS

Pump My Ride has recommended improvements for the vehicle mechatronics. This year we installed new software so it is easier to code, and hardware that would make it more robust to the environment.

Software

Regarding the software, next years' team may incorporate new modes because Pump My Ride made the coast mode default when there are no inputs. This means a pedaling regeneration can be installed by turning on the standing solenoid. As described in Section 10.1.1, there is a bug in the software where boost mode is initiated when the vehicle is powered, which releases the pressure stored in the accumulator. This is an obvious hazard and needs to be fixed. New software was created to try to fix this problem however mechatronics testing to discover the root-cause was unsuccessful.

Hardware - LCD

Pump My Ride recommends new hardware can be installed, including an LCD monitor. The LCD monitor, gifted by HydraForce, is compatible with the controller unit. The monitor can be used to control the inputs as well as display bike information such as modes, pressure, and any other features added. A mount was designed for the LCD monitor and is ready for 3D printing.

Wire Routing

The mechatronics subassembly requires a bundle of wires to connect the solenoid valves, hydraulic controller, input buttons, battery, and (future) LCD. Exposed and tangled wires are a hazard for the mechatronic components and for the rider. In addition, it subtracts from the vehicle's aesthetic. Pump my Ride recommends using the braided steel we purchased to organize and package wires for the mechatronics subassembly.

10.2.4 MANUFACTURING RECOMMENDATIONS

Machining

Recently, the Mustang ’60 Machine Shop obtained an industrial waterjet cutter. Pump My Ride utilized the waterjet cutter for manufacturing their mounts because its advantages are unsurpassable: efficiency, precision, and accuracy. Since manufacturing can interfere with testing time, we recommend next year’s team utilize the waterjet cutter. However, teams must schedule an appointment in advance to access the waterjet.

DFM

During construction of the motor mount, Pump My Ride discovered the frame is out of square. This is misleading, especially if you have used 3D assembly and analysis to design or package new components. Pump My Ride recommends next year’s team design for manufacturing that is adjustable. The team also found it useful to use rough prototypes from paper or cardboard as check with vehicle integration and would recommend similar procedures to future teams.

Other

During the NFPA FPVC Virtual Competition, we noted that judges were particularly impressed with teams that used a variety of manufacturing methods. While this is not explicitly stated in the judging criteria, we recommend next year’s team practice using 3D printing technology and other methods to build their manufacturing resume and stand out from other teams.

10.2.5 MODELLING & TESTING RECOMMENDATIONS

Pump My Ride suggests that the next team continues to improve the Simscape models in the manners discussed in Section 5.4.2. The models have been effective for our team and previous Cal Poly teams in determining design decisions and predicting vehicle performance. Also, the models provide the opportunity to investigate the effects of many vehicle properties and environmental factors on the performance. Other methods of modelling are unlikely to have this ability due to the oddity of the application. Also, the Simscape blocks and input variables can be chosen to represent vehicles of various styles and differing characteristics. However, the team does believe that other methods of modelling could be useful in validating the Simscape models and analyzing specific aspects of the project. For example, a software specifically used to model hydraulics could prove to be beneficial.

In regard to testing, we suggest future teams record information on environmental factors to provide justifications or awareness in discrepancies. This could be useful in early detection of unexpected damages or changes to the bike. For example, factors such as windspeed, rider energy or health, road incline, etc. could account for even significant differences in test results. However, if differences are observed when these factors are held constant, this could indicate that air is trapped in the system, there is fluid leakage, component damage or a variety of other. The ability to discount a list of potential sources at the start can save a lot of time in diagnostics.

10.2.6 RECOMMENDATIONS FOR COMPETITION

There are a few considerations future teams should be aware of in preparation of interactions with judges and other industry professionals. First, attention to hydraulics and other mechanical engineering jargon is important part for learning experiences, clear communication and professionalism. If vocabulary is misused, it will be immediately noticeable to the judges, and cause a reduction in team credibility. In particular, recognize the difference between accumulator pre-charge pressure and accumulator (system) pressure.

The judges are impressed with vehicles which seem to be ready for market. Therefore, safety, packaging, ergonomics and overall aesthetics improve their response to the vehicle. Also, additional features, even if unnecessary, will give the judges something unique to remember, an invaluable benefit when they are judging a multitude of vehicles. The NFPA holds the competition to get students interested in the industry, so try to have fun with final touches and overall vehicle design. Simple considerations, such as a cup holder or comfortable seat, can go a long way.

Lastly, the presentations are opportunities for teams to show off all their hard work; so, make sure to sell it! Highlight hydraulic aspects (the judges are in the hydraulic industry), and present with enthusiasm.

10.2.7 PROJECT MANAGEMENT RECOMMENDATIONS

The team found that assigning responsibilities was extremely helpful in managing the many aspects of the project. Even if all members contribute equally to all aspects, teams will reduce the likelihood of missing deadlines or forgetting details if one person is responsible for the integrity of each.

Also, important references to be aware of include:

- Mark Decklar provided our team with a great deal of help through all phases of the project. Even though he was not our assigned industry sponsor he never hesitated to provide us with HydraForce products and his assistance.
- Jim Gerhardt took the time to teach us to adjust accumulator pre-charge and provided us with the necessary tools.
- Shop technicians can provide knowledge, advice and assistance with manufacturing.

10.3 NEXT STEPS

In this section, we address important "next steps" to our advisor, Jim Widmann. The COVID-19 pandemic certainly caused unprecedented transformations to the originally planned competition. Furthermore, it causes challenges from the beginning for the next Cal Poly FPVC team. We know that the first two quarters are a critical time for teams to do research and test new hydraulic components for the vehicle. However, without access to the vehicle, we know it may be difficult to prototype. Given the circumstances, Pump My Ride believes the teams should use all the information available from our team including the previous design matrices, models used for improving performance, and future recommendations. In this way, the team can suggest improvements with some evidence supplied by our team.

10.4 CONCLUSION

The Final Design Review document describes the final design for Pump My Ride's entry in the NFPA 2020 Fluid Powered Vehicle Challenge. Each major decision was supported with engineering analysis and related to a competition score when applicable. While we preserved some elements of Cal Poly's previous vehicles, we modified the components and hardware according to models and tests that predicted the best vehicle performance at competition. The hydraulic system was optimized by minimizing hydraulic losses wherever possible, including reducing the number of fittings, and using a new custom manifold. The mechatronics were streamlined to be more robust and to add simplicity. Rolling resistance has been drastically reduced using quality road racing tires to increase scores in each challenge. The bike was designed to be more user friendly and to outperform last year's bike in every measurable aspect. Manufacturing and assembly were completed in house. Because a new manifold caused delays to our schedule, we forfeited the hydraulic hard lines to move forward with testing. This proved to be a good decision because we encountered several issues during testing involving mechatronics, chain tensioning, and measuring the accumulator pre-charge pressure. We were able to resolve these issues in time to begin design verification before the sudden halt caused by COVID-19. Based on the test results, we have evidence to support that Pump My Ride would have outperformed last years' vehicle at a live competition. Given the circumstances and change to a virtual competition, our team did not place 1st. Regardless, Cal Poly was honored with a Judge's Choice award that highlights the team's cohesiveness, collaboration, and confidence about our final vehicle design.

REFERENCES

[1] "Fluid Power Vehicle Challenge | Interactive Science." Fluid Power Challenge, www.nfpahub.com/fpc/vehicle-challenge/.

[2] Posin, R., Rodkiewicz, J., Vitt, D., Knickerbocker, A., Gholdian, N., Franck, K. *Fluid Power Vehicle Challenge The Incompressibles Final Design Report*. 2019.

[3] Denham, Alee. "Understanding Bicycle Frame Geometry." *CyclingAbout.com*, Cycling About, 28 Dec. 2017, www.cyclingabout.com/understanding-bicycle-frame-geometry/.

[4] Zinn, Lennard. "Resistance Is Futile: How Tire Pressure and Width Affect Rolling Resistance – VeloNews.com." *VeloNews.com*, Velo Magazine, 18 Mar. 2015, www.velonews.com/2014/12/bikes-and-tech/resistance-futile-tire-pressure-width-affect-rolling-resistance_355085.

[5] "Raspberry Pi 3 vs Arduino - Learn The 6 Amazing Differences." *EDUCBA*, 10 Oct. 2018, www.educba.com/raspberry-pi-3-vs-arduino/.

[6] Oertel, Clemens, et al. "Construction of a Test Bench for Bicycle Rim and Disc Brakes." *Procedia Engineering*, Elsevier, 11 June 2010, www.sciencedirect.com/science/article/pii/S1877705810003462.

[7] "Cervelo." *Further Clarity on Tire Clearance*, www.cervelo.com/en/further-clarity-on-tire-clearance.

APPENDICES

Appendix A: Efficiency Formula Calculations

Inputs

Pre-charge pressure [psi]
Max system pressure [psi]
Accumulator Volume, V_{accum} [in3]
Weight of Vehicle and Rider, W [lbs]
Distance Travelled, d [ft]

Calculations

$$V_{usable}\,[in^3] = V_{accum} - \frac{P_{pre-charge}\,[psia] \times V_{accum}}{P_{max}\,[psia]}$$

$$E_{out}[lb - ft] = \mathrm{W} \times cf \times d$$

$$P_{avg}[psi] = P_{pre-charge}\,[psi] + 0.29289 \times \left(P_{max}\,[psi] - P_{pre-charge}\,[psi]\right)$$

$$E_{input}[lb - ft] = \frac{P_{avg}\,[psi] \times V_{useable}}{12}$$

$$\%\,efficiency = \frac{E_{output}[lb - ft]}{E_{input}\,[lb - ft]}$$

Appendix B: Updated Information for Virtual Competition

NFPA Fluid Power Vehicle Challenge
SCORING RUBRIC

Judge: ______________________________

Team: ______________________________

VEHICLE DESIGN REVIEW	Poor	Moderate	Good	Very Good	Excellent
Quality of vehicle design associated with **reliability**. The vehicle is robust and durable, but not too heavy.	1	2	3	4	5
Quality of vehicle design associated with **operator safety and comfort**. The vehicle is ergonomic and easy to use.	1	2	3	4	5
Quality of vehicle design associated with **originality and uniqueness**. The vehicle incorporates innovative concepts and could be marketable as a production vehicle.	1	2	3	4	5

NFPA Fluid Power Vehicle Challenge
SCORING RUBRIC

Judge: ______________________________

Team: ______________________________

FINAL PRESENTATION	Poor	Moderate	Good	Very Good	Excellent
Summary of midway presentation is succinct and well organized.	1	2	3	4	5
Vehicle construction was completed ~~on-time~~ and performed mostly by the team members.	1	2	3	4	5
~~**Vehicle testing** was performed and improvements were made based on results.~~	~~1~~	~~2~~	~~3~~	~~4~~	~~5~~
Progress made towards the final vehicle ~~brought to competition~~ appears reliable, safe and of quality craftsmanship.	1	2	3	4	5
Lessons learned are clearly stated and appropriate to the design/build experience described.	1	2	3	4	5
Presentation is completed on time and demonstrates good team synergy.	1	2	3	4	5

NFPA Fluid Power Vehicle Challenge
SCORING RUBRIC

Judge: ______________________________

Team: ______________________________

FPVC Mentorship	Summary Submitted (Y/N)	Points
Introduction and initial discussion about **vehicle** design.		1
Discussion about **component** design.		1
Discussion about **assembly** and **testing**		1
Final discussion on **adjustments**		1
	Total Points	4

Comments: ______________________________

NFPA Fluid Power Vehicle Challenge
AWARDS

NOTE: All awards will be distributed directly to team participants

AWARD	PRIZE	CONSIDERATIONS
Overall Champion 1st place 2nd place 3rd Place	 $3,000 $2,000 $1,000	~~First place overall champion will not be eligible to win more than one of the following: sprint race, endurance or efficiency challenges~~. Funds will be distributed directly to team participants.
Best Presentations	$2,000	Midway review score to be included in evaluating winning presentation. Funds will be distributed directly to team participants.
~~Sprint Race~~	$1,000	Top three scores to be considered for placement. Final 1st place will be determined by a number of factors, including Overall Champion.
~~Efficiency Challenge~~	$1,000	Top three scores to be considered for placement. Final 1st place will be determined by a number of factors, including Overall Champion.
~~Endurance Challenge~~	$1,000	Top three scores to be considered for placement. Final 1st place will be determined by a number of factors, including Overall Champion.
Best Use of Pneumatics, Sponsored by Bimba	$500	To be considered for award, teams must display creativity, efficiency, and safety. Funds will be distributed directly to team participants.
Judges Choice: Design Award	~~$500~~ $1,500	To be considered for award, teams must display innovation, uniqueness and originality of the design. ~~Selected by Student Teams.~~
Judges Choice: Use of Components	~~$500~~ $1,500	~~To be considered for award, teams must take sufficient steps to prevent injuries from hardware and surpass a 1-year warranty.~~ To be considered for award, teams must produce an efficient final schematic. The number of components and cost effectiveness will be considered.
~~Best Workmanship~~	~~$500~~	~~Best degree of skill, expertise and quality in vehicle.~~
Judges Choice: Teamwork	~~$500~~ $1,500	Best attitude and cohesiveness of team.
12 Awards	$13,500	

Appendix C: Mentor Summaries

Mentor Summary #1
Date: Thursday 11/7/19
Participants: Bryson Chan, Aaron Trujillo, Jacob Torrey, Kayla Londono, Kevin Lingenfelter
Agenda Items:
1. Exchange introductions between the team and advisor
2. Discuss team progress and plans.
3. Obtain initial advice and recommendations.

Action Items:
1. Send Kevin our Critical Design Report for his review.

Discussion:
We discussed our progress in vehicle design with an emphasis on component selections. Pump My Ride presented our modeling, analysis and a summary of planned changes to the previous bike. Our advisor provided additional considerations for components, system limitations, calculations, resources and testing.

Mentor Summary #2
Date: Friday 11/22/19
Participants: Bryson Chan, Aaron Trujillo, Jacob Torrey, Kayla Londono, Kevin Lingenfelter
Agenda Items:
1. Review design decisions for component selections and hydraulic circuit.
2. Ask for general advice for the Midway Review.

Discussion:
We had a detailed review of the hydraulic circuits, component ordering and our future plans. We also discussed the need for a regeneration station. Our models show that we will not need one, but we will incorporate this task in our workload if there is time after building the bike.

Kevin provided advice for the Midway Review:
- Do not forget to use FEA on CAD models to prove structural integrity
- Make sure decisions are supported with calculations and models

Mentor Summary #3
Date: Friday 1/10/20
Participants: Bryson Chan, Aaron Trujillo, Jacob Torrey, Kayla Londono, Kevin Lingenfelter
Agenda Items:
1. Discuss Midway Review

Notes:
- Discussed roles and goals of each team member for the quarter (Aaron- focus on manufacturing, Bryson- design and implement mechatronics, Jacob- work on finalizing CAD designs, assist with manufacturing, testing, Kayla- project planning, improving simulations, assist with manufacturing)
- We ordered our components but have experienced some delay in receiving
- Plan to begin manufacturing next week

Mentor Summary # 4
Date: Tuesday 3/3/20
Participants: Bryson Chan, Aaron Trujillo, Jacob Torrey, Kayla Londono, Kevin Lingenfelter
Agenda Items:

1. Team check-in to discuss working vehicle and future plans.

Notes:
Kevin gave us answers to some logistics questions for the Endurance Challenge and proof of working vehicle. Realized that we need to incorporate a port for pressure testing by the judges. Discussed issues in manufacturing up to this point and showed off nearly completed bike. Plan to meet again after some testing is completed.

Appendix D: Customer Needs

Vehicle must be safe
Vehicle must satisfy all rules for FPVC 2020
Vehicle must win the overall competition
Vehicle must be constructed under budget
Vehicle must weigh less than 95 lbs

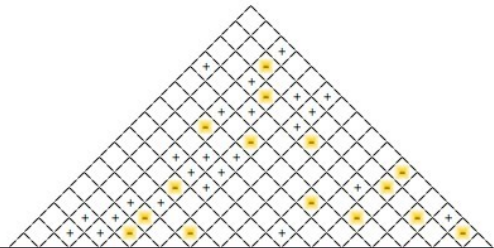
Appendix E: Quality Function Development House of Quality

Date: April 19, 2019

Correlations	
Positive	+
Negative	−
No Correlation	

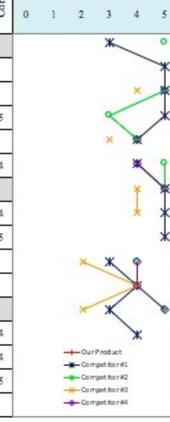
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



WHO: Customers | HOW: Engineering Specifications | WHAT: Customer Requirements (explicit & implicit) | NOW: Current Product Assesment - Customer Requirements

Row #	Weight Chart	Relative Weight	Dr. Widmann	NFPA Competition Judges	Pump My Ride Team		Maximum Relationship	WHAT: Customer Requirements (explicit & implicit)	Time to Assemble (min)	Turn Around Time (min)	Operation Pressure (psi)	Weight (lb)	Cost ($)	Top Speed (mph)	Height (ft)	Turning Radius	Steady State Power (W)	Power Required by Rider (W)	Life of the Bike (years)	Internal Leakage (psi/s)	Number of Components (S)	Acceleration (ft/s/s)	Reliability (%)	Max Torque	Our Current Product	Competitor #1: *Incompressibles*	Competitor #2: *Cleveland State*	Competitor #3: *Murray State*	Competitor #4: *Purdue*	Row #
								Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16						
								Direction of Improvement	▼	▼	◇	▼	▼	▲	▼	▼	▲	▼	▲	▼	◇	▲	▲	▲						
								Competition Awards																						1
1		10%	9	12	9		9	Sprint Race Speed			●	●		●				○		▽		○	○	●		3	5			2
2		9%	9	8	9		9	Endurance			○	●					●	○		○		▽	●	▽		5				3
3		16%	18	15	12		9	Safety			●			○					○		▽	○	●	○		5	5	4	5	4
4		11%	10	12	10		9	Efficiency / Regeneration			○	●			●					●		○	○			5	3			5
5		10%	9	8	12		9	Manufacturability	○	○		○	●						○		●					4	4	3	4	6
								Functional Performance																						7
6		5%	10	0	5		9	Durability			○		○				▽	▽	●		○	○	●	●		4	5		4	8
7		3%	5	0	5		9	Stability				●		●	●	●	▽	○				○	○	●		5	5	4	5	9
8		4%	5	0	6		9	Assembly	●	○		▽									●		▽			5		4		10
9		5%	8	0	7		3	Ease of Shipping				○	▽	○							○					5				11
								Human Factor																						12
10		7%	6	10	5		9	Ergonomics				●			●	○	●	●								3	4	2	4	13
11		8%	6	10	8		9	Control Interface		●				○		●	●	●			▽					4	4	4	4	14
12		6%	0	10	6		9	Aesthetics				▽	●		○						○					3	5	2	5	15
13		6%	5	5	7		9	Power Output Required by Ride				○		○	○		●	●				○	○	▽		4				16
								HOW MUCH: Target	10 minutes	7 minutes	3000 psi	210 lbs	$3,500	25 mph	3 ft	7 ft	500 W	150 W	2 years	2 psi/s	6 parts	0.73 ft/s^2	100%	75 ft-lb						



Appendix F: Ideation Sessions

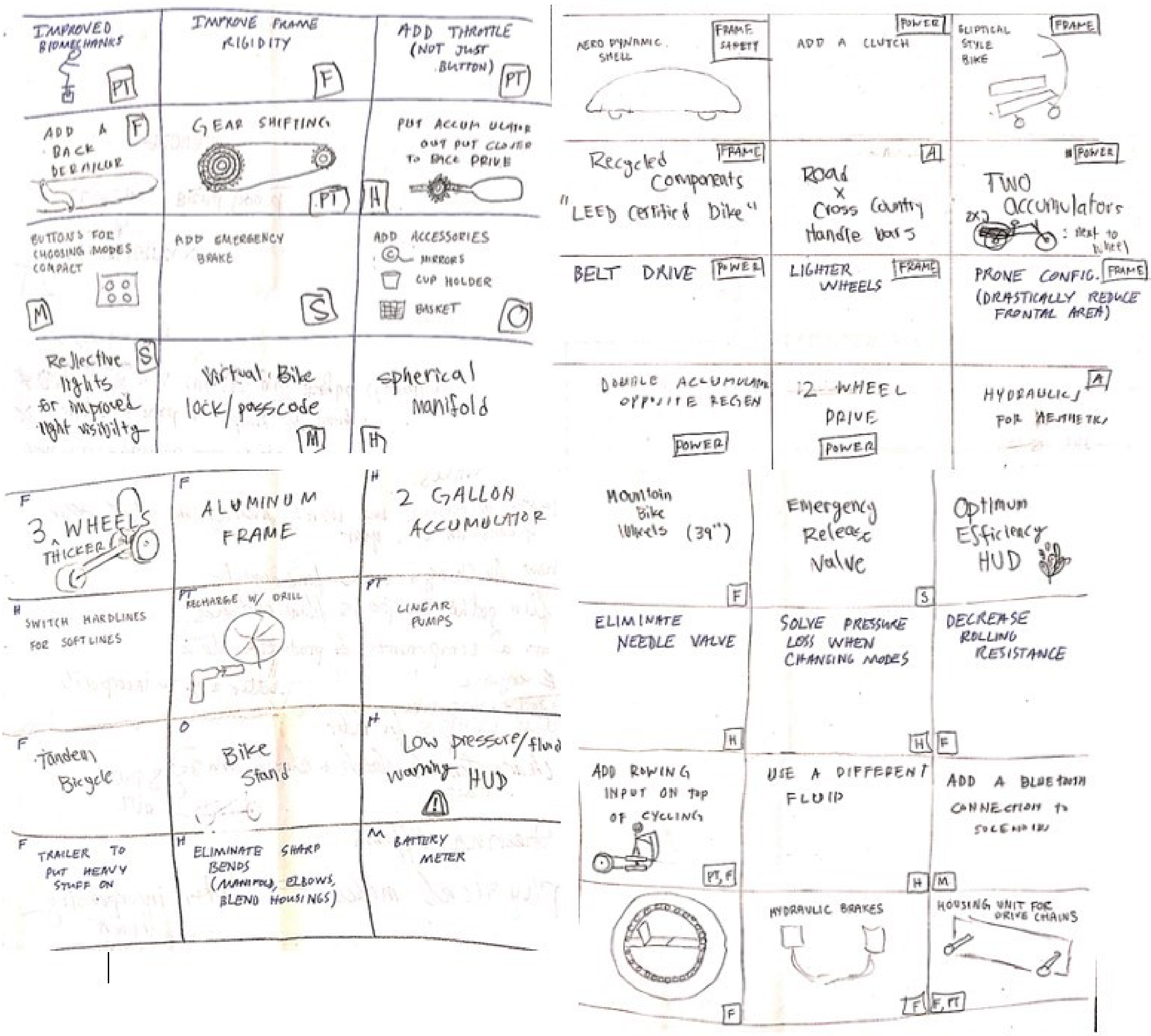


Figure F. 1: Brainwriting Results

Figure F. 2: Linear Pump Concept Model

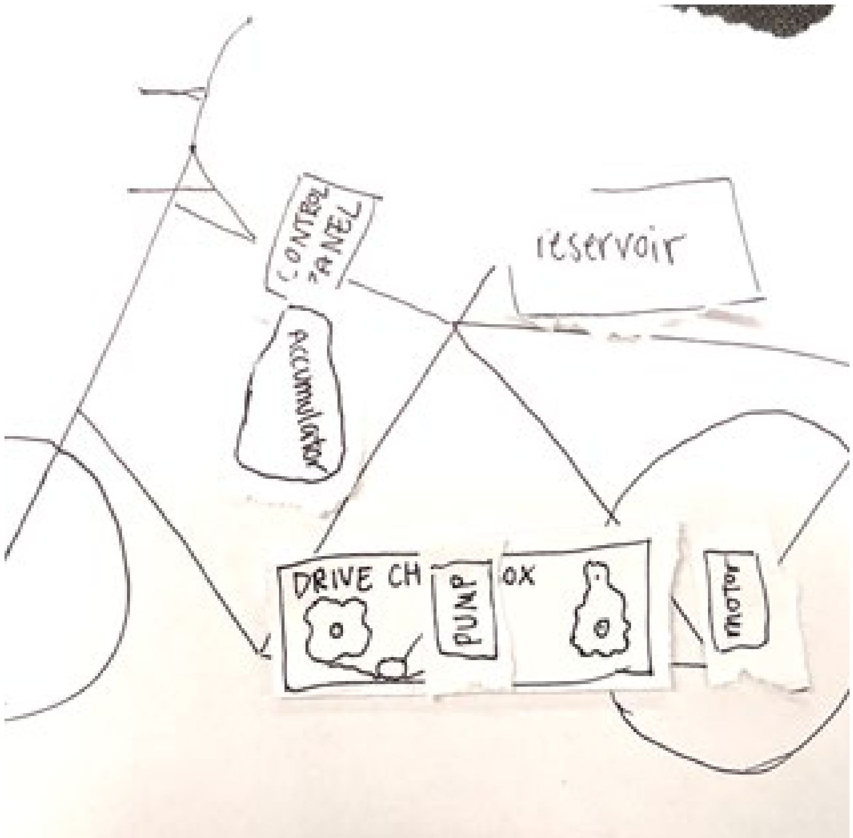
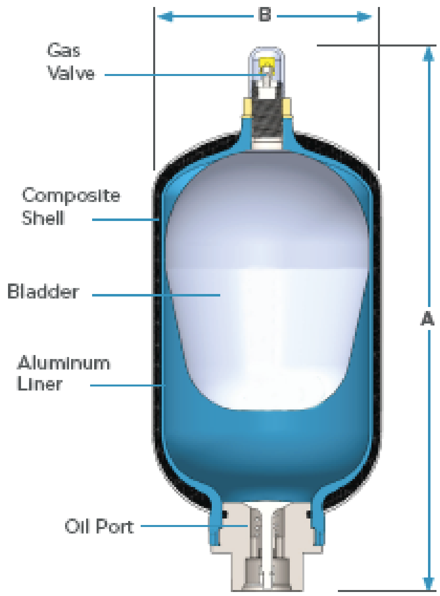


Figure F. 3: Component Layout Concept Model

Appendix G: Accumulator Specifications

MICROMAX SERIES
BLADDER ACCUMULATOR



Steelhead Composites Micromax series lightweight 3,000 psi (207 bar) to 5,000 psi (345 bar) bladder accumulators come in 1.0 gallon (4 liter) and 1.3 gallons (5 liter) capacities. These small and lightweight composite accumulators are a superior alternative to steel accumulators for any weight-restricted uses, mobile and industrial applications where access is remote, elevated or limited.

SPECIFICATIONS

- Type 3 Pressure Vessel
- Operating Pressure: 3000 psi (206 bar)-5,000 psi (345 bar)
- Minimum Burst Pressure: 3x Max Operating Pressure
- Fluid Connection: Industry standard port options available
- Operating Temperature Range: -4° to 160°F (-20° to 71° C)
- Liner: Impermeable 6061-T6 Aluminum
- Structural: Carbon fiber and epoxy composite
- Bladder: Buna-Nitrile (other materials available)

NOMINAL VOLUME GAL (L)	OPERATING PRESSURE PSI (BAR)**	DIMENSION A IN (MM)	DIMENSION B IN (MM)	WEIGHT LBS (KGS)
1 (4)	3,000 (206)	15.7 (399)	6.5 (165)	10.8 (5)
1.3 (5)	3,000 (206)	19.4 (493)	6.5 (165)	12.8 (6)
2.5 (10)	3,000 (206)	28.7 (729)	6.5 (165)	17.7 (8)

RUGGED 5,000 PSI MICROMAX

NOMINAL VOLUME GAL (L)	OPERATING PRESSURE PSI (BAR)**	DIMENSION A IN (MM)	DIMENSION B IN (MM)	WEIGHT LBS (KGS)
1 (4)	5,000 (345)	15.7 (399)	6.7 (170)	13.2 (6)
1.3 (5)	5,000 (345)	19.4 (493)	6.7 (170)	14.3 (6.5)

**Additional pressures available upon request.

Visit www.steelheadcomposites.com/about/lunch-learn/ to request a lunch and learn

CONTACT STEELHEAD COMPOSITES

720.524.3360

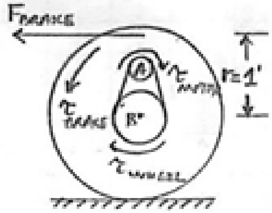
500 Corporate Circle, Suite O
Golden, CO 80401

www.steelheadcomposites.com

SHC/REV03/022117

Appendix H: Brake Calculations

ASSUME BRAKING FORCE @ WHEEL IS 400N $\approx$ 90lb_f = F_{BRAKE}



A = 13 TEETH
B = 35 TEETH
$\tau_{MOTOR} = 12\,ft\text{-}lb_f$

$$\tau_{BRAKE} = F_{BRAKE}\, r$$
$$= (90\,lb_f)(1\,ft)$$
$$\underline{\tau_{BRAKE} = 90\,ft\text{-}lb_f}$$

$$\tau_{WHEEL} = \tau_{MOTOR}\left(\frac{B}{A}\right)$$
$$= 12\,ft\text{-}lb_f\left(\frac{35\ \text{TEETH}}{13\ \text{TEETH}}\right)$$
$$\underline{\tau_{WHEEL} = 32.3\,ft\text{-}lb_f}$$

$$F.O.S. = \frac{\tau_{BRAKE}}{\tau_{WHEEL}}$$
$$= \frac{90\,ft\text{-}lb_f}{32.3\,ft\text{-}lb_f}$$

$\boxed{F.O.S. = 2.79}$ $\Rightarrow$ FACTOR OF SAFETY FOR BRAKE HOLDING TORQUE. BASIC RIM BRAKES ARE MORE THAN SUFFICIENT.

Appendix I: Design Hazard Checklist

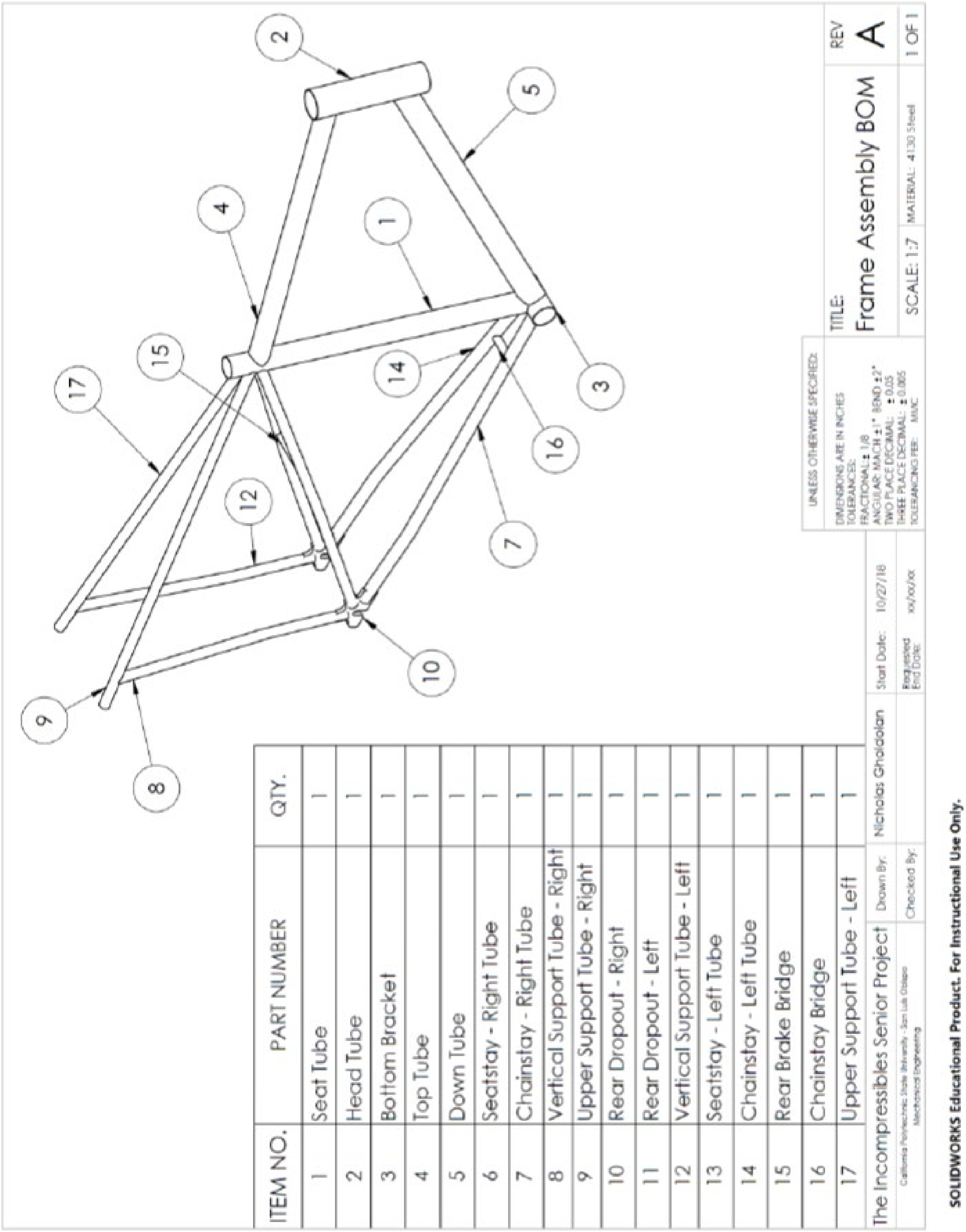
DESIGN HAZARD CHECKLIST

Team: Pump My Ride Advisor: John Fabijanic Date: 5/21/19

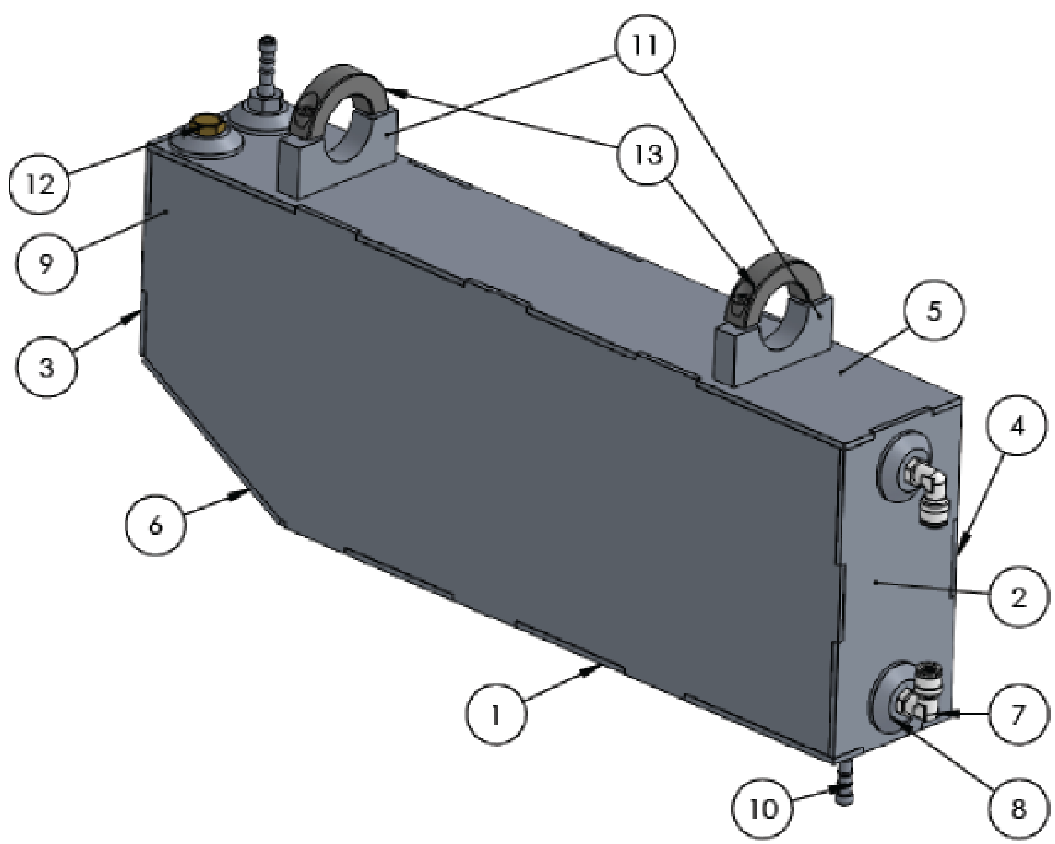
Y	N	
☑	☐	1. Will the system include hazardous revolving, running, rolling, or mixing actions?
☐	☑	2. Will the system include hazardous reciprocating, shearing, punching, pressing, squeezing, drawing, or cutting actions?
☑	☐	3. Will any part of the design undergo high accelerations/decelerations?
☑	☐	4. Will the system have any large (>5 kg) moving masses or large (>250 N) forces?
☑	☐	5. Could the system produce a projectile?
☑	☐	6. Could the system fall (due to gravity), creating injury?
☐	☑	7. Will a user be exposed to overhanging weights as part of the design?
☑	☐	8. Will the system have any burrs, sharp edges, shear points, or pinch points?
☐	☑	9. Will any part of the electrical systems not be grounded?
☐	☑	10. Will there be any large batteries (over 30 V)?
☐	☑	11. Will there be any exposed electrical connections in the system (over 40 V)?
☑	☐	12. Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases?
☑	☐	13. Will there be any explosive or flammable liquids, gases, or small particle fuel as part of the system?
☐	☑	14. Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design?
☑	☐	15. Will there be any materials known to be hazardous to humans involved in either the design or its manufacturing?
☐	☑	16. Could the system generate high levels (>90 dBA) of noise?
☐	☑	17. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use?
☑	☐	18. Is it possible for the system to be used in an unsafe manner?
☐	☑	19. For powered systems, is there an emergency stop button?
☑	☐	20. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.

Appendix J: Drawing Package

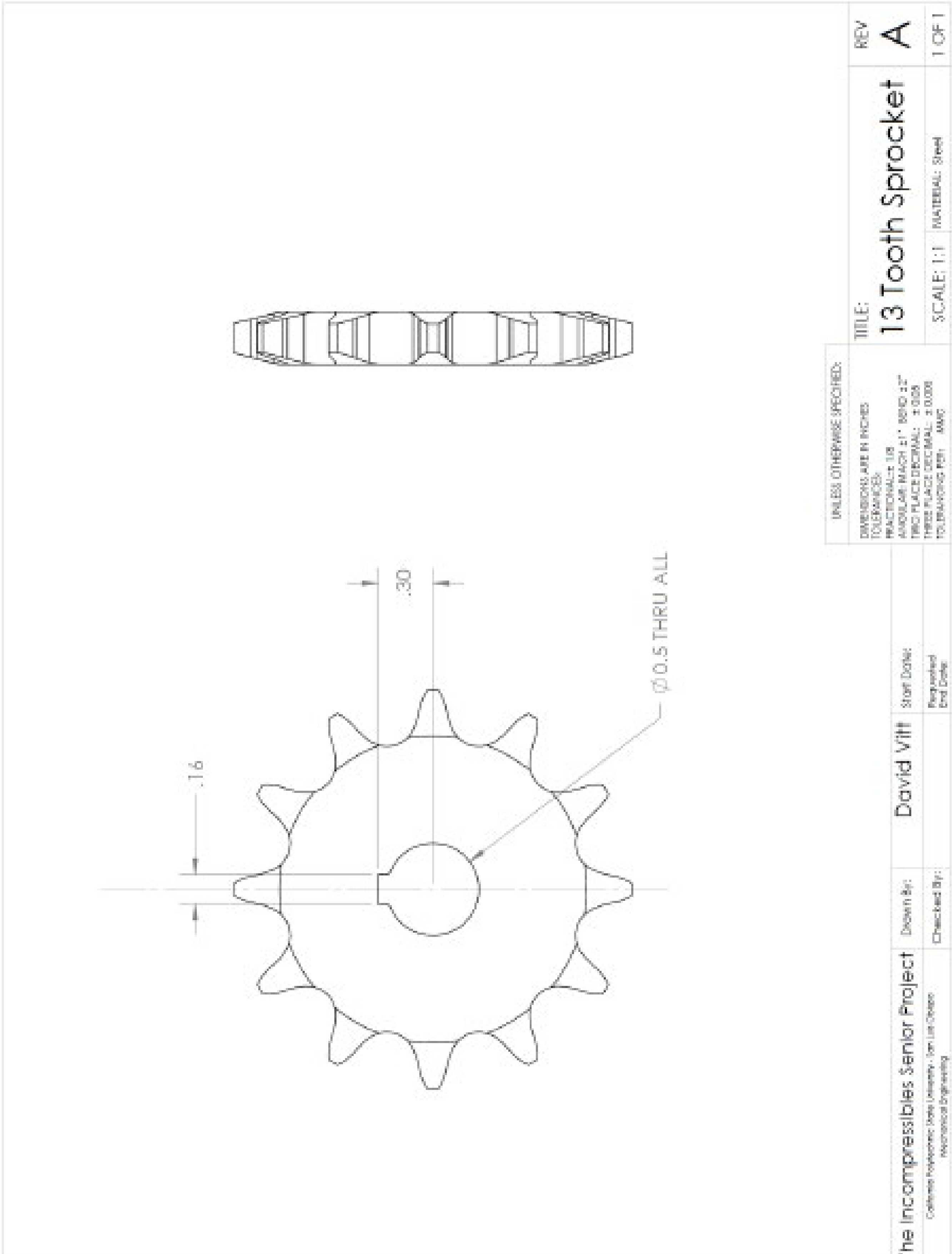


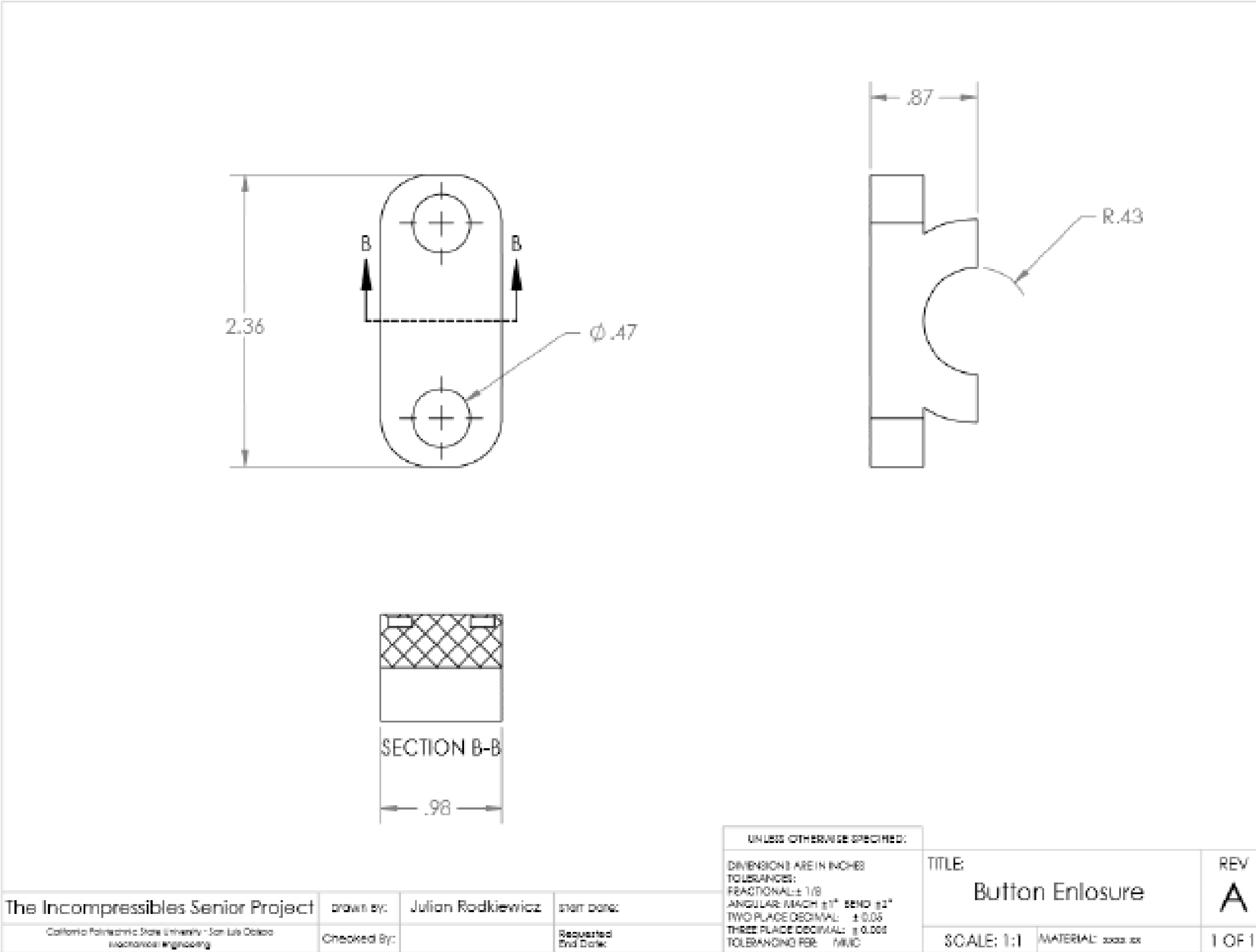
ITEM NO.	PART NUMBER	QTY.
1	Seat Tube	1
2	Head Tube	1
3	Bottom Bracket	1
4	Top Tube	1
5	Down Tube	1
6	Seatstay - Right Tube	1
7	Chainstay - Right Tube	1
8	Vertical Support Tube - Right	1
9	Upper Support Tube - Right	1
10	Rear Dropout - Right	1
11	Rear Dropout - Left	1
12	Vertical Support Tube - Left	1
13	Seatstay - Left Tube	1
14	Chainstay - Left Tube	1
15	Rear Brake Bridge	1
16	Chainstay Bridge	1
17	Upper Support Tube - Left	1

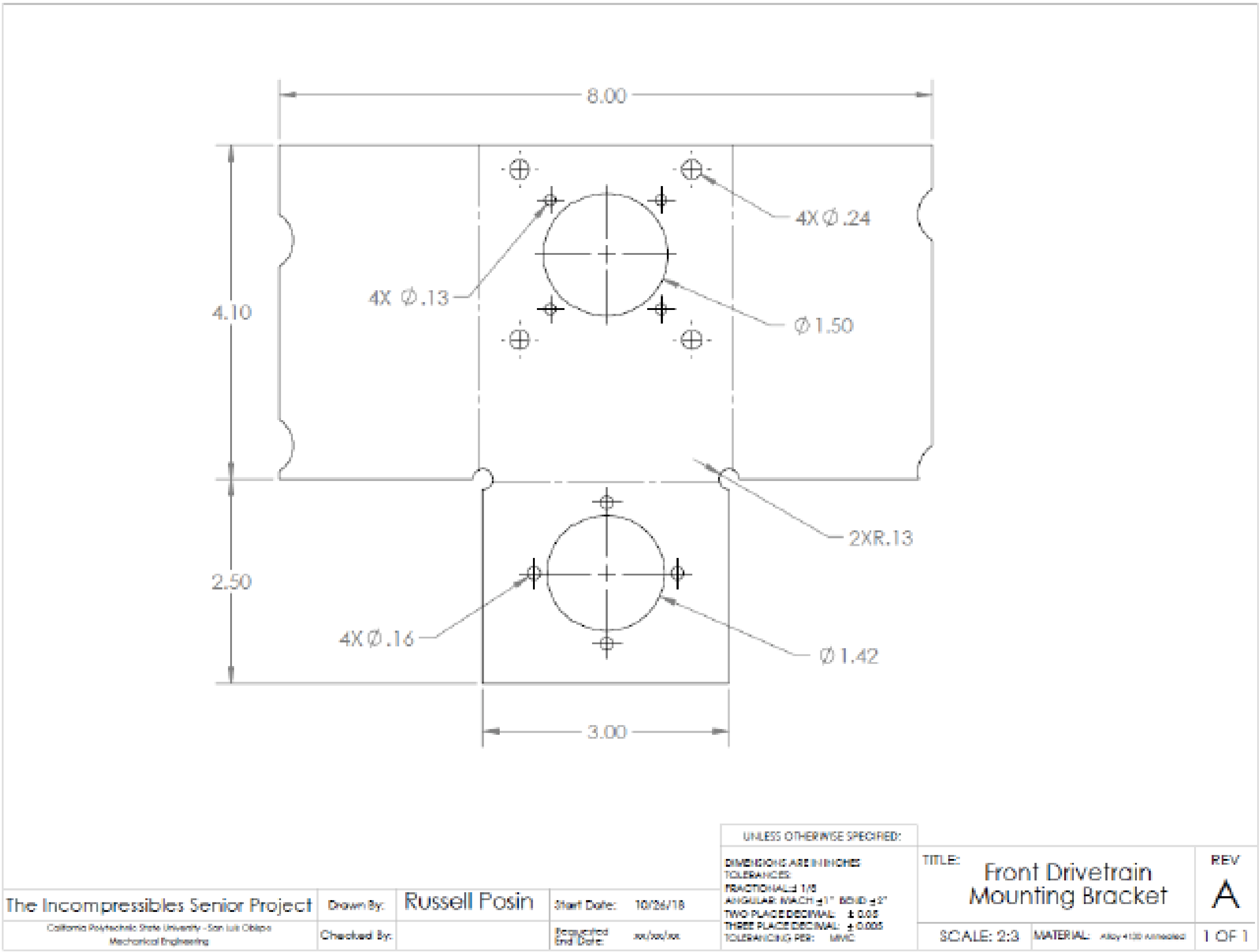


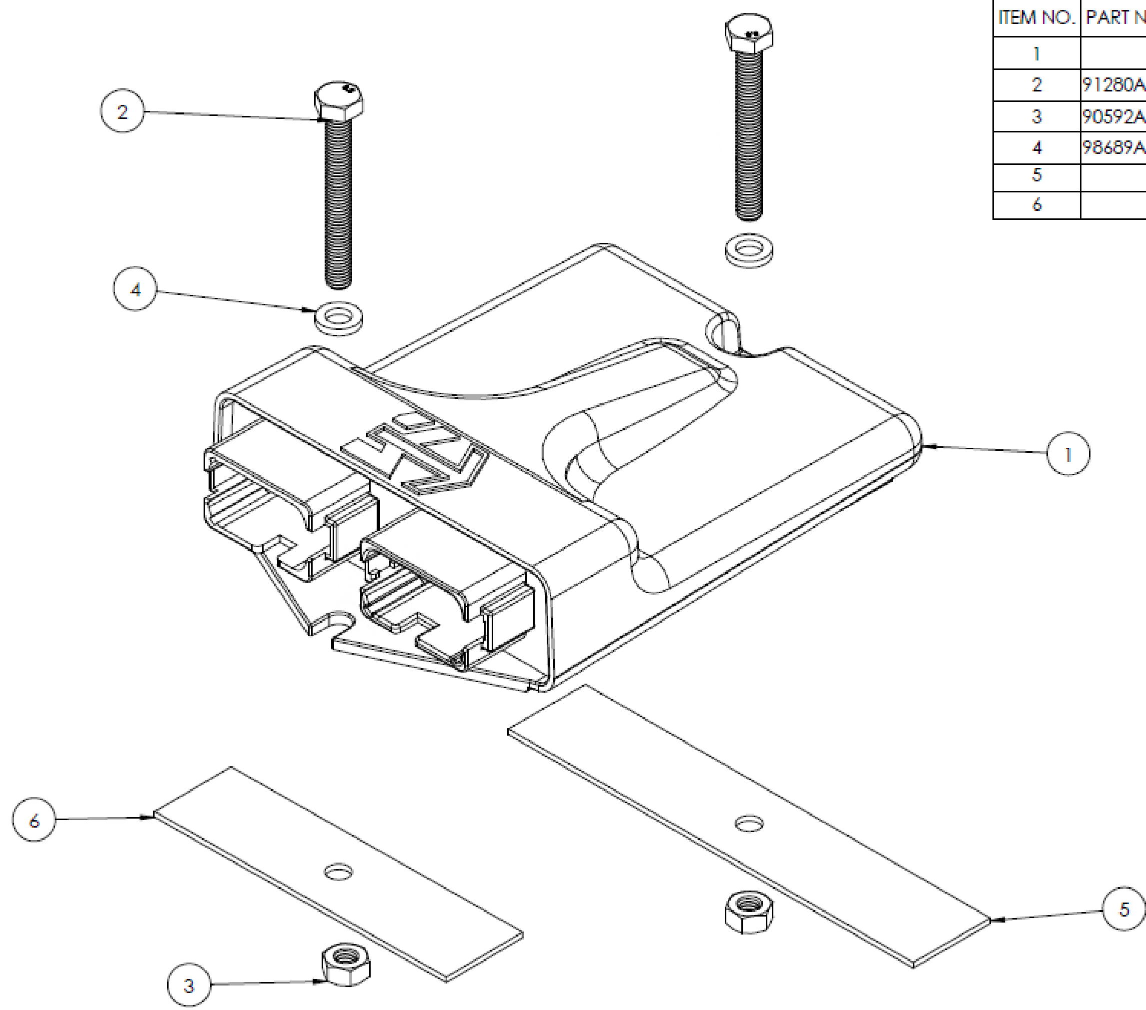
Part Name	P/N	Baloon #
Res. Bot. Panel	500-01	1
Res. Rear Panel	500-02	2
Res. Front Panel	500-03	3
Res. Right Panel	500-04	4
Res. Top Panel	500-05	5
Res. Angle Panel	500-06	6
1/4" 90Deg Push Fit.	500-07	7
1/4" NPT Weld Bung	500-08	8
Res. Left Panel	500-09	9
1/4" Barb Fit.	500-10	10
Weld Mount	500-11	11
1/4" Vent	500-12	12
Upper Mount	500-13	13

The Incompressibles Senior Project	Drawn By:	ALEX KNICKERBOCKER	Start Date:	10/26/18	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL: ± 1/8 ANGULAR: MACH ±1° BEND ±2° TWO PLACE DECIMAL: ± 0.05 THREE PLACE DECIMAL: ± 0.005 TOLERANCING PER: MMC	TITLE: 500 — REV A
California Polytechnic State University - San Luis Obispo Mechanical Engineering	Checked By:	JOHN FABIJANIC	Requested End Date:	10/27/18		SCALE: 1:3 — MATERIAL: 6061-t6 — 1 OF 1


.16
.30
Ø0.5 THRU ALL
UNLESS OTHERWISE SPECIFIED:
TITLE:
13 Tooth Sprocket
REV
A
SCALE: 1:1
MATERIAL: Steel
1 OF 1
The Incompressibles Senior Project
Drawn By:
David Vitt
Checked By:
Start Date:
Projected End Date:


.87
R.43
2.36
B
B
∅.47
SECTION B-B
.98
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 1/8
ANGULAR: MACH ±1° BEND ±2°
TWO PLACE DECIMAL ±0.05
THREE PLACE DECIMAL ±0.005
TOLERANCING PER: MMC
TITLE:
Button Enlosure
REV
A
SCALE: 1:1
1 OF 1
The Incompressibles Senior Project
California Polytechnic State University - San Luis Obispo
Mechanical Engineering
Drawn By:
Julian Rodkiewicz
Checked By:
Start Date:
Requested End Date:

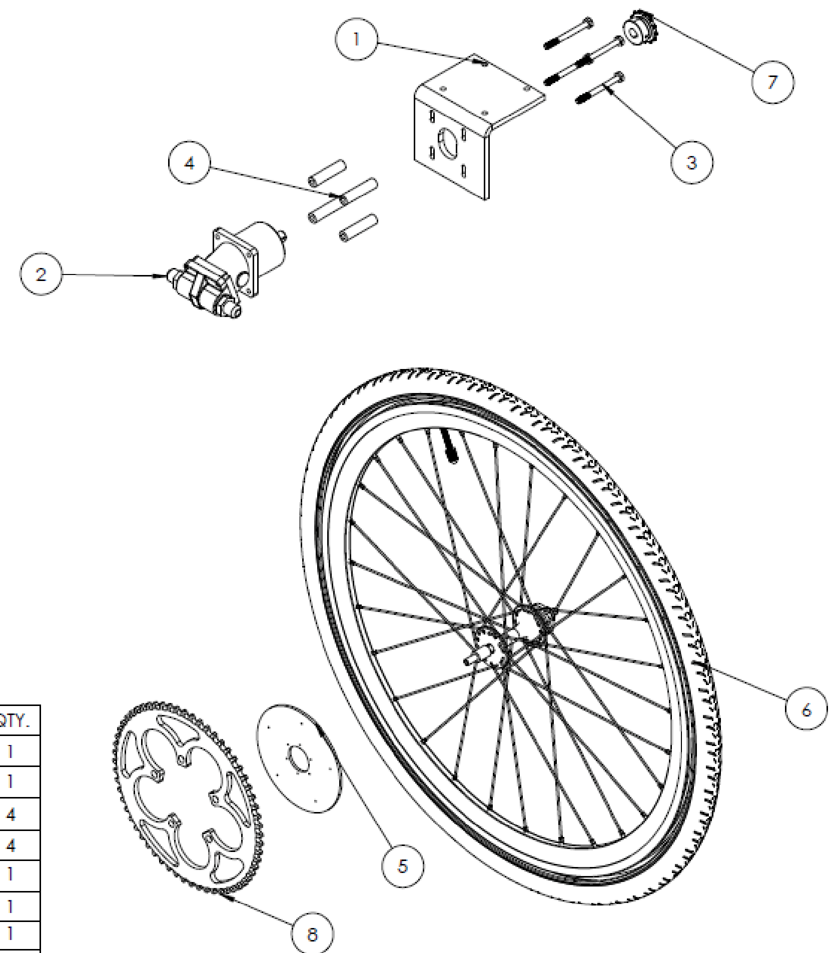

8.00
4X Ø.24
4X Ø.13
Ø1.50
4.10
2XR.13
2.50
4X Ø.16
Ø1.42
3.00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± 0.05
THREE PLACE DECIMAL ± 0.005
TITLE:
Front Drivetrain
Mounting Bracket
REV
A
The Incompressibles Senior Project
California Polytechnic State University - San Luis Obispo
Mechanical Engineering
Drawn By:
Russell Posin
Checked By:
Start Date:
10/26/18
SCALE: 2:3
MATERIAL:
1 OF 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1		ECDR	1
2	91280A346	M6 Bolt	2
3	90592A016	M6 Nut	2
4	98689A115	M6 Washer	2
5		Long Plate Mounting	1
6		Short Plate Mounting	1

UNLESS OTHERWISE SPECIFIED:
1. DIMENSIONS ARE IN INCHES
2. TOLERANCES:
X.XX = ±
X.XXX = ±
ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES 0.5 MAX
5. VOLUME =

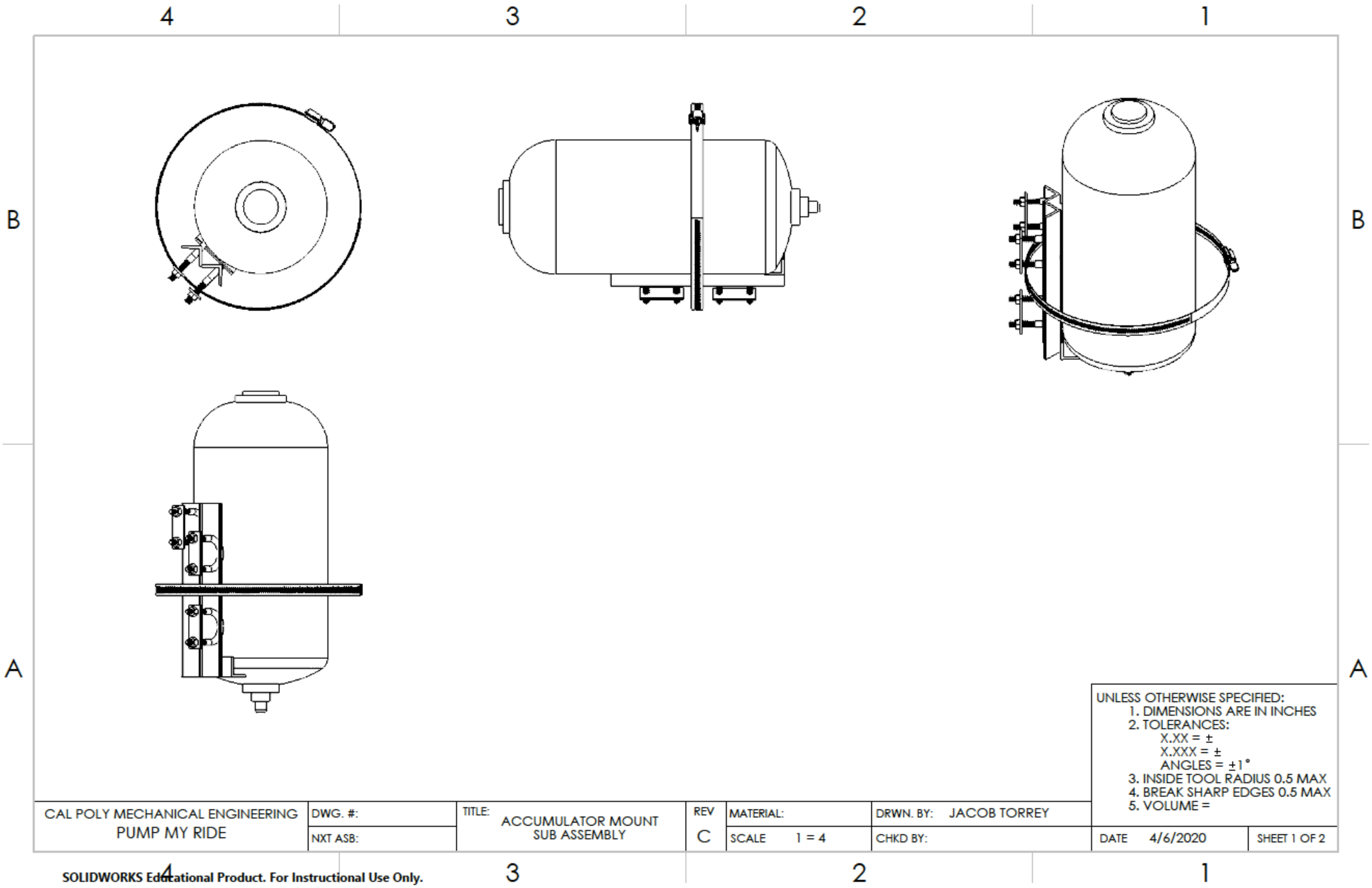
CAL POLY MECHANICAL ENGINEERING PUMP MY RIDE	DWG. #:	TITLE: ECDR ASSEMBLY	REV	MATERIAL:	DRWN. BY: KAYLA LONDONO		
	NXT ASB:			SCALE 1:2	CHKD BY:	DATE: 4/2/20	SHEET 1 OF 1



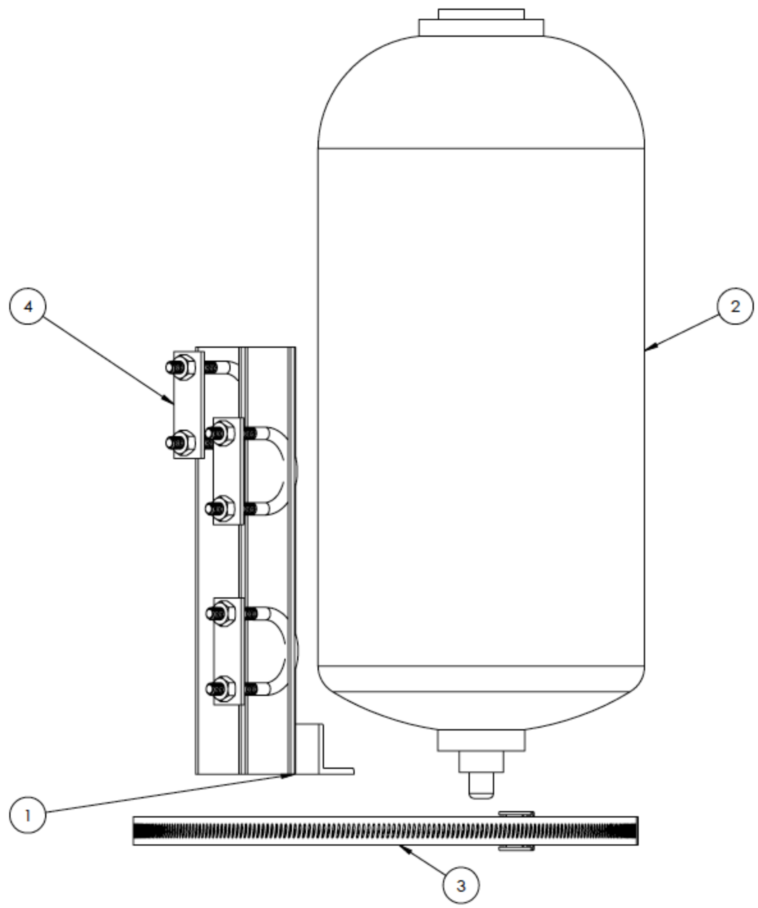
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	-	Motor Mount	1
2	-	Motor	1
3	91247A553	1/4"-20 Hex Head Screw	4
4	92511A085	StandOff	4
5	-	Hub Adapter	1
6	-	Rear Wheel	1
7	B06WRX7XF5	13T Sprocket	1
8	TA110EXT60S	60T Sprocket	1

UNLESS OTHERWISE SPECIFIED:
1. DIMENSIONS ARE IN INCHES
2. TOLERANCES:
X.XX = ±
X.XXX = ±
ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES 0.5 MAX
5. VOLUME =

CAL POLY MECHANICAL ENGINEERING PUMP MY RIDE	DWG. #:	TITLE: REAR DRIVE TRAIN	REV	MATERIAL:	DRWN. BY: KAYLA LONDONO	
	NXT ASB:			SCALE 1:5	CHKD BY:	DATE: 4/ 7/ 20 — SHEET 1 OF 1



4 3 2 1
B
A
UNLESS OTHERWISE SPECIFIED:
1. DIMENSIONS ARE IN INCHES
2. TOLERANCES:
X.XX = ±
X.XXX = ±
ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES 0.5 MAX
5. VOLUME =
CAL POLY MECHANICAL ENGINEERING
PUMP MY RIDE
DWG. #:
NXT ASB:
TITLE:
ACCUMULATOR MOUNT
SUB ASSEMBLY
REV
C
MATERIAL:
SCALE 1 = 4
DRWN. BY: JACOB TORREY
CHKD BY:
DATE 4/6/2020
SHEET 1 OF 2
SOLIDWORKS Educational Product. For Instructional Use Only.

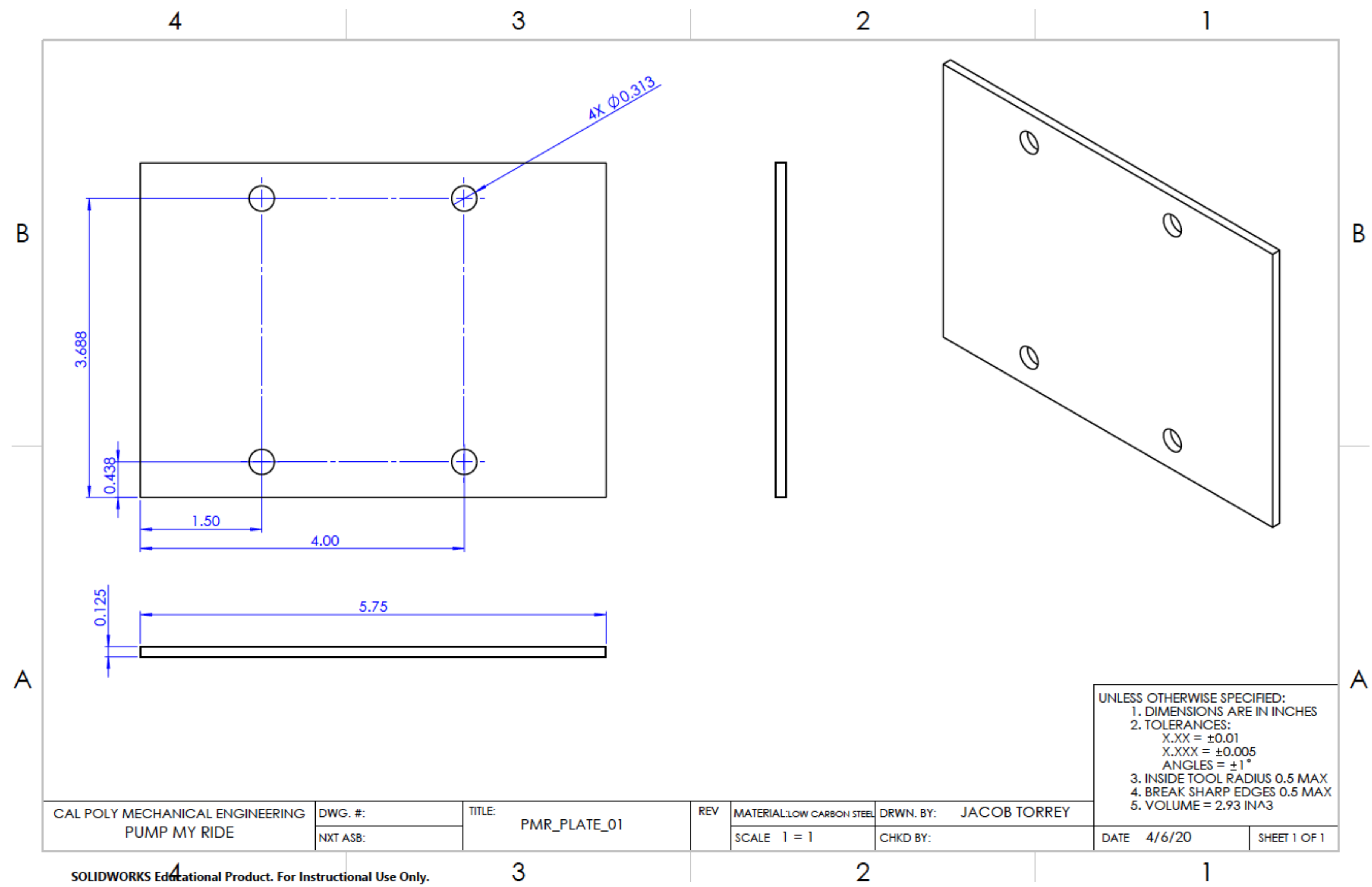


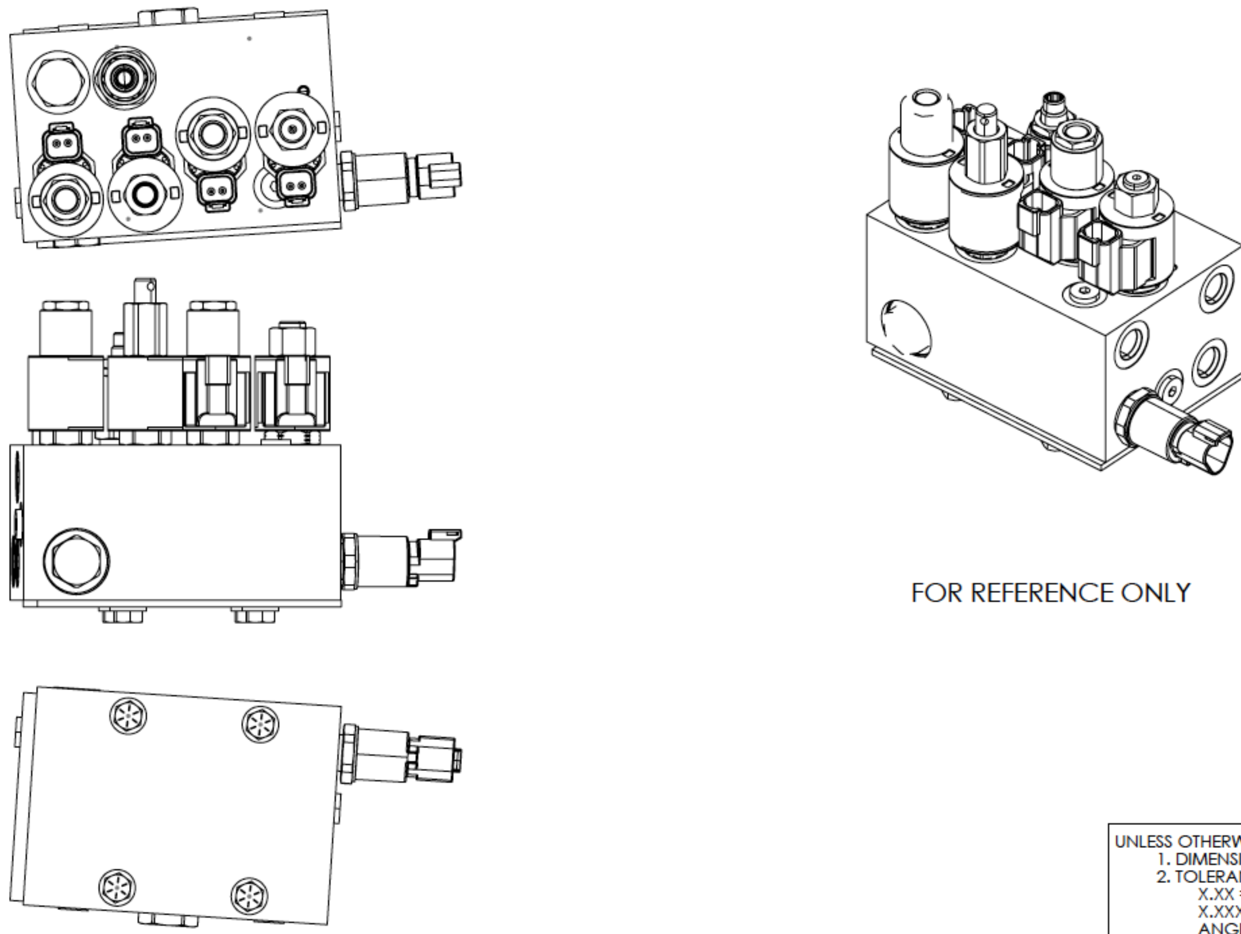
FOR REFERENCE ONLY

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	9017K444	Low-Carbon Steel 90 Degree Angle 1/8" Wall Thickness, 1" x 1" Outside Size	2
2	AB30CN010G0N	4L Composite Bladder Accumulator @ 3000psi	1
3	5362K868	Worm-Drive Clamps with Thumb Screw for Firm Hose and Tube, 7-1/8" to 10" Clamp ID Range	1
4	3043T645	U-Bolt with Mount Plate, Zinc-Plated Steel, 1/4"-20 Thread Size, 1-1/4" ID	3

UNLESS OTHERWISE SPECIFIED:
1. DIMENSIONS ARE IN INCHES
2. TOLERANCES:
X.XX = ±
X.XXX = ±
ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES 0.5 MAX
5. VOLUME =

CAL POLY MECHANICAL ENGINEERING PUMP MY RIDE	DWG. #:	TITLE: ACCUMULATOR MOUNT SUB ASSEMBLY	REV	MATERIAL:	DRWN. BY: JACOB TORREY	
	NXT ASB:		C	SCALE 1 = 2	CHKD BY:	DATE 4/6/20 — SHEET 2 OF 2


4 3 2 1
B
A
4X Ø0.313
3.688
0.438
1.50
4.00
0.125
5.75
UNLESS OTHERWISE SPECIFIED:
1. DIMENSIONS ARE IN INCHES
2. TOLERANCES:
X.XX = ±0.01
X.XXX = ±0.005
ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES 0.5 MAX
5. VOLUME = 2.93 IN^3
CAL POLY MECHANICAL ENGINEERING
PUMP MY RIDE
DWG. #:
NXT ASB:
TITLE:
PMR_PLATE_01
REV
MATERIAL:LOW CARBON STEEL
SCALE 1 = 1
DRWN. BY: JACOB TORREY
CHKD BY:
DATE 4/6/20
SHEET 1 OF 1
SOLIDWORKS Educational Product. For Instructional Use Only.



FOR REFERENCE ONLY

UNLESS OTHERWISE SPECIFIED:
1. DIMENSIONS ARE IN INCHES
2. TOLERANCES:
X.XX = ±
X.XXX = ±
ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.5 MAX
4. BREAK SHARP EDGES 0.5 MAX
5. VOLUME =

CAL POLY MECHANICAL ENGINEERING PUMP MY RIDE	DWG. #:	TITLE: MANIFOLD SUB ASSEMBLY	REV	MATERIAL:	DRWN. BY: JACOB TORREY		
	NXT ASB:		B	SCALE 1 = 2	CHKD BY:	DATE 4/2/20	SHEET 1 OF 2

Appendix K: MATLAB Scripts and Simscape Output Comparison to DV Testing

Fluid Power Vehicle Challenge- Cal Poly, San Luis Obispo Team

Usage and Description

*Original Version

The Incompressibles Senior Project 2018 - Simscape Model Script

Author Nicholas Gholdoian & Kyle Franck

Date Created 5/12/2018

*Modified Version

Pump My Ride Senior Project 2019 - Endurance Model Script

By Kayla Londono

Date 3/31/2020

This script defines the variables inside the Endurance and Accumulator Recharge Simscape models. Inspiration and details taken from Winston Wights' previous bike model.

Initializing Workspace

Clear the workspace and windows of any figures or misc. variables.

```
close all
clc
clear all
```

Define Universal Parameters

```
gravity = 32.2; % [ft/s^2] Gravity constant
air_density = 2.29E-3; % [slug/ft^3] Density of air at 70F
```

Declare Fluid Properties

Script below inputs the fluid properties into the Simscape model. The current fluid used is Mobil EAL 224H.

```
% [Inputs]
fluid_density = 1.787; % [slug/ft^3] Fluid density
fluid_kine_viscosity = 4.28E-4; % [ft^2/s] Fluid kinematic viscosity
fluid_bulk_modulus = 2.2E5; % [lb/in^2] Fluid bulk modulus
```

Declare Tubing Parameters

Script below inputs tubing data for a circular cross section

```
% [Inputs]
tube_internal_dia = 0.37; % [in] Internal tube diameter
tube_length = 120; % [in] Total tube length
tube_resistance_length = 0; % [in] Total aggregate equivalent length of local resistances
tube_surface_rough = 5E-6; % [ft] Internal tube surface roughness for drawn tubing

% [Calculations]
tube_area = pi*(tube_internal_dia/2)^2; % [in^2] Tube cross sectional area
```

Road Parameters

Script below defines the road parameters

```
% [Inputs]
wind_speed = 0; % [] Wind speed, positive is headwind
road_slope = 0; % [] Road slope, positive is incline
```

Declare Bike Parameters

Script below declares the global bike parameters.

```
% [Weight Inputs]
bike_weight = 103; % [lbf] Bike weight excluding driver, fluid, and accumulator weight
driver_weight = 160; % [lbf] Driver weight
fluid_weight = 1; % [lbf] Total fluid weight excluding accumulator fluid weight
front_wheel_weight = 1.7; % [lbf] Weight of front wheel
rear_wheel_weight = 1.7; % [lbf] Weight of rear wheel

% [Weight Distribution Inputs]
CG_front_distance = 28.5; % [in] Horizontal distance from CG to front axle
CG_rear_distance = 16.5; % [in] Horizontal distance from CG to rear axle
CG_height = 33; % [in] Vertical distance of CG above ground

% [Bike Parameter Inputs]
```

```
number_of_wheels = 1; % [-] Number of wheels on each axle
front_tire_dia = 686; % [mm] Front wheel diameter
rear_tire_dia = 686; % [mm] Rear wheel diameter
front_gear_ratio = 1/10.3; % [-] Front sprocket gear ratio (input/output)
rear_gear_ratio = 4.6; % [-] Rear gear ratio (pump input/wheel output)
rolling_resistance_coef = 0.004; % [-] Rolling resistance coefficient
frontal_area = 528.3; % [in^2] Frontal area of bike for aero
drag_coeff = 0.88; % [-] Drag coefficient for bike
crank_length = 6.5; % [in] Front crank arm length for pedal

% [Mass & Weight Distro. Calculations]
driver_mass = driver_weight/gravity; % [slug] Driver mass
bike_mass = bike_weight/gravity; % [slug] Bike mass excluding driver and fluid
fluid_mass = fluid_weight/gravity; % [slug] Fluid mass excluding accumulator fluid mass
front_wheel_mass = front_wheel_weight/gravity; % [slug] Mass of front wheel
rear_wheel_mass = rear_wheel_weight/gravity; % [slug] Mass of rear wheel
rear_wheel_inertia = rear_wheel_mass*((rear_tire_dia/2)^2); % [slug*mm^2] Moment of inertia of
wheel (thin hoop, mr^2)
```

Declare Accumulator Parameters (Single Run Mode)

The below script declares the accumulator parameters from the Hydac SB330 data sheet (http://www.hydac-na.com/sites/hydac-na/SiteCollectionDocuments/Accumulators.pdf) Accumulator Inputs accu_volume_range = [0.29, 0.98, 1.47, 2.45, 4.87, 9.00, 10.04, 13.87]; % [gal] Table of Hydac SB 330 bladder accumulator volumes accu_housing_weight = [10, 30, 33, 86, 140, 226, 270, 330]; % [lbf] Table of Hydac SB 330 bladder accumulator housing weights (excluding fluid weight)

```
% [Inputs]
accu_volume = 0.98; % [gal] Total accumulator volume
precharge_press = 500; % [psi] Accumulator nitrogen precharge pressure
accu_max_press = 3000; % [psi] Acumulator max allowable pressure
accu_housing_weight = 10.8; % [lbf] Weight of accumulator housing without fluid
accu_exit_dia = 0.75; % [in] Diameter of accumulator exit orifice
specific_heat_ratio = 1.47; % [-] Specific heat ratio of nitrogen in an adiabatic process

% [Accumulator Calculations]
accu_exit_area = pi*(accu_exit_dia/2)^2; % [in^2] Accumulator exit orifice cross sectional area
accu_housing_mass = accu_housing_weight/gravity; % [slug] Mass of accumulator housing without
fluid
accu_vol_fluid_storage = accu_volume*(1-
((precharge_press/accu_max_press)^(1/specific_heat_ratio))); % [gal] Initial fluid volume inside
accumulato before discharge
accu_fluid_mass = fluid_density*accu_vol_fluid_storage/7.48; % [slug] Mass of fluid inside
accumulator before discharge
```

Total Bike Mass Calculation

```
total_bike_mass = bike_mass + driver_mass + fluid_mass + accu_fluid_mass + accu_housing_mass +
rear_wheel_mass + front_wheel_mass; % [slug] Total bike mass including fluid mass and rider mass
```

Ride Power Definition

```
rider_power = 200; % [watts] Rider constant power input
```

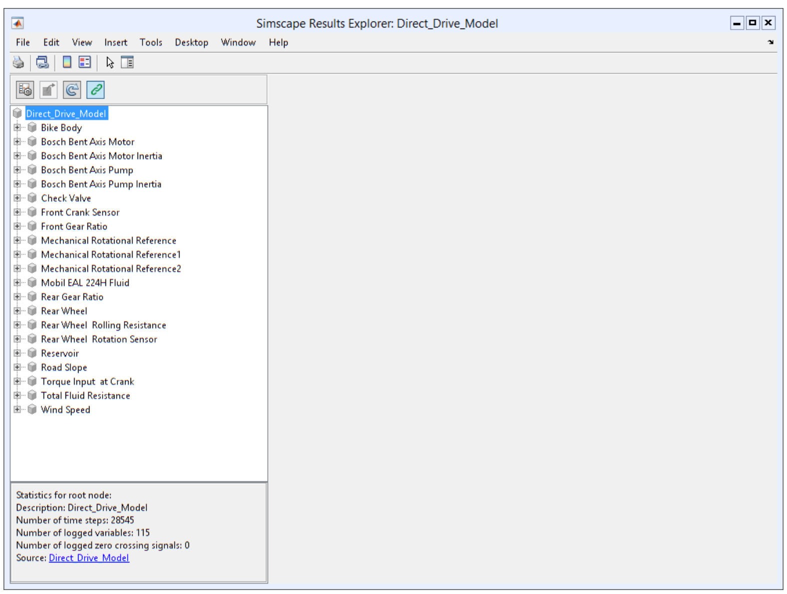
Model Runtime Definition

```
model_runtime = 350; % [sec] Model total runtime
```

Model Selection

```
model_sel = 2;
% Defined as:
% [1] for accumulator recharge model
% [2] for direct drive/ endurance model

if model_sel == 1
   sim('Accumulator_Discharge_ModelLP.slx')
elseif model_sel == 2
   sim('Direct_Drive_Model.slx')
else
   error('Invalid model or no model selected')
end
```



Published with MATLAB® R2019a

Fluid Power Vehicle Challenge- Cal Poly, San Luis Obispo Team

Usage and Description

Pump My Ride Vehicle Simulation for Efficiency & Sprint Simscape Models

Author Kayla Londono

Date

This script defines variables for the vehicle parameters and environmental conditions for the efficiency challenge, sprint challenge and recharge time. Inspiration and details taken from Nicholas Gholdoian & Kyle Franck previous bike model.

Workspace Initialization

Clear the workspace and windows of any figures or misc. variables.

```
close all
clear all
clc
```

Environmental Parameters

```
gravity = 32.2; % [ft/s^2] Gravity constant
air_density = 2.29E-3; % [slug/ft^3] Density of air at 70F
wind_speed = 0; % Wind speed, positive is headwind
road_slope = 0; % Road slope, positive is incline
```

Hydraulic Fluid Properties

Script below inputs the fluid properties into the Simscape model. The current fluid used is Mobil EAL 224H.

```
fluid_density = 1.787; % [slug/ft^3] Fluid density
fluid_kine_viscosity = 4.28E-4; % [ft^2/s] Fluid kinematic viscosity
fluid_bulk_modulus = 2.2E5; % [lb/in^2] Fluid bulk modulus
```

Accumulator Properties

```
accum_vol = 0.98; % [gal] Total accumulator volume
min_gas_vol= 0.1; % convert m^3 to gal
precharge_press = 200; % [psi] Accumulator nitrogen precharge pressure
specific_heat_ratio= 1.47; % [-] Specific heat ratio of nitrogen in an adiabatic process
hard_stop_stiff_coeff= 1E30; %[Pa/m^3]
hard_stop_damping_coeff= 1E30; %[s*Pa/m^6]
accum_press = 2800; % [psi] Acumulator max allowable pressure
```

```
accu_housing_weight = 10.8; % [lbf] Weight of accumulator housing without fluid
accu_exit_dia = 0.75; % [in] Diameter of accumulator exit orifice

% [Accumulator Calculations]
accu_exit_area = pi*(accu_exit_dia/2)^2; % [in^2] Accumulator exit orifice cross sectional area
accu_housing_mass = accu_housing_weight/gravity; % [slug] Mass of accumulator housing without
fluid
accu_vol_fluid_storage = accum_vol*(1-((precharge_press/accum_press)^(1/specific_heat_ratio))); %
[gal] Initial fluid volume inside accumulato before discharge
accu_fluid_mass = fluid_density*accu_vol_fluid_storage/7.48; % [slug] Mass of fluid inside
accumulator before discharge
```

Tubing Parameters

Script below inputs tubing data for a circular cross section

```
tube_internal_dia = 0.37; % [in] Internal tube diameter
tube_length = 120; % [in] Total tube length
seg_num= 6;
tube_resistance_length = 0; % [in] Total aggregate equivalent length of local resistances
tube_surface_rough = 5E-6; % [ft] Internal tube surface roughness for drawn tubing
```

Vehicle Parameters

```
bike_weight =103; % [lbf] Bike weight excluding driver, fluid, and accumulator weight
driver_weight = 160; % [lbf] Driver weight
fluid_weight = 1; % [lbf] Total fluid weight excluding accumulator fluid weight
front_wheel_weight = 1.7; % [lbf] Weight of front wheel
wheel_weight = 1.7; % [lbf] Weight of rear wheel

CG_front_distance = 28.5; % [in] Horizontal distance from CG to front axle
CG_rear_distance = 16.5; % [in] Horizontal distance from CG to rear axle
CG_height = 33; % [in] Vertical distance of CG above ground

tire_dia = 686; % [mm] Rear wheel diameter % [in] Rear wheel diameter
gear_ratio = 4.6; % [-] Rear gear ratio (pump input/wheel output)
rolling_resistance_coef = 0.004; % [-] Rolling resistance coefficient
frontal_area = 528.3; % [in^2] Frontal area of bike for aero
drag_coeff = 0.88; % [-] Drag coefficient for bike
crank_length = 7.0; % [in] Front crank arm length for pedal

driver_mass = driver_weight/gravity; % [slug] Driver mass
bike_mass = bike_weight/gravity; % [slug] Bike mass excluding driver and fluid
fluid_mass = fluid_weight/gravity; % [slug] Fluid mass excluding accumulator
wheel_mass = wheel_weight/gravity; % [slug] Mass of rear wheel
tire_inertia = wheel_mass*((tire_dia/2)^2); % [slug*mm^2] Moment of inertia of wheel (thin hoop,
mr^2)
vehicle_mass = bike_mass + driver_mass;
res_vol = 5; %[gal]
```

Model Run

```
sim('Sprint2019.slx')
```

Published with MATLAB® R2019a

Table K.1: Accumulator Discharge Model Compared with Sprint Test Results

Friday, March 6, 2020						
Course Distance: 600 ft.						
No.	**Pre-charge (psi)**	**Charge (psi)**	**Rider**	**Average (s)**	**Model**	**% error**
1	500	2840	Jacob	25.17	22.657	11.1
2	400	2800	Jacob	24.29	23.85	1.8
3	300	2800	Jacob	25.37	24.26	4.6
4	200	2825	Jacob	27.92	25.9	7.8
5	200	2800	Kayla	25.79	24.2	6.6
6*	125	2900	Jacob	31.95	27.78	15.0
*Thursday, March 5, 2020.						

Table K.2: Accumulator Discharge Model Compared with Efficiency Test Results

Friday, March 6, 2020									
No.	**Pre-charge (psi)**	**Charge (psi)**	**Rider**	**Distance (ft)**	**Model Distance**	**% error Distance**	**Efficiency Score (%)**	**Model Score**	**% error Score**
1	500	2840	Jacob	1192	3277	64	8.12	21.66	63
2	400	2800	Jacob	1345	3094	57	9.35	20.86	55
3	300	2800	Jacob	1261	1916	34	8.99	13.24	32
4	200	2825	Jacob	1152	1678	31	8.46	11.96	29
5	200	2800	Kayla	1232	-	-	7.36	-	-
6*	125	2900	Jacob	878	-	-	6.63	-	-

Appendix L: ECDR Specifications

Technical Data

Processor	ARM 32-bit Cortex™-M4 CPU, 72 MHz
Memory	Flash memory: total 128 kB. RAM memory: 32 kB
Power	Nominal supply voltage 12/24 Vdc systems (9 to 32 Vdc)
Diagnostics	Diagnostic LED (green/red)
Protection functions	Overvoltage protection, short-circuit protection for outputs
Interface software	HF-Impulse
Software installation	Download via SAE J1939 CAN.
Ingress protection rating	IP69K
Size	5.78 x 4.43 inches
Weight	366 g (0.8 lb)
Housing material	Noryl™ glass-filled PPE/PPO
Operating temperature	-40 to 85 °C (-40 to 185 °F)
Storage temperature	-40 to 85 °C (-40 to 185 °F)
Connectors	DT06-12SA, DT06-12SB
Communications / Interfaces	1 x CAN
Outputs	(4) Closed-loop current sourcing, 2 A continuous, PWM 40 to 400 Hz (1) Open -loop current sourcing, 2 A continuous, PWM 40 to 400 Hz
Inputs	**Multifunction input (4)** Voltage: 0 to 5 or 0 to 10 Vdc Current: 0 to 20 or 4 to 20 mA Resistive: 0 to 6 k ohms Temperature: ERT120 (HydraForce temperature sensor) Digital: switch to ground, switch to supply, floating **Multifunction input (2)** Digital: switch to ground, switch to supply PWM: 0 to 100%, 60 to 5000 Hz Frequency: 60 to 10 000 Hz, 4 to 2000 Hz, 4 to 10 000 Hz

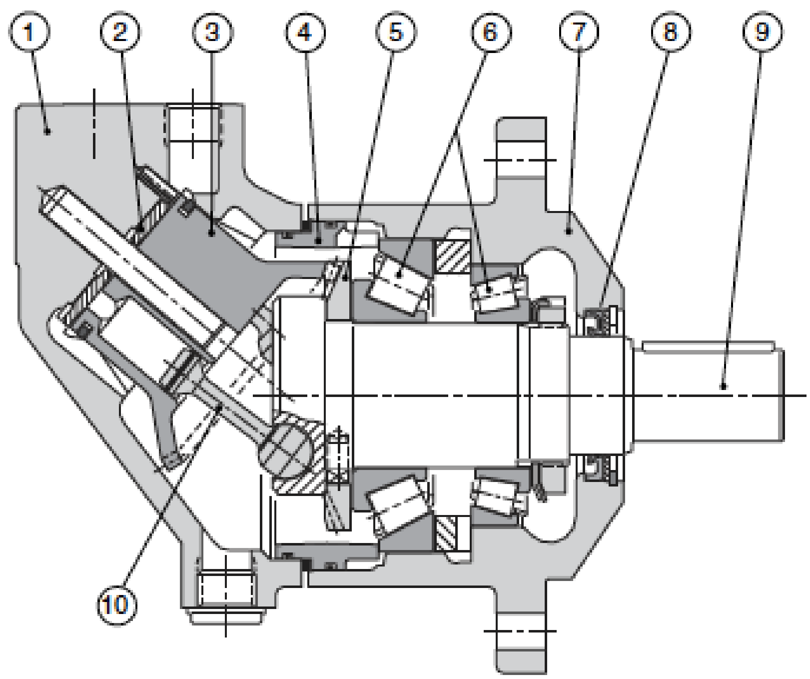
Appendix M: Motor Specifications

F11 and F12 are bent axis, fixed displacement heavy-duty motor/pump series. They can be used in numerous applications in both open and closed loop circuits.

- Series F11 is available in the following frame sizes and versions:
  - F11-5, -10, -14, 19 and -150 with CETOP mounting flange and shaft end
  - F11-14 with ISO flange and shaft
  - F11-14, -19, -150 and -250 with SAE flange and shaft
- Series F12 conforms to current ISO and SAE mounting flange and shaft end configurations. A very compact cartridge version is also available.
- Thanks to the unique spherical piston design, F11/F12 motors can be used at unusually high shaft speeds. Operating pressures to 480 bar provides for the high output power capability.
- The 40° angle between shaft and cylinder barrel allows for a very compact, lightweight motor/pump.
- The laminated piston ring offers important advantages such as low internal leakage and thermal shock resistance.
- The pump version has highly engineered valve plates for increased selfpriming speed and low noise, available with left and right hand rotation.
- The F11/F12 motors produce very high torque at start-up as well as at low speeds.
- Our unique timing gear design synchronizes shaft and cylinder barrel, making the F11/F12 very tolerant to high 'G' forces and torsional vibrations.
- Heavy duty roller bearings permit substantial external axial and radial shaft loads.
- The F11's and F12's have a simple and straight-forward design with very few moving parts, making them very reliable motors/pumps.
- The unique piston locking, timing gear and bearing set-up as well as the limited number of parts add up to a very robust design with long service life and, above all, proven reliability.

F11 cross section

1. Barrel housing
2. Valve plate
3. Cylinder barrel
4. Guide spacer with O-rings
5. Timing gear
6. Roller bearing
7. Bearing housing
8. Shaft seal
9. Output/input shaft
10. Piston with laminated piston ring



Frame size	F11-5	-10	-14	-19	F12-30	-40	-60	-80	-110	F11-150	-250
Displacement [cm³/rev]	4.9	9.8	14.3	19.0	30.0	40.0	59.8	80.4	110.1	150	242
[cu in/rev]	*0.30*	*0.60*	*0.87*	*1.16*	*1.83*	*2.44*	*3.65*	*4.91*	*6.72*	*9.15*	*14.8*
Operating pressure											
max intermittent[1] [bar]	420	———	———	420	480	———	———	———	480	420	420
[psi]	*6 000*	———	———	*6 000*	*7 000*	———	———	———	*7 000*	*6 000*	*6 000*
max continuous [bar]	350	———	———	350	420	———	———	———	420	350	350
[psi]	*5 000*	———	———	*5 000*	*6000*	———	———	———	*6000*	*5 000*	*5 000*
Motor operating speed [rpm]											
max intermittent[1]	12 000	11 000	10 000	9 000	7 100	6 400	5 600	5 200	4 700	3 000	2 700
max continuous	10 800	9 900	9 000	8 100	5 600	5 000	4 300	4 000	3 600	2 600	2 400
min continuous	50	———	———	———	———	———	———	———	———	———	50
Max pump selfpriming speed[2]											
L or R function; max [rpm]	4 600	4 200	3 900	3 500	3150	2870	2500	2300	2290	1 700	1 500
Motor input flow											
max intermittent[1] [l/min]	58	108	143	171	213	256	335	418	517	450	650
[gpm]	*15.3*	*28.5*	*37.8*	*45.2*	*56.3*	*67.6*	*88.5*	*110.4*	*136.6*	*119.0*	*172.8*
max continuous [l/min]	52	97	128	153	168	200	257	322	396	390	580
[gpm]	*13.7*	*25.6*	*33.8*	*40.4*	*44.4*	*52.8*	*67.9*	*85.1*	*104.6*	*103.0*	*153.6*
Main circuit temp.[3], max [°C]	80	———	———	———	———	———	———	———	———	———	80
[°F]	*175*	———	———	———	———	———	———	———	———	———	*175*
min [°C]	-35	-35	-30	-35	-35	———	———	———	-35	-35	-35
[°F]	*-31*	*-31*	*-22*	*-31*	*-31*	———	———	———	*-31*	*-31*	*-31*
Mass moment of inertia											
($x10^{-3}$) [kg m²]	0.16	0.39	0.42	1.1	1.7	2.9	5	8.4	11.2	40	46
($x10^{-2}$) *[lbft²]*	*0.38*	*0.92*	*1.00*	*2.61*	*4.03*	*6.88*	*11.86*	*19.93*	*26.58*	*94.92*	*109.16*
Weight [kg]	5	7.5	8.3	11	12	16.5	21	26	36	70	77
[lb]	*11*	*16.5*	*18.8*	*24*	*26*	*36*	*46*	*57*	*79*	*154*	*170*

1) Intermittent: max 6 seconds in any one minute.
2) Selfpriming speed valid at sea level.
3) See also Installation information, operating temperature.

Basic formulas for hydraulic motors

Flow (q)

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

Torque (M)

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

Power (P)

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

D - displacement [cm³/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 ($\eta_t = \eta_v \times \eta_{hm}$)

Bill of Materials (BOM) - Frame

Pump My Ride

Total Sub-System:

$340.89

Item #	Description	Manufacturer PN	Manufacuter	Link	Qty.	Cost.	Price Extended
1	Head Tube	NOV_COHT_46.4_220	Nova	https://www.cycle-f	2	$10.25	$20.50
2	Top Tube	NOV_COTT_858	Nova	https://www.cycle-f	2	$16.50	$33.00
3	Down Tube	NOV_CODT_38_969	Nova	https://www.cycle-f	2	$18.45	$36.90
4	Seat Tube	NOV_COST_33.5_560	Nova	https://www.cycle-f	2	$18.80	$37.60
5	Bottom Bracket Tube	NOV_LLBB_SL_73M	Nova	https://www.cycle-f	2	$6.00	$12.00
6	Chain Stay Tube	6' of 0.75" X 0.065" 4130 Tube	Online Metals	https://www.onliner	2	$24.18	$48.36
7	Seat Stay Tube						
8	Support Tube	6' 0.625" X 0.065" 4130 Tube	Online Metals	https://www.onliner	4	$31.43	$125.72
9	Upper Support Tube						
10	Tube Bridges	1' 0.5" X 0.065 4130 Tube	Online Metals	https://www.onliner	1	$9.26	$9.26
11	Rear Dropouts	2' of 0.25" x 3" 1018 Sheet	Online Metals	https://www.onliner	1	$14.93	$14.93
12	Cantilever Brake Studs	8mm Brake Stud	Nova	https://www.cycle-f	2	$1.31	$2.62
13	Order Error	1' of 0.75" X 0.065" 4130 Tube	Online Metals	https://www.onliner	2		$0.00
14	Order Error	1' 0.625" X 0.065" 4130 Tube	Online Metals	https://www.onliner	4		$0.00
15	Order Error	1' of 0.25" x 3" 1018 Sheet	Online Metals	https://www.onliner	1		$0.00

Bill of Materials (BOM) - Front Drivetrain
The Incompressibles

Total Sub-System: $1,031.00

Item #	Description	Source PN	Source	Qty.	Cost.	Price Extended	Link
1	Chain	CN-HG93	Amazon.com	1	$18.40	$18.40	https://www.an
2	Sprocket	2299K21	McMaster	1	$22.74	$22.74	https://www.m
3	Planetary Gearbox	KF060-004-S2	Apex Dynamics	1	$700.00	$700.00	https://www.ne
4	Standoff	92510A459	McMaster	4	$6.39	$25.56	https://www.m
5	Stock for Mount	9663	Online Metal	1	$15.91	$15.91	https://www.or
6	Shimano Alivio Side Swing 9-speed front derailleur	FD-M4020-M-B	Amazon.com	1	$28.99	$28.99	
7	Chain Tensioner	CHA2281k	ebay.com	1	$16.99	$16.99	
8	Hex Head Screw Package	91247A555	Mcmaster	1	$6.49	$6.49	https://www.m
9	Hex Head Nut Package	95462A029	Mcmaster	1	$4.40	$4.40	https://www.m
10	White Plastic 5" x 20" Shim Sheet, 0.025" Thick	9513K24	Mcmaster	1	$4.90	$4.90	
11	Aluminum Unthreaded Spacer, 8 mm OD, 20 mm Long, for M5 Screw Size	94669A063	Mcmaster	4	$2.02	$8.08	
12	Aluminum Male-Female Threaded Hex Standoff, 10mm Hex, 45mm Long, M5 x 0.80 mm Thread	98952A429	Mcmaster	4	$3.62	$14.48	
13	Aluminum Male-Female Threaded Hex Standoff, 10mm Hex, 51mm Long, M5 x 0.80 mm Thread	98952A430	Mcmaster	4	$3.72	$14.88	
14	Zinc-Plated Steel Washer for M5 Screw Size, 5.3 mm ID, 10 mm OD, Packs of 100	91166A240	Mcmaster	1	$2.31	$2.31	
15	Zinc-Plated Steel Hex Nut, Medium-Strength, Class 8, M5 x 0.8 mm Thread, Packs of 100	90591A260	Mcmaster	1	$2.80	$2.80	
16	Medium-Strength Steel Nylon-Insert Locknut, Class 8, Zinc-Plated, M5 x 0.8 mm Thread, Packs of 100	90576A104	Mcmaster	1	$4.50	$4.50	
17	Zinc Yellow-Chromate Plated Grade 8 Steel Washer for 1/4" Screw Size, 0.281" ID, 0.625" OD, Packs of 100	98023A029	Mcmaster	1	$7.70	$7.70	
18	High-Strength Steel Nylon-Insert Locknut, Grade 8, Zinc Yellow-Chromate Plated, 1/4"-28, Packs of 25	97135A215	Mcmaster	1	$3.66	$3.66	
19	Zinc Yellow-Chromate Plated Steel Thin Hex Nut, Grade 8, High-Strength, 1/4"-28 Thread Size, Packs of 100	93839A805	Mcmaster	1	$11.45	$11.45	
20	Aluminum Unthreaded Spacer, 8 mm OD, 22 mm Long, for M5 Screw Size	94669A329	Mcmaster	4	$2.25	$9.00	
21	M5-0.8 x 20mm ISO 4762/DIN 912 Hex Drive Class 12.9 Black Oxide Finish Alloy Steel Socket Cap Screw	1139547	Fastenal	50	$0.22	$11.20	
22	M5-0.8 x 35mm DIN 931 Class 8.8 Zinc Finish Hex Cap Screw	38548	Fastenal	5	$0.54	$2.69	
23	M5-0.8 x 40mm DIN 931 Class 8.8 Zinc Finish Hex Cap Screw	38549	Fastenal	5	$0.58	$2.91	
24	1/4"-28 x 1" Grade 8 Yellow Zinc Finish Hex Cap Screw	18755	Fastenal	5	$0.32	$1.58	
25	1/4"-28 Yellow Zinc Finish Grade 8 Finished Hex Nut	36452	Fastenal	5	$0.13	$0.65	
26	M5-0.8 DIN 439B Class 04 Zinc Finish Steel Jam Nut	141487	Fastenal	5	$0.06	$0.31	
27	1/4"-20 x 1/2" Grade 8 Yellow Zinc Finish Hex Cap Screw	15001	Fastenal	3	$0.19	$0.56	
28	14 Tooth Threaded Track Cog, 3/32"		Surly	1	$19.94	$19.94	
29	Freewheel Adapter for 5/8" Axle with 1.375" OD x 24 TPI Clockwise Right Hand Threads	FWM-ADAPTEF	Electric Scooter F	1	$32.44	$32.44	
30	Irwin 8338 10mm X 1.0 Metric Tap	8338	Amazon.com	1	$8.04	$8.04	
31	Shimano Acero MTB Shifter	SL-M3010	Amazon.com	1	$27.44	$27.44	
32	Chain Cover						

Bill of Materials (BOM) - Rear Drivetrain
Pump My Ride

Total Sub-System:
$337.81

Item #	Description	Source PN	Source	Qty.	Cost.	Price Extended	Link
1	Motor Mount	-	-	1			
2	Motor						
3	1/4"-20 Hex Head Screw						
4	Standoff	92511A085	McMaster	5	$3.81	$19.05	https://www.mcmaster.com/92511a085
5	Hub Adapter	N/A	Scrap	1	$0.00	$0.00	
6	Rear Wheel	N/A	Bike Kitchen	1	$5.00	$5.00	
7	Motor Sprocket 13T	B06WRX7XF5	Pure Cycles	1	$14.99	$14.99	=sr_1_6?dchild=1&keywords=fixed%2Bgear%2Bsprocket&qid=1571500013&sr=8-6&th=1&psc=1
8	Wheel Sprocket 60T	TA110EXT60S	TA Specialties	1	$120.00	$120.00	erwhitecycles.com/ta-chainrings.php
9	Skewer			1	$5.45	$5.45	
10	Tire Inner Tube 700c x 28-35 PV 48 mm			2	$11.49	$22.98	
11	Continental GP 5000 700x32C Tires	B07BHWZ87D	Continental Tires	2	$ 44.30	$88.60	&creative=9325&linl
12	NJS Chain	B00PB5DXLC	Izumi	1	$ 50.25	$50.25	DXLC/ref=sr_1_1
13	Street Fit 360 Tue, 700 x 28-35 32mm Schrader Valve		Sunlite Bicycles	1	$11.49	$11.49	
14	Various Aluminum Spacers						

Bill of Materials (BOM) - Mechatronics
Pump My Ride

Total Sub-System: $373.50

Item #	Description	Qty.	Cost.	Price Extended	Link
1	Low Voltage Alarm	1	1.26	$1.26	2?dchild=1&keyw
2	Zee 14.8 V 50C 5200mAh 4S Lipo Battery	1	$48.99	$48.99	
3	Braided Steel Casing	1	$20.25	$20.25	https://www.amaz
4	Opus A3F Wachendorff Display Units	1	$303.00	$303.00	
5	Juicebox	1	$0.00	$0.00	

Bill of Materials (BOM) - Auxiliaries

Pump My Ride

Total Sub-System:

$2,097.03

Item #	Description	Manufacturer PN	Manufacturer	Link	Qty.	Cost.	Price Extended
1	Front and Rear Brakes	BR-CX50	Shimano	https://www.amazo	2	$35.35	$70.70
2	Front Fork	FK0912	Surly	https://www.bikepa	1	$125.00	$125.00
3	Headset	BAA0058K (ZS44)	Cane Creek	https://www.amazo	1	$34.81	$34.81
4	Front Handlebar Stem	17 Degree 70mm	Wake	https://www.amazo	1	$13.00	$13.00
5	Crankset	EFCM3000BC62X (170mm)	Shimano	https://www.amazo	1	$46.99	$46.99
6	Bottom Bracket	BB-UN26 (73X113mm)	Shimano	https://www.amazo	1	$12.99	$12.99
7	Regular Pedals	PD-M424	Shimano	https://www.amazo	1	$46.27	$46.27
8	Power Measuring Pedals	Assioma Duo	Favero	https://cycling.favei	0	$747.00	$0.00
9	Bike Kitchen Order	Purchased handlebars, seat, seatpost, rims and stem			1	$85.12	$85.12
10	Front and Rear Shimano V Brake	BR-T4000	Shimano	Amazon	1	$28.20	$28.20
11	Shimano Universal Brake Cable Set	Y80098022	Shimano	Amazon	1	$11.99	$11.99
12	DEERU Carbon Fiber Headset Spacers		DEERU	Amazon	1	$9.99	$9.99
13	Shimano MTB Shift Cable Set	CABGR7BK	Shimano	Amazon	1	$20.00	$20.00
14	Fyxation Gates Pedal Strap Kit	B00AWAS4EM	Fyxation	3MB5&dchild=1&ke	1	$58.64	$58.64
15	Bontrager Race Lite Aero Clip-On Handlebar	437611	Trek	https://www.trekbik	1	$128.99	$128.99

Bill of Materials (BOM) - Hydraulics

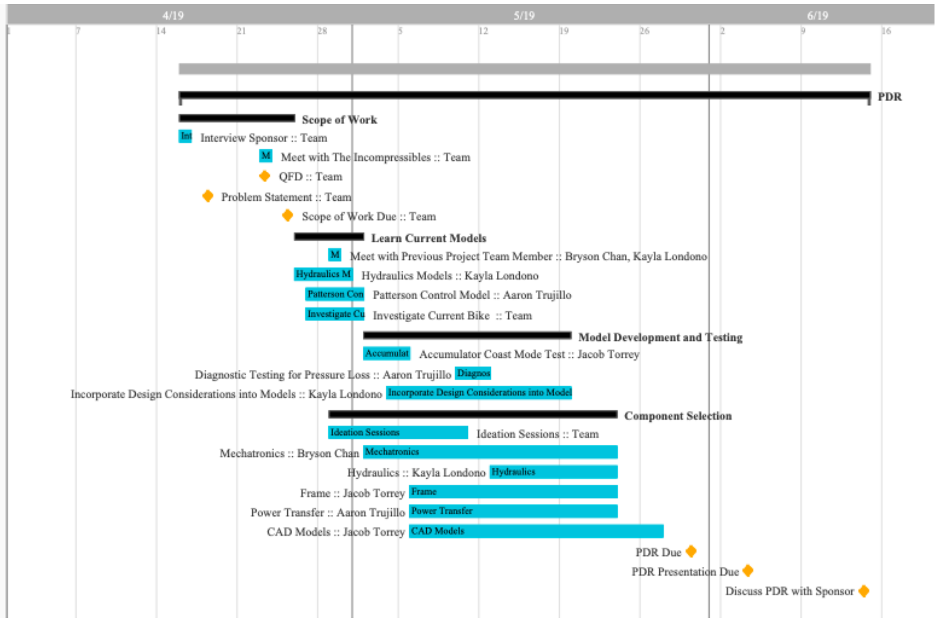
Pump My Ride

Total Sub-System: $1,408.00

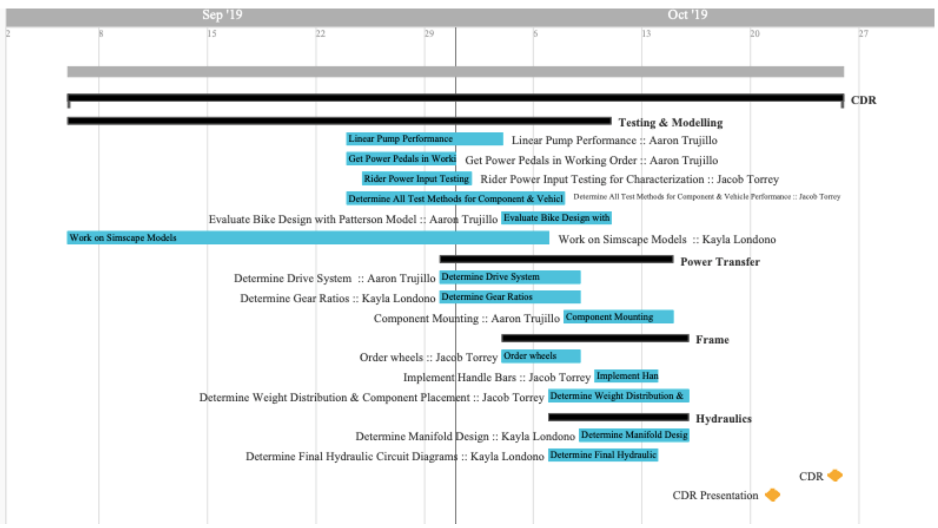
Item #	Description	Source PN	Source	Qty.	Cost.	Price Extended
1	Coil, 12VDC DIN , J type	300AA00081A	Eaton	2	$12.22	$24.44
2	Coil, 12VDC DIN , H type	300AA00121A	Eaton	2	$15.69	$31.38
3	Fitting, -6 JIC male "T"	2033-6-6S	Eaton	4	$1.84	$7.36
4	Fitting, -6 SAE male to -6 JIC male, straight	202702-6-6S	Eaton	14	$0.75	$10.50
5	Flow Control, Needle Valve	NV1-8-S-0	Eaton	1	$11.61	$11.61
6	Line Body, VC08-2, Aluminum SAE -6	02-160731	Eaton	1	$11.29	$11.29
7	Line Body, VC10-2, Aluminum SAE -6	876700	Eaton	4	$11.98	$47.92
8	Solenoid, 2 pos. 2 way Bi-poppet, normally Closed	SBV1-10-C-0-00	Eaton	2	$35.54	$71.08
9	Solenoid, 2 pos. 2 way Bi-poppet, normally Open	SBV11-10-0-0-00	Eaton	2	$45.20	$90.40
10	6061-T6 0.375" Aluminum Sheet	23816	Online Metals	1	$44.10	$44.10
11	Clamping Two-Piece Shaft Collar Metric	6063K23	McMaster Carr	3	$15.25	$45.75
12	Clamping Two-Piece Shaft Collar Imperial	6436K15	McMaster Carr	2	$7.89	$15.78
13	Aluminum Bare Sheet 6061 T6 24" x 48"	1246	Online Metals	1	$100.00	$100.00
14	Alumium Weld Bung 1/4 NPT	8694T42	McMaster Carr	5	$8.00	$40.00
15	Push-to-connect fittings 90deg. 1/4 ID/NPT	5486K122	McMaster Carr	2	$5.42	$10.84
16	Breather Fitting 1/4 NPT	9833K22	McMaster Carr	1	$1.61	$1.61
17	Barbed Fitting 1/4 NPT	5357K32	McMaster Carr	2	$4.02	$8.04
18	Pump/Motor Parker	-	Parker	2	$0.00	$0.00
19	4L Composite Bladder Accumulator @ 3000psi	AB30CN010G0N	Steelhead Composites	1	$785.00	$785.00
20	Accumulator Mounting Bracket	BI56AD	Steelhead Composites	2	$25.00	$50.00
21	1/4-20 2" Bolt	-	-	2	$0.12	$0.24
22	1/4-20 1" Bolt	-	-	4	$0.09	$0.36
23	1/4-20 Nut	-	-	6	$0.05	$0.30
24	Manifold	-	HydraForce	1		

Appendix O: Gantt Chart

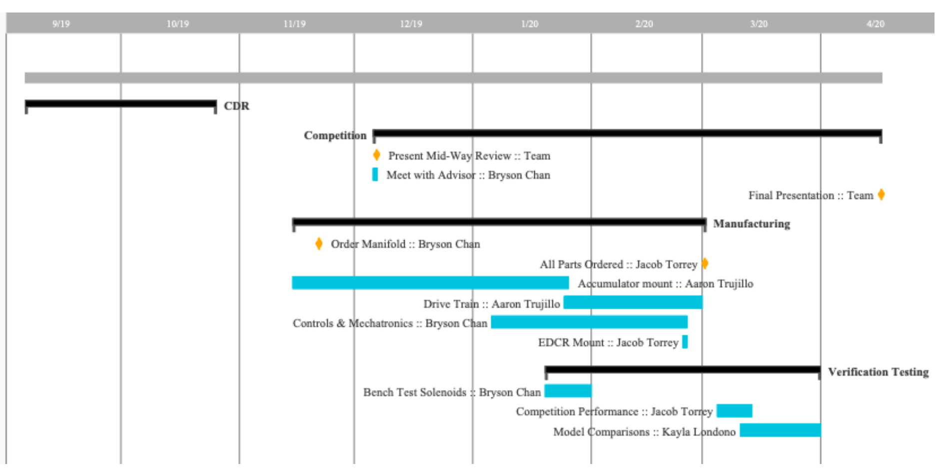
Pump My Ride Senior Project	start	end	100%
PDR	04/16/19	06/14/19	100%
Scope of Work	04/16/19	04/25/19	100%
Interview Sponsor	04/16	04/16	100%
Meet with The Incompressibles	04/23	04/23	100%
QFD	04/23	04/23	100%
Problem Statement	04/18	04/18	100%
Scope of Work Due	04/25	04/25	100%
Learn Current Models	04/26/19	05/01/19	100%
Meet with Previous Project Team Member	04/29	04/29	100%
Hydraulics Models	04/26	04/30	100%
Patterson Control Model	04/27	05/01	100%
Investigate Current Bike	04/27	05/01	100%
Model Development and Testing	05/02/19	05/19/19	100%
Accumulator Coast Mode Test	05/02	05/05	100%
Diagnostic Testing for Pressure Loss	05/10	05/12	100%
Incorporate Design Considerations into Mode...	05/04	05/19	100%
Component Selection	04/29/19	05/23/19	100%
Ideation Sessions	04/29	05/10	100%
Mechatronics	05/02	05/23	100%
Hydraulics	05/13	05/23	100%
Frame	05/06	05/23	100%
Power Transfer	05/06	05/23	100%
CAD Models	05/06	05/27	100%
PDR Due	05/30	05/30	100%
PDR Presentation Due	06/04	06/04	100%
Discuss PDR with Sponsor	06/14	06/14	100%



Pump My Ride Senior Project	start	end	100%
CDR	09/06/19	10/25/19	100%
Testing & Modelling	09/06/19	10/10/19	100%
Linear Pump Performance	09/24	10/03	100%
Get Power Pedals in Working Order	09/24	09/30	100%
Rider Power Input Testing for Characterizati...	09/25	10/01	100%
Determine All Test Methods for Component ...	09/24	10/07	100%
Evaluate Bike Design with Patterson Model	10/04	10/10	100%
Work on Simscape Models	09/06	10/06	100%
Power Transfer	09/30/19	10/14/19	100%
Determine Drive System	09/30	10/08	100%
Determine Gear Ratios	09/30	10/08	100%
Component Mounting	10/08	10/14	100%
Frame	10/04/19	10/15/19	100%
Order wheels	10/04	10/08	100%
Implement Handle Bars	10/10	10/13	100%
Determine Weight Distribution & Component...	10/07	10/15	100%
Hydraulics	10/07/19	10/15/19	100%
Determine Manifold Design	10/09	10/15	100%
Determine Final Hydraulic Circuit Diagrams	10/07	10/13	100%
CDR	10/25	10/25	100%
CDR Presentation	10/21	10/21	100%



Pump My Ride Senior Project	start	end	100%
CDR	09/06/19	10/25/19	100%
Competition	12/06/19	04/16/20	100%
Present Mid-Way Review	12/06	12/06	100%
Meet with Advisor	12/06	12/06	100%
Final Presentation	04/16	04/16	100%
Manufacturing	11/15/19	03/01/20	100%
Order Manifold	11/21	11/21	100%
All Parts Ordered	03/01	03/01	100%
Accumulator mount	11/15	01/25	100%
Drive Train	01/25	02/29	100%
Controls & Mechatronics	01/06	02/25	100%
EDCR Mount	02/25	02/25	100%
Verification Testing	01/20/20	03/31/20	100%
Bench Test Solenoids	01/20	01/31	100%
Competition Performance	03/05	03/13	100%
Model Comparisons	03/11	03/31	100%



Appendix P: Design Verification Plan and Report (DVPR)

DESIGN VERIFICATION PLAN

Pump My Ride's design verification plan (DVP) outlines the original written tests, their methods, materials, and facilities needed to confirm that the final prototype meets our engineering specifications. Some paragraphs have been added to inform the reader of significant changes to the DVP.

The DVP was written prior to the COVID-19 pandemic. We did not plan for the unprecedented circumstances. Since, the move to a virtual competition many of the tests for specific challenge events may be unnecessary. Regardless, we made progress through most of the DVP, so the information and results are relevant because they pertain to the engineering specifications.

Sprint Time Verification Plan

The engineering specification for Pump My Ride's sprint time is 18 seconds over a distance of 600 ft. This specification was written with the goal to place first in the sprint race during competition.

Testing Location

Pump My Ride plans to conduct testing at Mt. Bishop Road since it is the longest, straight road with light traffic on Cal Poly's campus (see Figure #.#) Riding from north to south, there is a negative grade which may influence the finishing time of the sprint and will be considered upon design verification.

Chapter 7 in the report shares that the testing location changed to Sports Complex Road for the final prototype tests. The reasoning is because Pump My Ride fell behind schedule by a week and a half. Thus, a testing location available 24/7 without traffic was needed. Fortunately, we found the Sports Complex to be a better alternative (i.e. flatter road, less traffic, longer track).

Figure P.1: Sprint time testing location for design verification plan.

Test Equipment

The required equipment for testing is listed:

- Fluid Powered Vehicle
- Cones (2)

- Stopwatch (2)
- Pen and paper

Sprint Time – Test Method

Pump My Ride plans to perform 3-5 trials of the 600 ft. sprint to provide reliable data that our engineering specification is met. Three team members are needed to participate in each trial. Prior to each trial, the team members assist in charging the accumulator to maximum pressure (3000 psi). With the lightest team member operating the vehicle, the rider rests in direct drive mode with their foot on the ground. The two other team members stand at the course start and finish marked by cones. When ready, the team member at the course start can signal to the rider to switch to "boost" and begin recording time. When the vehicle begins moving, the rider lifts their foot off the ground. At a comfortable speed, the rider translates their position from "upright" to "tuck" with use of the tri bars. When the vehicle crosses the finish, the rider pumps their brakes until they reach a stop. Two team members will record their times.

As mentioned in Chapter 7, COVID-19 ended the planned time for testing abruptly. Therefore, Pump My Ride could not complete more than one trial for the sprint race.

Endurance Time Verification Plan

The engineering specification for Pump My Ride's endurance time is 4 minutes and 30 seconds. This specification was written according to the NFPA rules for the endurance challenge.

Endurance Time – Test Location

Pump My Ride needed a location large enough to ride the vehicle a distance of 1 mile. The H-1 parking lot, used in the baseline tests, is the best area since it is the largest lot Cal Poly's campus (see Figure #.#). 5.5 laps equal 1 mile which satisfies the course distance for the competition challenge.

Like the sprint race, Pump My Ride changed the testing location to the Sports Complex. However, the lot for the endurance race was smaller than the H-1 lot by a factor of about 0.5.

Figure #.#: Endurance time testing location for design verification.

Endurance Time – Test Equipment

The required equipment for testing is listed:

- Fluid Powered Vehicle
- Stopwatch
- Pen and paper

Endurance Time – Test Method

The endurance testing method is parallel to the 2020 NFPA rules for the endurance challenge. Pump My Ride plans to conduct 3 trials. Two trials will be completed with individual riders, one trial will be completed where riders are switched midway. These trials will verify the engineering specification for the endurance time and investigate any possible advantage of using two riders.

Efficiency Score Verification Plan

The engineering requirement for the efficiency score is 18%. Verifying this score will require measuring the following parameters prior to testing

- Gas pre-charge pressure in pounds per square inch (psi) (Note: minimum 100 psi)
- Maximum system pressure that the accumulator is charged to.
- Volume of the accumulator (maximum 231 in^3).
- Weight of the vehicle and rider in pounds.
- Total distance traveled from starting point in feet.

Efficiency Score – Test Location

In order to get accurate results for the efficiency score, Pump My Ride needs a flat testing location because an incline will skew the distance travelled. Currently, the best bet for conducting this test is the H-1 parking lot.

Changing the test location to Sports Complex Road improved the reliability of our data because the location provided a flatter course.

Efficiency Score – Test Equipment

- Fluid Powered Vehicle
- Nitrogen high pressure tank
- High pressure hose (whip)
- Cones (2)

Efficiency Score – Test Method

The test methods are concurrent with the NFPA rules for the efficiency challenge. To find our bike's optimum operating efficiency, Pump My Ride plans to perform 9 trials. Prior to the first trial, we will pre-charge the accumulator to 900 psi with the nitrogen tank and Jim Gearhart's assistance. The heaviest team member will operate the vehicle. At 3000 psi, the rider will boost from a standing start and continue riding without braking until the vehicle stops from resistance alone. The measured distance will be recorded and entered into the efficiency score calculator to obtain the most advantageous settings. This procedure will be repeated, each time reducing the pre-charge in 100 psi increments. The last trial will conclude at 100 psi, the minimum pre-charge allowed.

Pump My Ride separated the various pre-charge tests from the efficiency tests for the design verification because we needed to test pre-charge against endurance time and sprint time too. As shown in Chapter 7, we described these tests in a subsection called pre-charge determination. In addition, we did not want to test the accumulator at a pre-charge above 500 psi because we did not want to explode the bladder.

Weight Verification Plan

The vehicle weight according to the engineering specification is 100 lbs. Pump My Ride will utilize bathroom scales, one for each wheel, to weigh the vehicle after manufacturing and build.

Pump My Ride did not acquire bathroom scales. Instead, we used the large scale available in the Bonderson Projects Center.

Top Speed Verification Plan

The vehicle top speed should be less than or equal to 40 mph according to the engineering specifications. The top speed will be measured along Mt. Bishop Road. A laser tachometer will be rigged to the bike to act as a speedometer. The vehicle will be charged to maximum pressure and operated in its boost mode. Using laser tachometer, we will measure the vehicles speed after it has traveled approximately 600 feet.

Pump My Ride did not obtain a tachometer from Formula SAE or HPV clubs before campus closure due to COVID-19. Therefore, Pump My Ride relied on observations and timed results from the sprint test at maximum pre-charge.

Braking Torque Verification Plan

The engineering specifications state that the braking torque compared to the motor torque has a factor of safety of 2. While calculations can verify this requirement is met, real tests may reveal only a factor of safety of 1. With the accumulator is charged to 3000 psi, a rider will switch to the vehicle boost while pressing on the front and rear brakes. Assuming the vehicle does not move, we may be confident that the tests and calculations show our braking torque satisfies at least a factor of safety of one.

Turn Around Time Verification Plan

The turn-around time specification refers to the time it takes to charge the accumulator to maximum pressure. Currently, Pump My Ride requires a turn-around time of 7 minutes so that we are well under the allotted time of 10 minutes during competition. Our design verification plan, is to record the time it takes to charge to 3000 psi, in between trials of the sprint time tests.

Power Required by Rider Verification Plan

Pump My Ride expects a rider should input a maximum of 300 W to operate the vehicle. The equipment available to our team does not allow us to accurately measure human power during operation. Thus, our team will rely on our observations during performance testing. Simply, if a rider can operate and control the vehicle while using direct drive mode, then we may assume they are not exceeding the 300 W maximum power requirement.

Life of the Vehicle Verification Plan

Pump My Ride wrote the life of the vehicle engineering requirement of 2 years to ensure this project can be passed down to future Cal Poly students. Since most of our components, especially the hydraulic motor, are operating under their specified flow rate, we cannot test the expected life accurately. Thus, Pump My Ride does not have design verification plan for the life of the vehicle, but it is assumed that since each component is understressed, there should be no significant wear.

Internal Leakage Verification Plan

According to the engineering specifications, Pump My Ride requires a maximum internal leakage rate of 2 psi/s. We will test internal leakage by measuring the accumulator pressure before and after storing the vehicle. If internal leakage is present, then we should expect to see a pressure drop over time and corrective action should take place. No leakage will show no pressure drop over stowage period.

External Leakage Verification Plan

Per the NFPA competition rules, it's required that all vehicles have no external leakages. Thus, our engineering specifications are concurrent with the rules. External leakage will be tested concurrently with performance testing by observation.

DESIGN VERIFICATION REPORT

The design verification plan and report summarizes the design verification test and whether they meet the design verification. This table is referenced in Chapter 7.

Design Verification Report						
#	**Verification Description**	**Specification Requirement**	**Verification Plan**	**Results**	**Specification Met (Y/N)**	**Conclusion**
1	Sprint Time	18s	Record time.	21.96s	N	More testing required.
2	Endurance Time	4 min 30 s	Record time.	5 min 40 s	N	More testing required.
3	Efficiency Score	23%	Record revolutions. Calculate efficiency.	12.17%	N	More testing required.
4	Weight	100 lbs.	Record weight.	103 lbs.	N	Replace soft lines with hard lines.
5	Top Speed	40 mph	Record speed.	N/A	Y	Future tests use tachometer.
6	Braking Torque	FoS = 2 Compared to Motor Torque	Pass or fail.	Pass	Y	Rim brakes provide sufficient torque.
7	Turn Around Time	7 min	Record time.	6 min	Y	Successful regenerative mode.
8	Power Required by Rider	300 W	Pass or fail.	Pass	Y	Power required within range of human limit.
9	Life of the Vehicle	2 years	Pass or fail.	Pass	Y	Frame and components rated appropriately.
10	Internal Leakage	2 psi/s	Pass or fail.	Pass	Y	Accumulator working properly.
11	External Leakage	0 drips	Pass or fail.	Pass	Y	Successful hydraulic circuit.

Appendix Q: User Manual

Disclaimer: This User Manual is meant to be used as a guide for BASIC orientation with the Cal Poly Fluid Powered Vehicle (hereafter referred to as the DMS). This is a dangerous machine that can cause grave bodily injury if misused. This manual is in no way complete, and should not be treated as such. High pressure hydraulics are inherently dangerous, and care should be taken whenever in the vicinity of the DMS. Likewise, the Li-Po battery used on this project must be fully understood to prevent injury or fires. By using the DMS, you take full responsibility for your safety and the safety of those around you.

Caution: The DMS may start in boost mode when the battery is connected. Before the battery is plugged in, the system pressure (gauge attached in-line with the accumulator) must be checked, all moving parts of the rear drivetrain must be clear of obstructions, and the rear wheel should be free to rotate.

INATTENTION WILL CAUSE INJURY.

Pump My Ride's design philosophy with the DMS was to refine the good work done by The Incompressibles (Cal Poly's 2018 FPV team), primarily by increasing hydraulic efficiency, improving repairability, and testing many operating points to find the "best" for each competition. This guide is meant to help you orient yourselves and save you time, as we did not have any information when we received the bike.

Li-Po Battery Notes:

Li-Po batteries such as the one used on this project are a major fire risk. Only a Li-Po specific balance charger should be used to charge the battery. Each cell should be kept between 4.2V max and 3.7V min. Use a battery alarm to ensure that these limits are kept. If any physical damage to the battery cells occurs, discharge the battery by the manufacturers recommendations if it is safe to do so, and discard at the nearest battery disposal site.

Failure to follow these instructions will result in thermal runaway and/or battery explosion.

Disconnect the battery and store in a safe place whenever not in use.

Accumulator Pre-charging:

The accumulator must be pre-charged with zero system pressure. This may mean boosting many times during the charging procedure to reduce system pressure to 0psi. See Jim Gerhart for charging instructions. The bladder in the accumulator is basically a balloon that inflates with pre-charge pressure. Pre-charge is never meant to be above system pressure, but for this application, that is not possible. The efficiency challenge requires discharging the system pressure all the way to zero while the pre-charge pressure remains unchanged. Because of this, care must be taken when choosing a pre-charge pressure, or the bladder will rupture.

MAKE SURE YOU UNDERSTAND THE DIFFERENCE BETWEEN PRECHARGE AND SYSTEM PRESSURE.

Selecting Modes:

The buttons on the handlebars are marked with their mode. Pressing a button once selects that mode. Pressing the same button again deselects that mode. Mode deselection defaults to direct drive mode. See Pump My Ride's FDR for a description of operation for each mode.

Rear Chain Tension:

The rear chain must be tight to keep the chain from being thrown off. We found that ~3/8" of play kept the chain from being thrown off. You may need to experiment further. ! As a note, pay attention to side to side alignment of the motor when reinstalling the motor mount.

Charging the System:

Start by selecting Regen Mode. Push the bike such that the rear wheel rolls on the ground. It will take some time before the accumulator is full of fluid and pressure starts to build. Within 3 minutes of continuous pushing, resistance will start to build. Pressure should be monitored constantly by checking the system pressure gauge. Once the pressure reaches ~1500psi, pressure and resistance will build exponentially, and it will be necessary to have a helper push down and forward on the rear of the bike to avoid tire slip. System charging is complete when system pressure has reached 3000psi. Heat dissipation and leakdown when switching modes will likely leave final system pressure at ~2800psi. A second round of charging may be used to "top off" the accumulator to 3000psi.

DO NOT EXCEED 3000PSI SYSTEM PRESSURE.

Troubleshooting:

If system function is ever in doubt, first check that the correct solenoids are being energized. This is done by backprobing the connectors going into the solenoids. See FDR for a description of which solenoids should be energized for a given mode. ! Note: If a plug is removed, the ECDR (computer) will detect a problem and will not operate. Do not unplug connectors to diagnose. It may be necessary to bleed the air out of the system if any component is removed from the hydraulic system. The circuit in question should be pressurized, and the line should be cracked open at the highest point in the circuit.

Caution: High pressure hydraulic fluid may be released. Use good judgement and wear PPE during bleeding procedures

Appendix R: Testing Procedures

This document outlines the procedures necessary to evaluate the vehicle performance in accordance with the NFPA 2020 FPVC Rules for three important categories: sprint, efficiency, and endurance.

Testing Materials Checklist

- ☐ FPV
- ☐ Battery
- ☐ Safety gear
- ☐ Cones
- ☐ Stopwatch
- ☐ Pen

SPRINT	
PROCEDURE	**INITIAL**
Assign one team member the role of "RIDER", two the role of "RECORDER", and another the role of "LEAD."	LEAD: RIDER: RECORDER 1: RECORDER 2:
All members meet at Bonderson. The LEAD will make sure all necessary materials are gathered.	
Prior to leaving, fully discharge the accumulator. Then, pressurize the accumulator to desired **pre-charge**.	
Use cones to mark approximately 600 ft along Sports Complex Road. Refer to the figure below, where "A" and "B" designate cone locations. 	

Start at “A.” Use the vehicle regenerative mode to pressurize the accumulator charge to 3000 psi. Record the time it takes.	
Switch to vehicle “coast” mode. Align vehicle front wheel with starting point.	
At the LEAD’s signal, the RIDER will initiate boost mood and RECORDER 1 & 2 will record time it takes to travel to the finish cone.	
Repeat the procedure for additional trials.	
EFFICIENCY	
Start at cone marker “A.” Use the vehicle regenerative mode to pressurize the accumulator charge to 3000 psi.	
Switch to vehicle “coast” mode. Align vehicle front wheel with starting point.	
At the LEAD’s signal, the RIDER will initiate boost mood.	
As soon as the RIDER reaches a stable speed, immediately switch to vehicle “coast.”	
RIDER: When you arrive to a slow, unstable speed, switch to vehicle “boost.”	
RIDER: Switch between “boost” and “coast for unstable and stable speeds, respectively, until you roll to a forced stop.	
Return to “B” while count the number of revolutions on the front wheel. Record the revolutions.	
Repeat the procedure for additional trials.	
ENDURANCE	
Use cones to mark off approximately 1/10 mile around outdoor basketball courts (see figure below). 	

Release all charge pressure in the accumulator.	
Move bike and rider to start position. Have RIDER and LEAD initiate bike's "direct drive" mode.	
At the LEAD's signal, the RIDER will begin pedaling around the course, and one RECORDER will start a watch.	
[OPTIONAL] At the end of lap 5, switch riders.	
At the end of lap 10, record mile time.	
Repeat previous steps for more trials.	