PURDUE UNIVERSITY
NFPA Fluid Power Vehicle Challenge
Project Report

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RESTRICTED INFORMATION

Any reference required by University

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1 ABSTRACT OR EXECUTIVE SUMMARY

1.1 Executive Summary

Through the challenges to interface hydraulics and human powered vehicles, the engineering team from Purdue University has developed and constructed a hydraulic hybrid bicycle specifically designed to excel in all categories of the NFPA Fluid Power Vehicle Challenge. The bike, named PurdueTracer, is shown in figure 1.1.1, and it consists of a custom frame designed to integrate the oil reservoir and the hydraulic components in a light and ergonomic solution. The hydraulic circuit of the PurdueTracer allows for different modes of operation, which the user can easily select while operating the vehicle: normal pedaling, propulsion boost and regenerative braking. Electrohydraulic components are used to allow the switching between different modes through an electric controller. The bike is entirely controlled by a smartphone app, which communicates via Bluetooth with a controller and data acquisition module implemented through Arduino. From the smartphone app, the user can monitor online the main operating features of the system, including the operating pressure and the instantaneous efficiency of the hydraulic transmission. The sizing of the hydraulic circuit was made through numerical optimization, using the commercial AMESim software, so that the size of the hydraulic units, as well as the gearboxes ratios are optimal for the three races of the competition. The model was also validated from a preliminary test campaign performed on the prototype.

The Purdue team believes that the PurdueTracer will be suitable not only for the purpose of the competition but it also offers elements of novelty and performance level suitable to justify further commercialization. This report details the main aspects related to the design, modeling and the manufacturing of the PurdueTracer. A cost analysis and considerations on the possible commercialization of the Purdue Tracer are also included in the report.

Figure 1.1.1: PurdueTracer

1.2 Vision and Ideas

Although the project started from a simple idea to build a bicycle with the use of fluid power instead of a chain, it quickly became obvious that the project could be so much more. While the bike maintains many of the standard features of a traditional bicycle like its shape, driving position, and pedaling style, the team has added many new features not seen on most bikes on the market.

The team's vision is to maintain the style of a classic bike, which not only ensures stability, simplicity and driving easiness but also incorporating innovated technologies. The two wheels' design also minimizes the weight of the bike, which once was a major issue of the HydroKart (previous Purdue design of the 2016 competition).

While the output of a normal bike is directly dependent on the energy supplied by the rider at that moment, the PurdueTracer allows for disconnection of the input and output of energy. It is achieved by giving the rider an option of storing their power for later use. This allows the total output greater than the output of the rider at a given instant. The storage of the power is simple: the rider is capable of building up the pressure in the accumulator through a hand pump fixed on the vehicle before riding.

The team included a regenerative braking system within the hydraulic circuit to reduce the waste of energy. The bike's kinetic energy will be stored as the pressure in the accumulator; this backup can be released, for example, to help the rider with a starting or an uphill climb. The regenerative braking system is designed with a proportional command to be sensitive to specific kind of braking wanted by the user.

Another feature integrated into the bike is an electronic control system. This system enables users to interact with the hydraulic vehicle system through a smartphone application. Various functions are realized through the application, including vehicle's working condition monitoring, valves control, and gear shifting. Besides, the heart rate sensor monitors the physical condition of the rider. The application is able to give suggestions to the rider in real time to maximize the efficiency of the energy output.

Although features like regeneration system, user interface, automatic shifting, heart rate monitor, etc. make PurdueTracer a technological marvel compared to traditional chained bike, these features were designed with modularity in mind, allowing independent sub-systems to be added on based cost and buyers' preference.

2 PROBLEM STATEMENT

The team's prototype was designed to meet two objectives: to excel within the challenge and to be a competitive addition to the marketplace. The traditional bicycle with chain transmission is recognized as extremely efficient in terms of input versus output. The design of traditional bicycle has been refined for decades and gradually reaches a plateau in terms of speed and efficiency. The Chainless Challenge held by NFPA aims to break away from the convention and achieve the goal of driving a bike with a brand-new way—fluid power. Fluid power has already been successfully applied in the machine-powered vehicle. However, the combination of fluid power and human-powered vehicle are uncommon. Fluid power transmission has its indispensable advantages, such as smooth shifting, low noise, and simple energy regeneration, etc. Nevertheless, there are several drawbacks of this combination. The efficiency of fluid power transmission at low speeds environment is relatively low compared to a mechanical transmission. The heavy hydraulic components add extra weight to the bike, and the leak of the fluid will cause the system to fail. How to effectively mitigate and eliminate the undesired feature and keep the advantages of fluid power vehicle is the major problem the team is going to solve in the contest.

3 PROJECT PLAN /OBJECTIVES

3.1 Task Breakdown

To clearly present the task breakdown, a list of goals was developed at the beginning of the project and shown in Table 3.1.1. These goals have been arranged into the project timeline described as Figures 3.2.1 and 3.2.2.

Table 3.1.1: Description of project activities

Task	Activities
Goal 1: Project initiation	
1.1 Team member recruitment	a) Recruit team members from: 1. ABE 435 Class; 2. ABE Capstone Project; 3. ABE Department; 4. ME Department; 5. Visiting Scholar.
1.2 Brainstorming	a) Ask suggestions from former team members. b) Brainstorm ideas on: 1. Basic Design Philosophy; 2. Frame Structure; 3. Components Arrangement; 4. Electronic Control.
1.3 Design selection	a) Display all the ideas came up during the brainstorming phase; b) Discuss in the group and decide which design proposal to select.
Goal 2: Hydraulic circuit design	
2.1 Main idea	a) Development of a hydraulic transmission capable of competing in the three events of the challenge; b) Configure the system so that it is capable of easily shifting among the configurations: 1. Pedaling mode; 2. Charging mode; 3. Braking mode; 4. Boost mode; c) Basic sizing of the main components.
2.2 AMESim simulations	a) AMESim model development; b) AMESim model improvement, refining the several parameters of the system; c) Implementation of model with maps of pump/motor efficiency; d) Validation of the model based on the previous bike (HydroKart 2016).
2.3 AMESim optimizations	a) Selection of the optimization strategy and the algorithm (NLPQL) for this process;

	b) Design of new sub-models to run the iterations so that the optimization process could be completed in a reasonable time; c) Analysis of the best design obtained and verification of the performances of the system.
2.4 Components selection	a) Thoughtful selection of components from sponsor supplies and marketplace; b) Simulations through AMESim of the hydraulic system with the selected components; c) Comparison between the performances of the optimized system and the performances of the system with the parameters of the selected components;
2.5 Order hydraulic parts	a) Filling the order forms both for the sponsor's parts and for the purchasing component.
Goal 3: CAD modeling	
3.1 First idea	a) Choice of the configuration; evaluating the pros and cons of a different number of wheels. b) Design criteria; first arrangement of the components on the frame.
3.2 CAD modeling preparation	a) Design of the frame; design of the gearboxes; collection of the CAD files of every hydraulic component;
3.3 CAD modeling	a) FEA analysis to test the frame; b) Assembling; c) Piping and tubing.
3.4 Components selection	a) Choice of the materials finalized to obtain the prefixed features.
3.5 Order mechanical parts	a) Filling the order forms with the ordering codes.
Goal 4: Electronic controller development	
4.1 Brainstorming target function	a) Idea formation of an electronic system: capable of collecting and displaying vehicle data, as well as control hydraulic system. b) Choose the platform for electronic system 1. Data collection: Sensors 2. Data Analysis: Arduino 3. Data Transmission: Bluetooth Low Energy 4. Data display and command collection: smartphone application c) Brainstorming of safety design
4.2 Program Arduino codes for sensors	a) Pressure Sensor b) Velocity Sensor c) Heart rate Sensor
4.3 Design Android APP	a) Application platform selection: Cordova b) Design of data display and control page c) Supplementary function development d) Company information display

4.4 Order hardware	a) Bluetooth Low Energy (BLE) for data transmission b) Arduino for data analysis and system controls c) Sensors for data collection d) Relays and optoisolators for valve and Shimano controls e) hardware for safety design
4.5 Build App-Arduino Interaction	a) Embed BLE plugin in smartphone for data transmission b) Import BLE library and execute functions in Arduino code c) Design data interpretation principles for transmission
Goal 5: Midway review	
5.1 Midway presentation	a) Gather related material; b) Make PowerPoint Presentation; c) Rehearse the presentation.
Goal 6: Electronic controller debugging	
6.1 Debug the codes by testing	a) Debug data collection based on sensors and Arduino Debug window b) Debug data transmission through data display on smartphone c) Debug system controls by analyzing the hardware response
Goal 7: Manufacture	
7.1 Frame manufacture	a) Cut the aluminum plates and tubes; b) Weld the parts together.
7.2 Bike assembly	a) Assemble the bike; b) Integrate mechanical, hydraulic and electronic control system together.
7.3 Vehicle adjustment	a) Make necessary adjustments before the field test.
7.4 Field test	a) Conduct the field test; b) Troubleshoot the potential problems; c) Compare the result with expectancy.
7.5 Vehicle refinement	a) Reoptimize the model base on the field test result; b) Make final refinement for the bike.
Goal 8: Documentation	
8.1 Cost analysis	a) Cost analysis for prototype; b) Cost analysis for mass production; c) Cost analysis for different grades product.
8.2 Report	a) Compose the final report for the competition b) Provide the report to advisor for revision before final submission
8.3 Final presentation	a) Gather related material. b) Make PowerPoint presentation c) Rehearse the presentation.
Goal 9: Competition	
9.1 Competition	a) Ship the bike to the competition location; b) Participate in final competition; c) Give a final presentation.

3.2 Project Plan

(Activities of electronic design need to be added)

The team formed at the end of August 2016. In September, the team started brainstorming ideas. Alternative designs were compared among each other, and the best design was selected during group discussions. The team then moved onto the detailed design phase. In October, the team finished hydraulic circuit design and simulation, started developing CAD model and Android APP and programmed Arduino. The team continued adjusting and refining the CAD model and the electronic control system in November. Components were selected based on the design, and orders were placed in December.

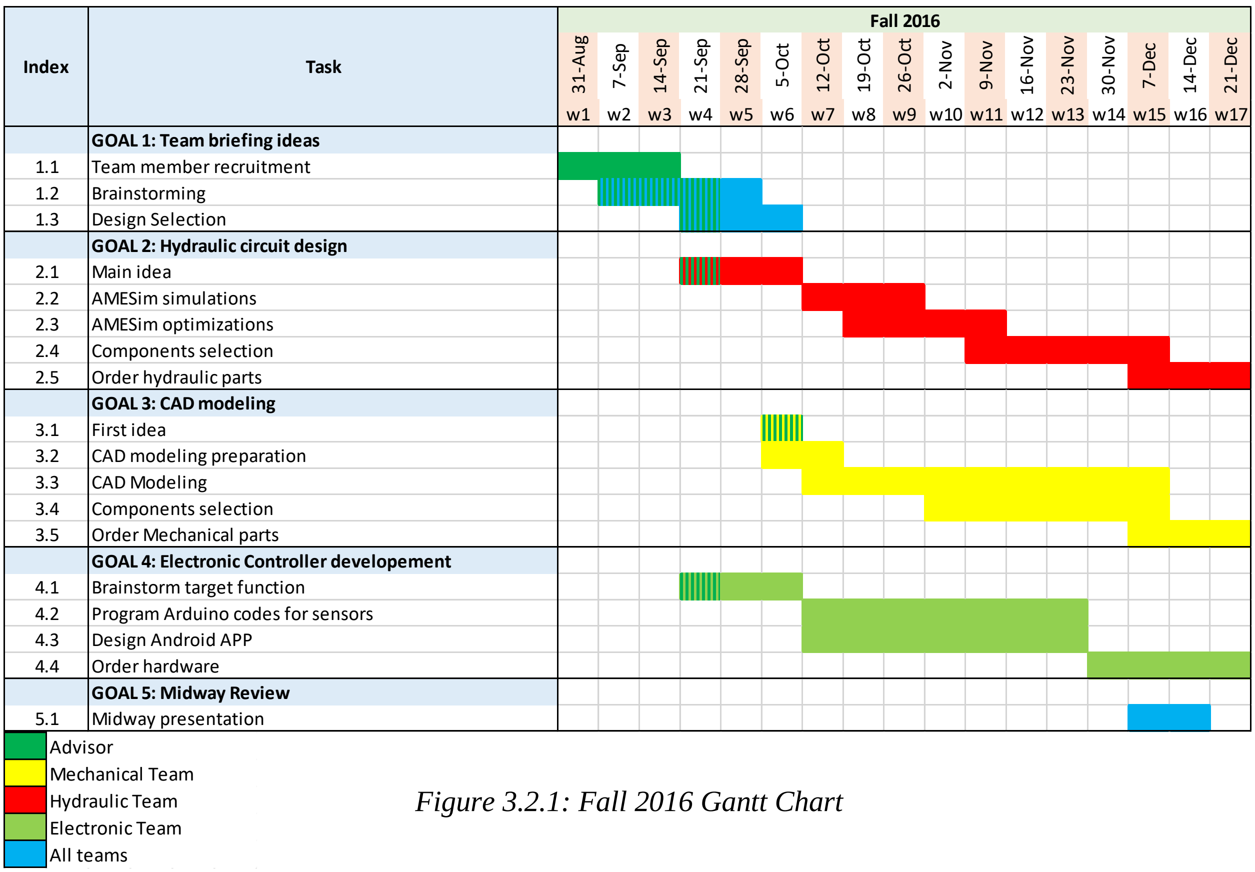


Figure 3.2.1: Fall 2016 Gantt Chart

A Gantt chart shown in Figure 3.2.2 for 2017 spring semester was created at the end of fall, 2016. The team expects most of the parts arriving at the beginning of January 2017. By then the team will be ready to manufacture parts and assemble the prototype. The manufacturing process will start from the main frame and supporting plates. The hydraulic system and electronic control will then be gradually integrated on the bike. The team plan to finish the manufacturing process by the end of February and proper adjustment will be made. Field test and some final refinement will be conducted in March. With everything prepared, the team will be ready for April's FPVC competition.

Index	Task	Spring 2017															
		9-Jan w1	16-Jan w2	23-Jan w3	30-Jan w4	6-Feb w5	13-Feb w6	20-Feb w7	27-Feb w8	6-Mar w9	13-Mar w10	20-Mar w11	27-Mar w12	3-Apr w13	10-Apr w14	17-Apr w15	20-Apr w16
	GOAL 6: Electronic Controller debug																
6.1	Debug the codes by testing	Green	Green	Green	Green	Green	Green										
	GOAL 7: Manufacture																
7.1	Frame manufacture	Yellow	Yellow	Yellow	Yellow	Yellow											
7.2	Bike assembly						Blue	Blue	Blue	Blue							
7.3	Vehicle Adjustment										Blue						
7.4	Field Test											Blue					
7.5	Vehicle Refinement												Blue	Blue	Blue	Blue	
	GOAL 8: Documentation																
8.1	Cost analysis												Blue	Blue			
8.2	Report												Blue	Blue	Blue	Blue	
8.3	Final presentation														Blue	Blue	
	GOAL 9: Competition																
9.1	Competition																Blue

Dark green	Advisor
Yellow	Mechanical Team
Red	Hydraulic Team
Light green	Electronic Team
Blue	All teams

Figure 3.2.2: Spring 2017 Gantt Chart

3.3 Team Recruitment

The team consists of students from different grades and majors. Chenxi Li is a junior student majoring in Agricultural Engineering. Zhuangying Xu is a junior student majoring in Mechanical Engineering. Zhengpu Chen and Yizhou Mao are senior students majoring in Agricultural Engineering. Gianluca Marinaro is a visiting scholar from Italy, majoring in Mechanical Engineering for Energy and Environment. The multidisciplinary background of the team is a key advantage when developing the project. Each team member contributes their unique ideas to the team and collaborates to make project possible.

3.4 Classroom Support

To better conduct the project, most of the team members have been enrolled in a course named ABE 435 Hydraulic Control Systems. The course enables students to analyze hydraulic system state, design hydraulic components, design basic hydraulic control circuits and specify components and troubleshooting mobile equipment malfunctions. Two of the team members participate in Capstone Project: ABE 484 Project Planning and Management & 486 Agricultural Engineering Design. The courses teach students basic skills of managing project, communication, technical writing and oral presentations.

4 DESIGN ANALYSIS

4.1 Hydraulic System Design

Hydraulic system design is one of the key section of the whole project, which determines the performance of the vehicle. The hydraulic system not only plays the part of the transmission but it also closely interacts with mechanical systems and electronic control systems. To start with, a hydraulic circuit was designed based on the objective functions. A layout of the circuit was drawn to show the working principles of the system explicitly. As the system is relatively complex in which various parameters need to be considered, a computer software named LMS AMESim was used to conduct the simulation and optimization test of the design. The hydraulic and some mechanical components were then selected based on the results being acquired from the optimization tests. Besides, the team put efforts on properly arranging the components. Optimizing the locations of the components along the frame cuts down the length of the pipe and improves the appearance of the vehicle.

4.1.1 Hydraulic Circuit

A hydraulic circuit layout was developed as shown in Figure 4.1.1. This layout describes the hydraulic system and the control function of two on-off switching valves. The detailed working principle of the circuit will be explained in the following sections.

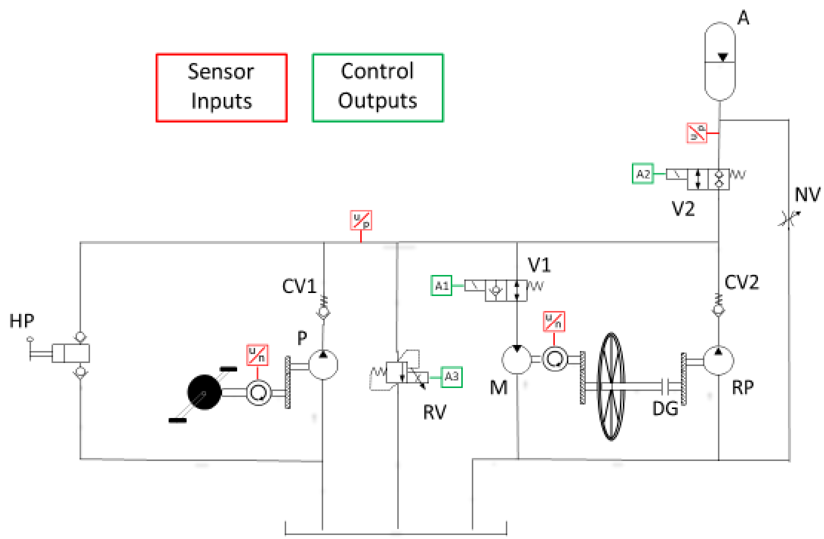


Figure 4.1.1: Final Layout of Hydraulic Circuit

P: Main Pump

RP: Regeneration Pump

HP: Hand Pump integrated with check valves on both sides

M: Motor

CV: Check Valve
RV: Proportional Relief Valve
NV: Needle Valve
V1: Two-way On-Off Valve normally-open
V2: Two-way On-Off Valve normally-closed
A: Accumulator
DG: Dog Gear

- The Valve Actuation for Different Modes

The open (1) and closed (0) positions of the valves are such that controlled by electric solenoids, which determine the mode of the vehicle. Table 4.1.1 shows how different positions of valve 1 (normally open) and valve 2 (normally closed) realize the different operating conditions of the system.

Table 4.1.1: Valve Actuation for Different Modes

Mode	V1	V2
Pedaling	0	0
Charging	1	1
Boost	0	1
Regeneration	0	1

0: The valve is not activated

1: The valve is activated

Working Modes

To better understand the hydraulic circuit in different working modes, individual layouts were created for each mode: i.e. pedaling mode, charging mode, boost mode and regeneration mode. Low and high-pressure lines, flow directions, and actuation of the valves are clearly presented in the following figures.

- Pedaling Mode

Figure 4.1.2 is the hydraulic circuit for pedaling mode. The vehicle normally works in pedaling mode. In this mode, valve 1 and 2 are not activated. When the rider is pedaling the vehicle, usually at speed of 50 to 70 rpm, the front gearbox will first increase the angular velocity to make sure the main pump having a high efficiency. The pump will use the mechanical energy to generate a flow and drive the motor connected to the rear wheel. Finally, the rotation of the rear wheel will move the vehicle forward.

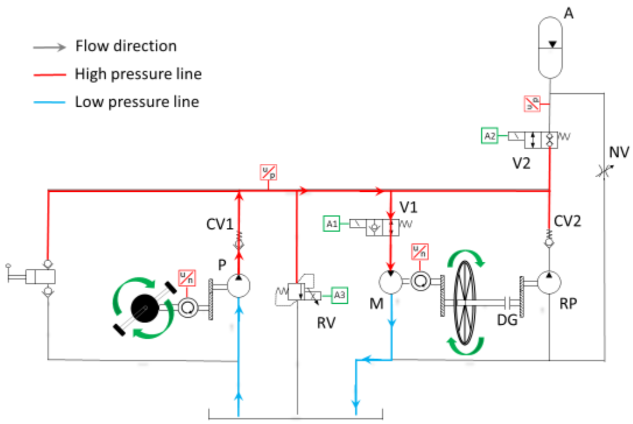


Figure 4.1.2: Pedaling Mode Hydraulic Circuit

- Charging and Boost Mode

Figures 4.1.3 and 4.1.4 show the working principle of charging and boost mode. Charging and boost modes are designed for Efficiency Challenge. The vehicle starts from charging mode with valve 1 and 2 both activated and storage device (accumulator) void of hydraulic fluid pressure. The rider first manually pressurizes the accumulator with the hand pump for a certain amount of time (10 minutes in the contest). In this process, the mechanical energy is converted to hydraulic energy and is stored in the accumulator. When valve 2 is activated and valve 1 is deactivated, the vehicle is switched to boost mode. In boost mode, the energy stored in the accumulator will be released to drive the vehicle forward through the motor system.

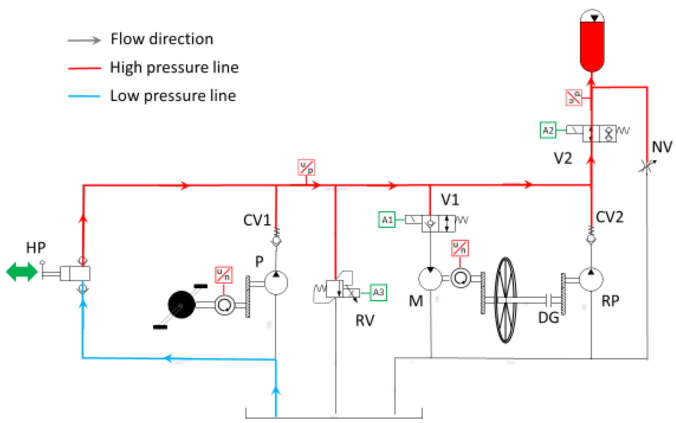


Figure 4.1.3: Charging Mode Hydraulic Circuit

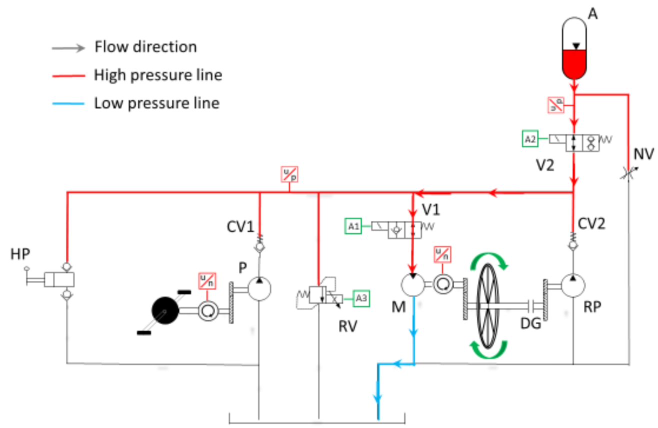


Figure 4.1.4: Boost Mode Hydraulic Circuit

- Regeneration Mode

Hydraulic circuit for regeneration mode is shown in Figure 4.1.5. Regeneration mode considers recapturing the kinetic energy of the vehicle during the braking process and storing it for later use like starting and climbing hills. To be more specific, when the rider hits the brake, a dog gear will engage with the gearbox connected with the regeneration pump. The rotation of the wheel will be resisted. The kinetic energy of the wheel will be captured and used to generate a flow in the system through the regeneration pump. The fluid will pressurize the accumulator and store the kinetic energy generated during the braking process in the form of hydraulic energy.

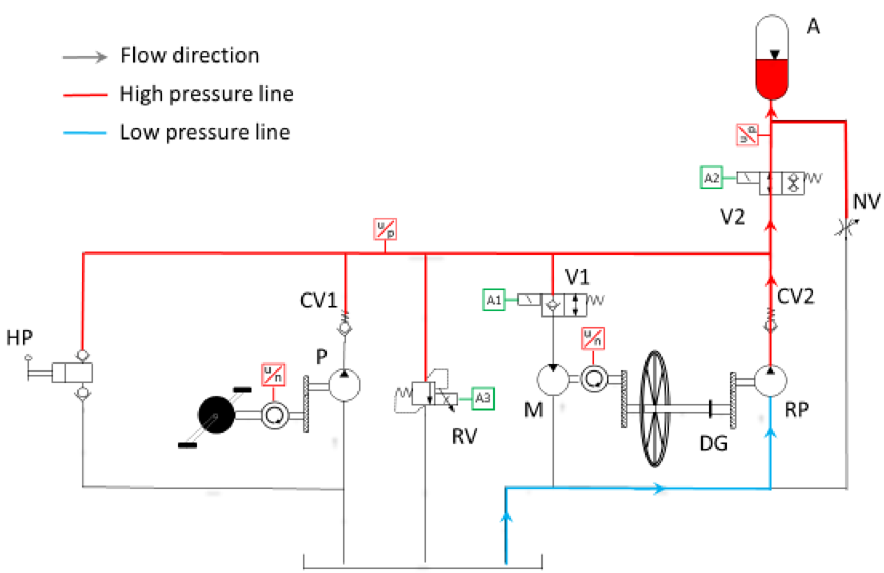


Figure 4.1.5: Regeneration Mode Hydraulic Circuit

4.1.2 Numerical Sizing

Basic Calculation Estimation

After the hydraulic circuit has been designed, basic calculations were conducted before a simulation test was run through AMESim. This helped designers to make the proper assumptions for simulation, better understand the mathematical relationship between parameters and gain basic ideas on the magnitude of parameters like pressure and flow rate. However, the results cannot be used as final results of the design, due to the complexity of the system. The number of design variables far exceeds what hand calculations can handle, and therefore, AMESim optimization tools are employed for further calculation. Nevertheless, the basic estimation made by hand calculation was still helpful at the very beginning of the design, which can be used to check the reasonability of the simulation result. The basic calculation process is shown as following:

Starting with the resistance force, with θ slope, the bike is experienced a resistant force,

$$F = Mgsin(\theta) + Mgfcos(\theta) \qquad [1]$$

That would apply a torque on the motor shaft,

$$T_m = Frg_m \qquad [2]$$

Assuming a main line pressure p, the motor displacement is then,

$$V_m = T_m / p\eta_{hm,m} \qquad [3]$$

The pump displacement is then,

$$V_p = T_p / p\eta_{hm,p} \qquad [4]$$

With a cadence of n, the flow rate is then,

$$Q = \eta_{vp} n g_p V_p \qquad [5]$$

The bike speed would be,

$$v = \eta_{vm} Q / V_m r g_m \qquad [6]$$

The unknown variables include the pump gear ratio (g_p), the motor gear ratio (g_m), the displacement of the pump(V_p), and the displacement of the motor(V_m). The known values of the parameters and assumptions are listed in Table 4.1.2.

Table 4.1.2: Known Values and Assumptions

Variable	Name	Assumption
M	Vehicle mass	140 kg
$\boldsymbol{\theta}$	Slope	1 degree
r	Wheel radius	334 mm
n	Cadence	70 rpm
$\mathbf{T_p}$	Human torque	25 Nm

Substituting the variables in the equations with known values or assumptions can give predictions of the system. It is possible to solve a basic sizing targeting for a specific objective. However, since the problem can be seen as a classic multi-objective opt problem, the calculation process is too complicate for hand calculation. Moreover, these calculations are only for pedaling mode, which is an only fragmented portion of the whole design. Thereby, numerical optimization aided by the computer software, like AMESim, is needed. In addition, realistic efficiency, losses, vehicle dynamic modeling can also be included in AMESim optimization models.

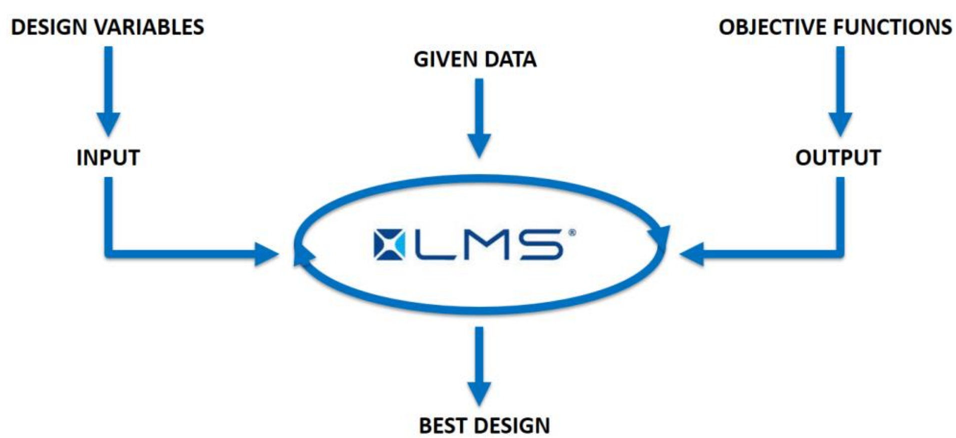
Simulation Models

Base on the calculation experience described in the former section, two AMESim models were built. The first model is used to conduct an optimization test and help to size the components. The second model is used to simulate the vehicle's hydraulic system with optimized components size, which shows the performance of the bike works in different modes.

- Models for Optimizations

Besides the function of the simulating mechanical and hydraulic system, AMESim is also able to conduct optimization test. AMESim tutorial introduced that "optimization allows designers to experiment with a collection of parameters in order to optimize certain criteria. The objective of optimization is to obtain the best possible values of parameters in the design space with regard to one or more objective functions while respecting certain constraints." The default setting is to minimize the objective functions. "If there are several objective functions to minimize, they are aggregated into a single sum to be minimized."[1]

The optimization process is shown in Figure 4.1.6. Design variables are set as input parameters. Objective functions are set as output parameters, and the known parameters are set as given data. By conducting the optimization, the best combination of the design variables, which result in minimum values of objective functions, can be found. In following sections, design variables, given data and objective functions of each model will be discussed in detail.



[1] AMEsim Tutorial: Optimization Section

Figure 4.1.6: Optimization Process

The models were built as shown in Figure 4.1.6 (Pedaling Mode), 4.1.9 (Boost Mode) and 4.1.10 (Regeneration Mode). To simplify the problem, charging mode was not included in the optimization test. This is because the charging process will be done by hand pump, instead of pedaling like last year's design. The pump gearbox is no longer used in charging modes. Besides, the hand pump does not need to be sized through the optimization in AMESim. Separated programs were built for the other three modes. The pedaling and boost modes were run in one program, since these two modes shared the same elements, including motor and motor gearbox. The regeneration mode was run in another program with its own pump and gearbox.

"1D vehicle with 2 axles" was used as a new model to simulate the motion and forces acted on the vehicle. Rolling friction of the wheels, road slope, and aerodynamic loss are taken into the consideration inside the model. The input of the model is the torque acted on the wheel, while the outputs were traveling distance, speed, and acceleration of the vehicle. The parameters of the bike model were set according to the assumptions and calculation made in basic calculation section.

In pedaling mode, angular velocity or cadence is given as an assumption, which starts from 0 rpm and ends at 70 rpm. The acceleration process simulates the start of riding will last for 100 seconds, and the speed will keep constant at 70 rpm for another 500 seconds. According to *High-Tech Cycling*, low cadences range from 50 to 60 rpm, while a pedaling cadence over 90 rpm is considered as high value. A cadence of 70 rpm is chosen in between 50 to 90 rpm as the maximum pedaling speed of the rider for this system. In addition, the volumetric and hydro-mechanical shown in Figure efficiency tables of the pump and motor shown in Figures 4.1.7 and 4.1.8 were applied for main pump and motor to increase the accuracy of the simulation.

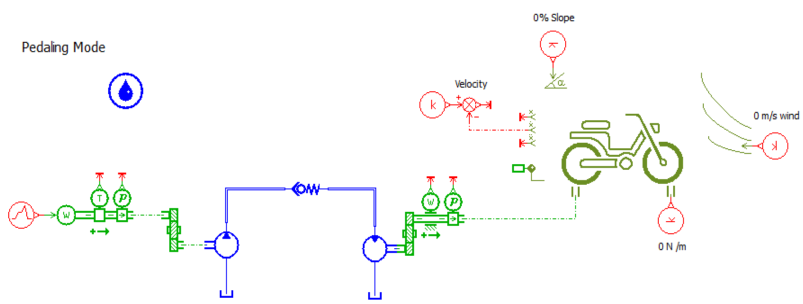


Figure 4.1.6: Pedaling Mode AMESim Model for Optimization

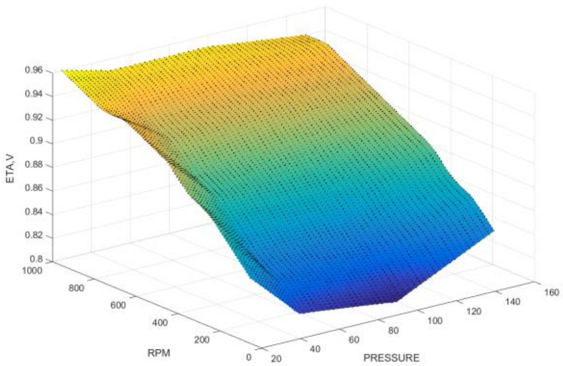


Figure 4.1.7: Volumetric Efficiency for an External Gear Pump

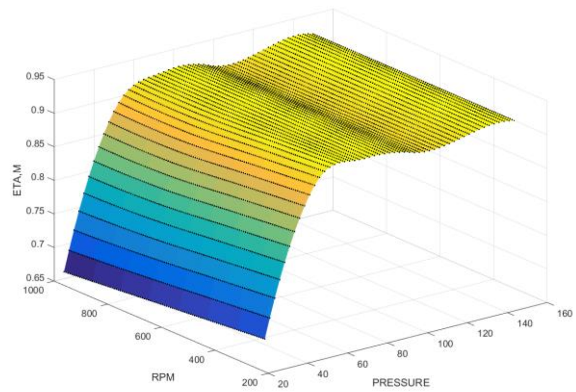


Figure 4.1.8: Hydraulic-mechanical Efficiency for an External Gear Pump

In boost mode, the initial pressure of the accumulator is 180 bar, which is assumed as the maximum pressure the accumulator will reach in charging mode. The slope of the ground was adjusted to 1% to gain a scoring ratio closer to past field test. Scoring Ratio was calculated through the signal processing section. According to the FPVC rules and requirement, the scoring ratio equals to [(W x L)/ (P x V)].

- L = total distance traveled from the starting point in inches.
- W = weight of the vehicle and rider in pounds.
- P = gas pre-charge pressure in pounds per square inch (PSI)
- V = gas volume of the storage device in cubic inches.

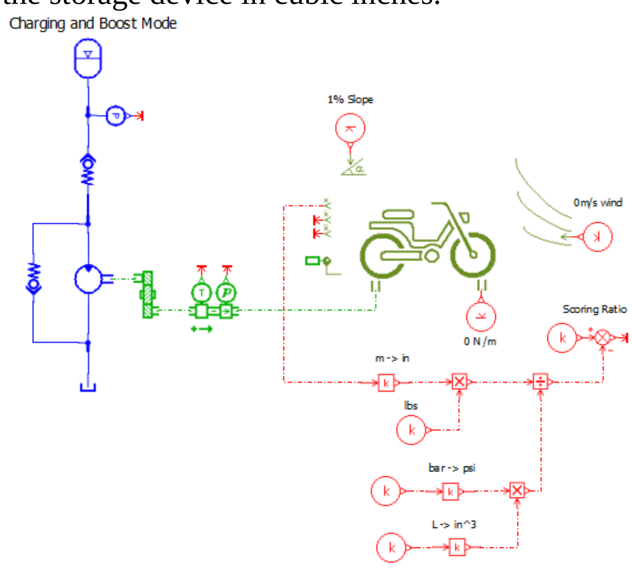


Figure 4.1.9: Boost Mode AMESim Model for Optimization

For regeneration mode, the accumulator starts from a void of fluid energy. The bike decreases its speed from a certain value. The accumulator reaches the maximum pressure when the bike's speed drops to zero.

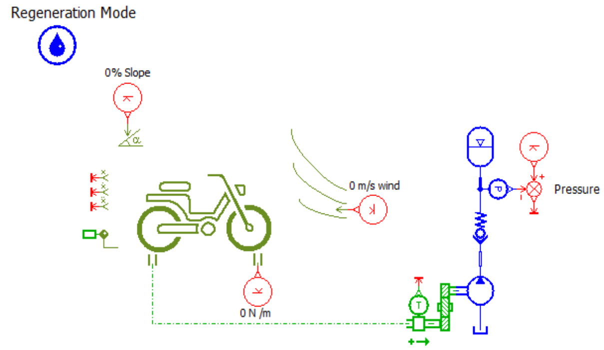


Figure 4.1.10: Regeneration Mode AMESim Model for Optimization

Optimizations of the two programs were conducted after building the models. For pedaling and boost mode, the input parameters (design variables) are the pre-charge pressure of the accumulator, the main pump gearbox's gear ratio, the motor gearbox's gear ratio, the pump displacement and the motor displacement. The output parameters (objectives) being optimized are the scoring ratio in the boost mode, and the bike's linear speed is evaluated in the pedaling mode. The input torque in the pedaling mode was constrained to 25 N/m, which is the average torque the rider can provide. The initial speed of the bike is set arbitrarily as 8.00 mph (3.58 m/s), which is lower than the maximum velocity acquired from pedaling mode simulation. For regeneration mode, the input parameters (design variables) are the regeneration pump gearbox's gear ratio and regeneration pump displacement. The output parameter (objectives) is the final pressure of the accumulator.

According to the AMESim tutorial, a global optimization (genetic algorithm) should be performed first with a large number of parameters and/or objectives, in order to explore the design space and to avoid local minima. Then a local algorithm (NLPQL) should be performed to refine the convergence. For this design, a genetic algorithm with a large difference between lower and upper bounds was performed first, and then several NLPQL with narrowed lower and upper bounds were performed.

- Model for System Performance

An AMESim model for the whole hydraulic circuit was built based on the layout in the former section to show the performance of the vehicle working in different modes. The schematic is provided in Figure 4.1.11.

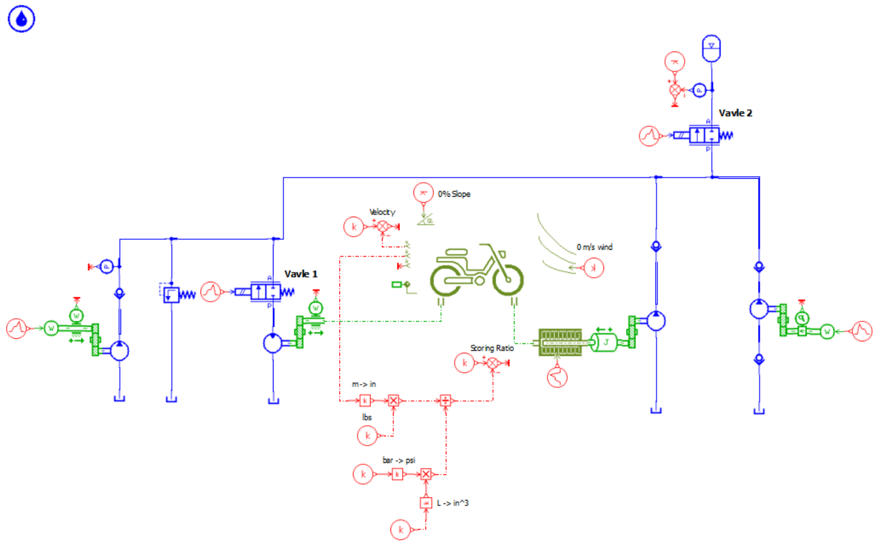


Figure 4.1.11: AMESim Model for System Performance

Table 4.1.3 shows the actuation of the valves switching the system to different modes. The system started from the rider operating the hand pump. The charging mode lasted for 100 seconds. Then the accumulator released the stored fluid energy to drive the vehicle forward. At 220 seconds, the rider started to pedal the vehicle and reached a constant speed at 280 seconds. The dog gear engaged the regeneration system at 320 seconds and stopped the vehicle within 10 seconds. In the model, a disc clutch was used as a substitution of the dog gear system.

Table 4.1.3: Modeling Sequence

Stage	Time (s)	Valve Position 1	Valve Position 2	Mode
1	100	Close	Open	Charging
2	120	Open	Open	Boost
3	100	Open	Close	Pedaling
4	10	Close	Open	Regeneration

Simulation and Optimization Results

- Optimizations Result:

The results of optimization for pedaling, charging & boosting, and regeneration models are listed in Table 4.1.4.

Table 4.1.4: Optimization Result

Pedaling Mode

Best Design	
Components:	
Pump Displacement	4.52 cc/rev
Motor Displacement	2.13 cc/rev
Accumulator Volume	2.00 L
Acc. Pre-charge Gas Pre	25 bar
Front Gear Ratio	1/6.48
Rear Gear Ratio	4.00
Performances in pedali	
Power	183 W
Torque IN (Human)	25 Nm
Pump shaft	453 rpm
Bike speed	5.10 m/s
Main line pressure	45.93 bar
Mainline flow rate	1.81 L/min
Pump volumetric efficie	88.91%
Pump mechanical efficie	86.76%
Motor volumetric efficie	94.62%
Motor mechanical effici	85.55%
Hydraulic Transmission	62.44%
Performances in Boost	
Max speed	5.21 m/s
Efficiency function	51.1232
Distance covered	221 m

Regeneration Mode

Best Design	
Components:	
Regeneration pump disp	4.23 cc/rev
Regeneration gear ratio	17.82
Performances in regen.	
Accumulator pressure ir	3.81 bar
Braking	5.29m/3.05s
Max breaking torque	52 Nm
Max deceleration	1.2 m/s^2

The optimization result gives the bike a speed of 5.23 meter per second for normal pedaling, which is a reasonable value comparing to the speed of common bikes. The efficiency score of this model reads 51.969. The value is reasonable and will be competitive in the contest since the winning scoring ratio of last year's efficiency challenge was 49.0. As for the regeneration mode, the bike stops in 3.05 seconds after braking when it is going at 8 mph (13 km/hr). The accumulator is charged from 25 bar to 28.8 bar. Though the regeneration performance can be improved, these overall results are acceptable.

- Result of Model for System Performance:

As described in the modeling section, Model 2 has four stages. The operating sequence of the four stages is charging mode (100 sec), boost mode (120 sec), pedaling mode (100 sec), and regeneration mode (10 sec). Figure 4.1.12 is a plot of the linear velocity of the vehicle, indicating the performance of the system.

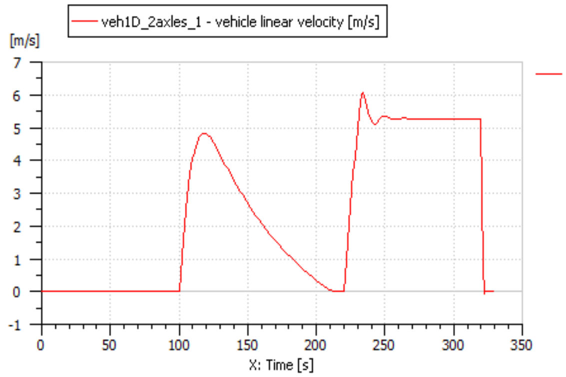


Figure 4.1.12: Vehicle Linear Speed in Four Different Modes

The results are mostly aligned with expectations. In the charging mode (0s~100s), the pressure of the accumulator increased from pre-charge pressure (25 bar) to maximum pressure (200 bar). In the boost mode (100s~220s), the accumulator gradually released its stored fluid energy to move the vehicle forward. In the pedaling mode (220s~320s), a flow was generated by the main pump and the vehicle reached and sustained a linear velocity of 5.3 m/s. At the start of the pedaling mode, the pressure and the flow of the pump experience a short period of oscillation. This is because when the vehicle just starts, the pedaling speed is low. Thus, the shaft speed of the pump is low, which affects the efficiency of the pump and causes oscillation. In the regeneration mode (220s~330s), the vehicle stopped within 3 seconds with the resistance generated by the dog gear. The model can be refined further by accurately setting the parameters of the pipes, check valves, on-off directional valves. Besides, if the site condition of the competition, such as road material (gravel/sand/asphalt), road slope, approximate wind velocity, are provided, more refinement can be done to the bike model.

4.1.3 Hydraulic Components Selection

The components of the hydraulic system selected are shown in table 4.1.5. The expected performance of the bike is also listed in the table. It is a usual case that the suppliers do not have the products with exactly the same size as the simulation result. The basic principle when selecting the components is to be as close to the simulation result as possible to ensure a high performance. Different components selection scenarios were evaluated and compared, and the one with an overall the highest performance was chosen.

Table 4.1.5: Hydraulic Components Selection and Corresponding Performance

Pedaling Mode **Regeneration Mode**

Selected Components	
Components:	
Pump CASAPPA PLP 10-4	4.27 cc/rev
Motor CASAPPA PLM 102	2.13 cc/rev
Acc. STEELHEAD COMPOSITES	2.00 L
Acc. Pre-charge Gas Pressure	25 bar
Front Gear Ratio (MISUMI) 19t/120t	1/6.32
Rear Gear Ratio (MISUMI) 100t/25t	4.00
Performances in pedaling mode:	
Power	223 W
Torque IN (Human)	30 Nm
Pump shaft	442 rpm
Bike speed	5.87 m/s
Main line pressure	64.59 bar
Mainline flow rate	1.64 L/min

.

Selected Components	
Components:	
Pump CASAPPA PLP 10-4	4.27 cc/rev
Regeneration gear ratio (3stage)	16.80
Performances in regen. mode:	
Accumulator pressure increase	3.81 bar
Braking	5.56m/3.16s
Max breaking torque	49 Nm
Max deceleration	1.2 m/s2

Pump volumetric efficiency	86.36 %
Pump mechanical efficiency	90.85 %
Motor volumetric efficiency	90.81%
Motor mechanical efficiency	90.43%
Hydraulic Transmission eff.	64.44%
Performances in Boost mode:	
Max speed	4.86 m/s
Efficiency function	50.5471
Distance covered	214 m

4.2 Mechanical System Design

Mechanical system design is another key factor of this project. It mainly includes the design of vehicle frame, power trains, and components assembly. The vehicle frame design is of highest priority since it determines the overall layout as well as the physical appearance of the vehicle. To meet the team's needs, a vehicle frame with the following features has been designed and approved by the team in the early design phase: 1) Light-weighted but sturdy; 2) Capable of fitting desired components, and 3) Aesthetically attractiveness.

Reducing the vehicle weight is the lesson learned from past years, where large weight greatly hindered the speed during the challenges. The team agreed that a light-weighted vehicle should be competitive in both the competition and the market. However, stability should also be considered while aiming for the lower weight. The second criteria ask the design to be capable of fitting desired components, which means the frame should yield room for components at proper locations. Design at those locations should also consider the balance of vehicle to provide easy control. Thirdly, the team agreed that the vehicle should appear as pretty and fashionable to be another winning point.

Powertrains design is important in such a way that it demands the most accuracy, because gear transmission is almost inevitable on a fluid power vehicle, and its preciseness greatly influences vehicle efficiency. Any design failure like poor gear engagement resulting in damaged hydraulic components should not be tolerated.

4.2.1 Frame Design

As mentioned earlier, a two-wheel bicycle is selected as the final vehicle type. Under this circumstance, the team had two choices over the frame, one is using a commercial bike frame, and the other is building a custom frame. What the team agreed on was the latter though it seemed challenging. The reason is that once customizing frame is realized, it can bring much more advantage during assembly. On the contrary, a commercial frame is too compact to fit any additional parts on, because it was not initially designed that way. Extension support plates are needed here and there to create space, which, the team did not like much.

The team members had several design ideas before this final version is shown in Figure 4.2.1 was chosen. One thing made this design stand out was that it utilizes the advantage of customizing the frame, having the feature of "built-in oil tank". The oil reservoir will be integrated into the frame, saving both the space and weight for an external reservoir. Referring to Figure 4.2.1, the tubes in blue dotted lines are the "built-in oil tanks". One cap, one vent, and several openings were added to serve the purpose of oil filling, supplying, and returning. As is designed, the total volume available in the tank is 3.5 Liters, which should satisfy the demand.

The frame was to be built by welding aluminum tubes. The main reason is obviously that aluminum is lighter than other commonly used materials. Building the frame consists of three steps. First, a CAD model was made to check if the design yields enough room for every component. After making sure the sizes are reasonable, team members created drawings for each tube, taking dimensions from the frame CAD model. Next, aluminum tubes with different sizes were ordered. The quantity was determined by the CAD model. Finally, the tubes were cut into the desired length and welded.

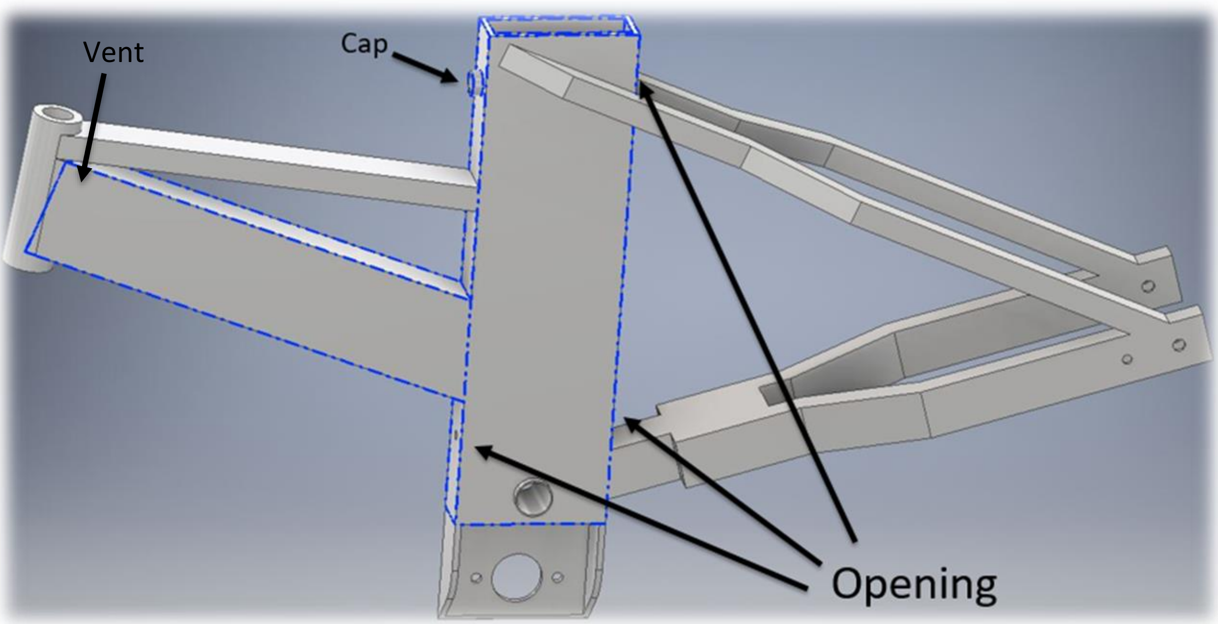


Figure 4.2.1: Bike Frame 3D Model

4.2.2 FEA Analysis

The team found Finite Element Analysis a necessity to ensure the structure would not fail under loads. FEA of the frame was conducted on AutoCAD Inventor 2017, and the results are as shown below in Figure 4.2.2. Since the frame follows the conventional triangular structures, the team predicted the stresses and deformations stayed within the acceptable ranges, and the analysis results demonstrated this.

For this analysis, the material of the frame selected was aluminum 6061 welds, who has a yield strength of 55 MPa. Figure 4.2.2 shows the forces and constraints applied. The yellow arrows indicate the locations of applied forces. The magnitude of each force was presumed based on the components' and rider's weights distribution. The five white chips indicate zero displacements.

A summary of the properties and settings is listed in Table 4.2.1.

Table 4.2.1: Bike Frame Properties and Settings

Specifications	Note
Material	Aluminum 6061 weld
Yield Strength	55 MPa
Elastic Modulus	68.9 GPa
Density	$2.7(10^3)$ kg/m^3
Material Weight	10 kg
Total Weight	150 kg
Mesh Size	1/10 border length
Maximum mesh angle	60 degree
Nodes	15245
Elements	7915

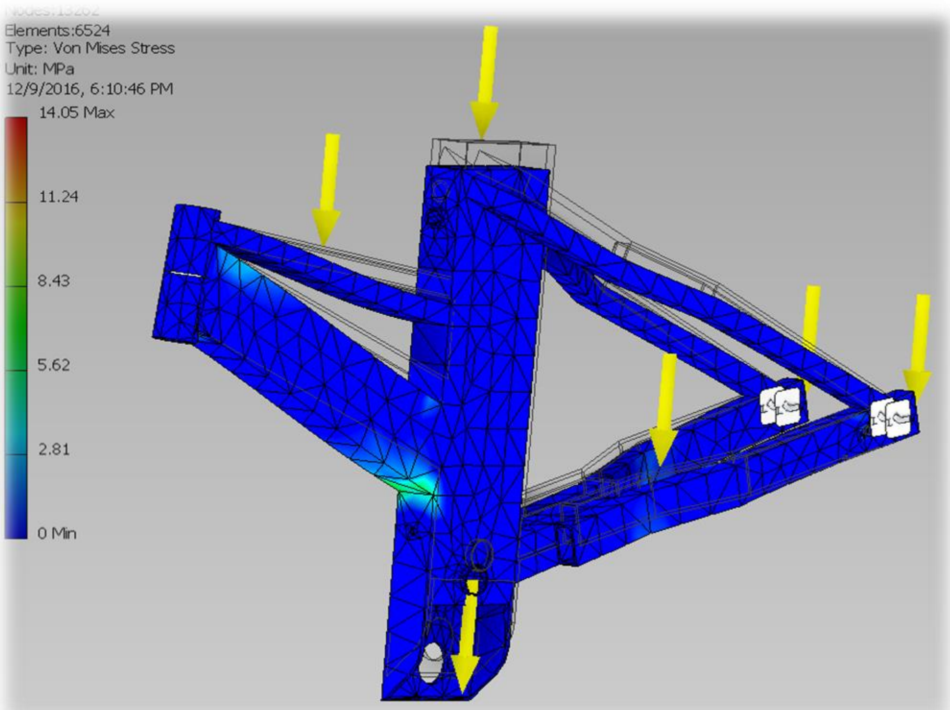


Figure 4.2.2: Bike Frame FEA Analysis (Forces and Constraints)

Figure 4.2.3 shows the overall stress on the frame. Most of the structures are under small stresses (about 0 – 3 MPa), indicating the whole frame is stable. Looking at places with relatively high stresses, a factor of safety is calculated. The maximum stress (14.05 MPa) is presented in a small area around the rear axle shown in Figure 4.2.4. The factor of safety here is:

$$F.S. = \frac{\sigma_{yield}}{\sigma_{max}} = \frac{55MPa}{14.05MPa} = 3.9$$

The conclusion can be made that the factor of safety at every location of the frame should be over 3.9, a safety factor of the weakest place. Maximum displacement found in Figure 4.2.5 is 0.064 mm. the overall results give the team confidence that the frame will be able to safely support all of the weights encountered under operating conditions.

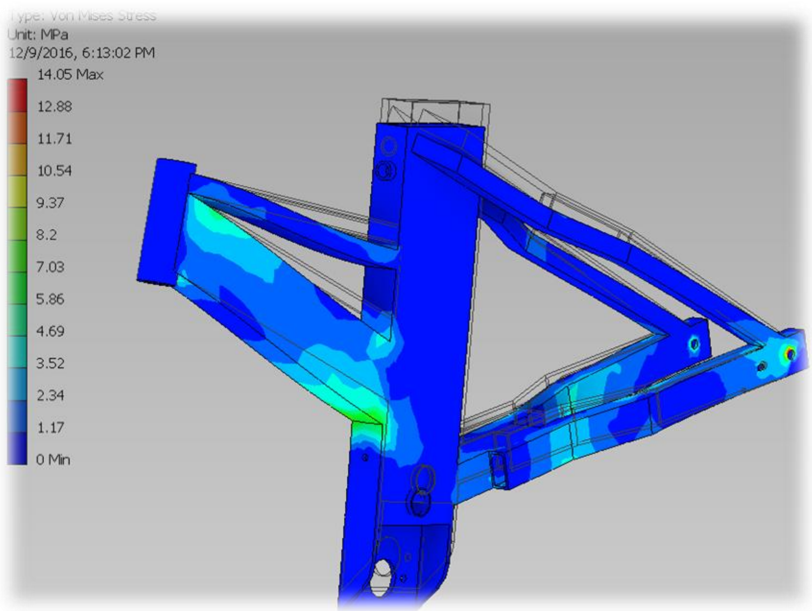


Figure 4.2.3: Bike Frame FEA Analysis (Von Mises Stress)

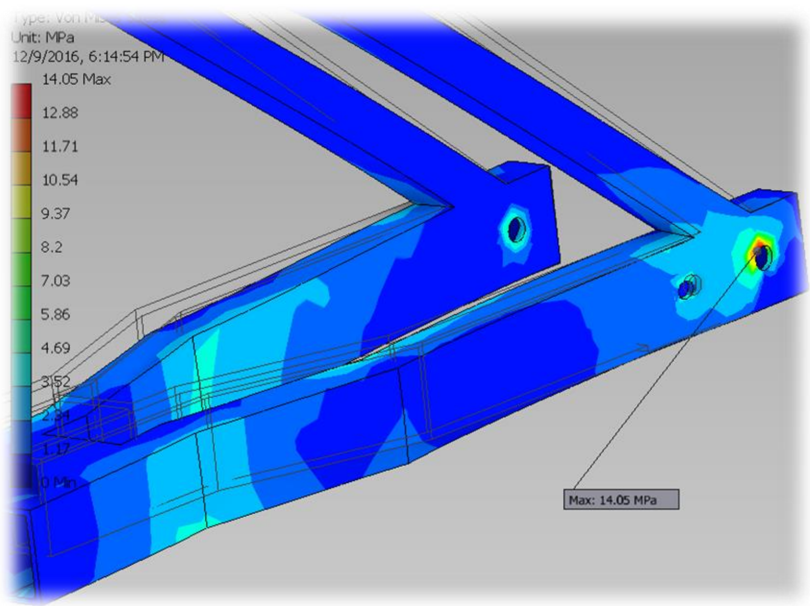


Figure 4.2.4: Bike Frame FEA Analysis (Critical Area)

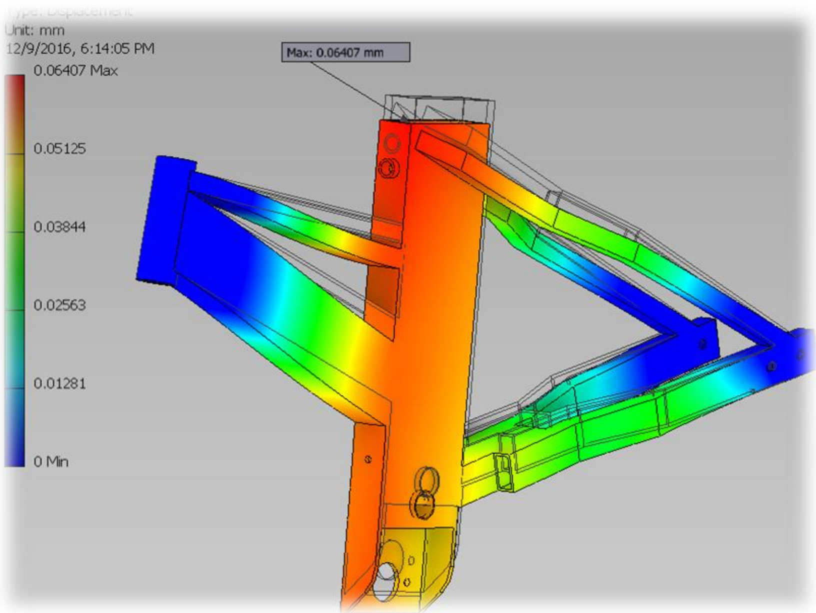


Figure 4.2.5: Bike Frame FEA Analysis (Displacement)

4.2.3 Front Gearbox

The design of front gearbox followed several criteria:

1) Consistent with the recommendations of AMESim optimizations;
2) Enough clearance with the environment; and
3) Less gear abrasion.

The AMESim model determined the optimal gear ratio for the front to be 1: 6.16. Based on the desired gear ratio, the team went to one of their sponsors, Misumi USA, and acquired the best gear combination Misumi can provide. One stage transmission can meet the requirements here, and the final adapted front gear ratio is 1:6.32 (19/120).

This front gearbox design takes the lower part of the seating tube to be the support of the gearbox. This effort can minimize the error of the distance between gears because all of the machinings would be done on one single piece of material. Therefore, there would have less gear abrasion. In addition, though the machining of the gearbox was done along with the frame, special tolerance was required at this place. Careful attention was paid when designing the drawing of the plate. Before actual machining, the front gearbox assembly was put into the CAD model shown in Figure 4.2.6 to see the show if there is enough clearance with the environment.

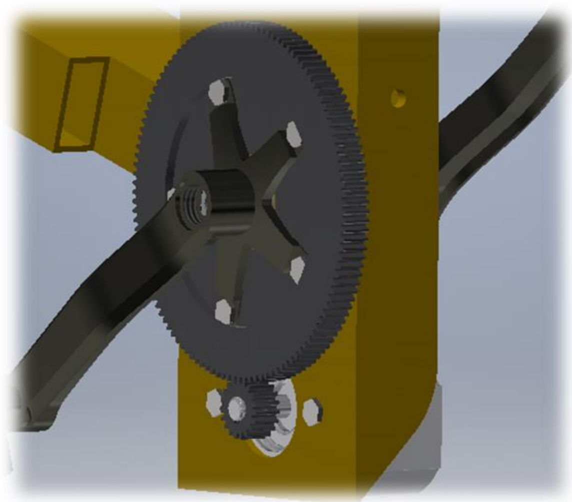


Figure 4.2.6: Front Gearbox CAD Model

4.2.4 Motor Gearbox

The design of motor gearbox also followed the same criteria:

1) Consistent with the recommendations of AMESim optimizations;
2) Enough clearance with the environment; and
3) Less gear abrasion.

The AMESim model determined the optimal gear ratio for the motor to be 5.7: 1. Again, the best gear combination found at Misumi USA was 100/17, in turn making a final gear ratio of 5.9: 1. An extensional plate was designed to hold the motor. The plate is made of aluminum to reduce weight, and it was machined under careful calculations and sketching to make sure the gear distance is reliable so that gears can engage properly. The motor gearbox assembly was then put into the CAD model to ensure enough clearance with the environment. This is shown in Figure 4.2.7.

Besides the wheel-to-motor gear transmission, there is also an internal gear hub allowing gear shifting. The internal gear hub model used was Shimano Alfine 8-Speed. This model was chosen for its flexible control. The rider can switch gears via electrical signals during the ride. This internal gear hub provides 8 different gear ratios from a minimum of 0.5: 1 to a maximum of 1.6: 1. This feature makes the bike easier to start and also have higher full-speed, while the average ratio is still maintained within a small range around the target.

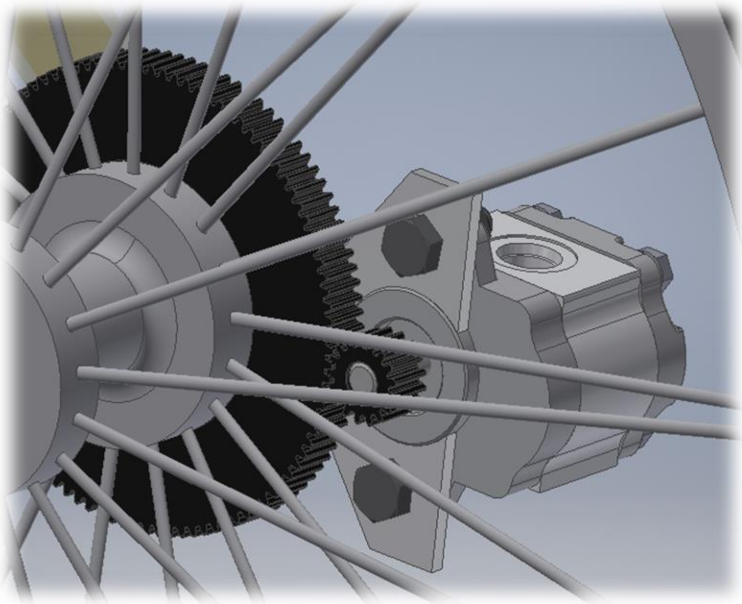


Figure 4.2.7: Motor Gearbox CAD Model

4.2.5 Regeneration Pump Gearbox

The regeneration system went through phases from initial design to demanding improvements, to alternative design & re-evaluation, and to the final design. Though the whole regeneration system does not improve the vehicle performance, the team had put many efforts in it, because regeneration is an interesting and potential feature. The team wants to demonstrate their innovation, and the whole design process turned out to be a best practice to the team members.

The main difference between the initial design and the final design is the number of transmission stages. The initial design has up to four stages including a 1:1 stage only to reverse the rotation. It is too cumbersome compared to the alternative design which has only two stages. A list of the stages is shown below in Table 4.2.2.

Table 4.2.2: Regeneration Pump Gearbox Stages

# Design	First stage	Second stage	Third stage	Fourth stage	Total ratio
Initial	56: 20	20: 20	48: 20	50: 20	16.8: 1
Alternative/ Final	120: 20	56: 20	/	/	16.8: 1

When the prototype of the initial design came out, a lot of improvements were needed. For example, the initial design did not take it into consideration that the gears in the first stage are always working along with the wheel, so the first stage should have very low friction. Otherwise, the bike would stick here. The solution is to have something like a bearing. However, due to the limited space in this prototype, this could not be achieved. It was then an alternative design came out. The team liked the latest one for its light design. Reducing the stages helps reduce the weight, as well as the difficulty to machine the support plate. Plus, the newer version took the lesson from the earlier one, making the first stage rotate freely with a bearing. Figure 4.2.8 shows the comparison between the two designs. Apparently, the final selected design is much light, efficient and compact.

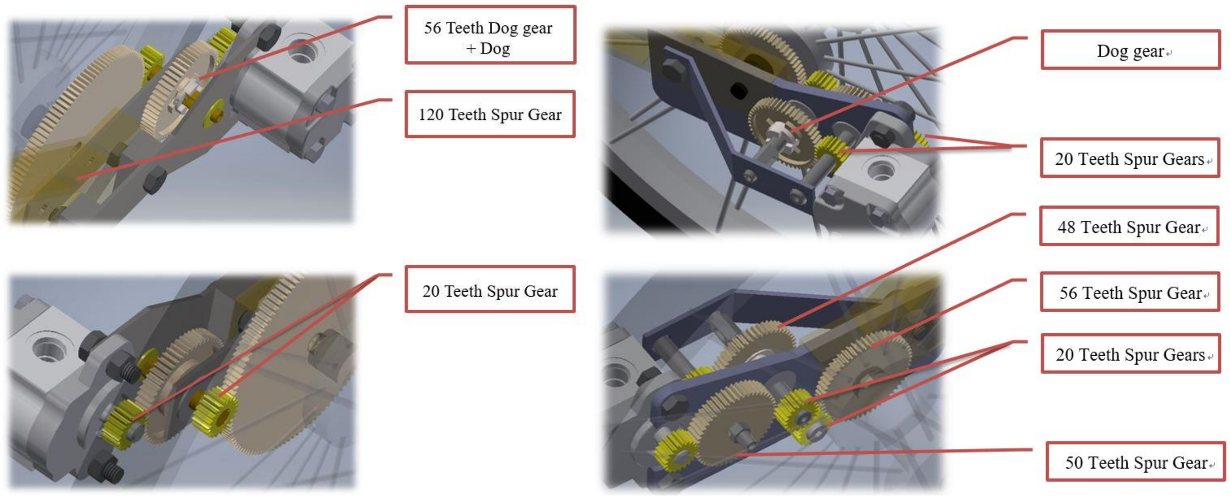


Figure 4.2.8: Regeneration System Comparison
Alternative/Final Design (Left); Initial Design (Right)

4.3 Electronic Control System Design

The electronic system is designed to achieve better interaction between users and hydraulic systems, as well as improve the safety and intelligence of the vehicle. To realize those goals, considerations were made during the designing process. To begin with, the electronic system uses a smartphone as the platform to build on the electronic system. As the most prevailing electronic device, the smartphone is familiar to everyone, which makes the system capable of extensive spreading and have commercial potential. Besides, the electronic system facilitates the control procedure. Compared to conventional controls, it is no longer necessary for users to develop knowledge in electronic circuits. The control processes have already been translated into codes and users only need to click the buttons on the screen. In addition, the electronic system provides insights for some areas of research and real applications. Applying the idea of “Internet of Things (loT)”, the system targets at providing an interactive user experience for machine controls. Pressure, velocity, and heart rate information are collected and interpreted automatically before being displayed to the users, with intellectual control and supplementary functions enabled. Besides, the concepts of the remote control are used in the design. Instead of using wires, the team chose BLE as the method of data transmission to enable the users to control and get the data without much space limitation.

The electronic system is designed to enable users to interact with the hydraulic vehicle system through smartphone applications. The data display function is achieved using a smartphone, Arduino and Bluetooth Low Energy (BLE). The general connection between each device are shown in Figure 4.3.1 and the detailed explanation will be shown in the following chapters. The electronic system has two parts – receiving part and control part. For one thing, by obtaining information from pressure, velocity, and heart rate sensors, Arduino analyzes, calculates data and transmits them wirelessly through BLE. Integrating smartphone into the system, the electronic system displays vehicle information directly on the screen. For another, the electronic system enables users to control the hydraulic systems. Buttons on screen concerning mode and gear ratio change are developed, as well as a recommendation window indicating the personal health condition and proper mode change.

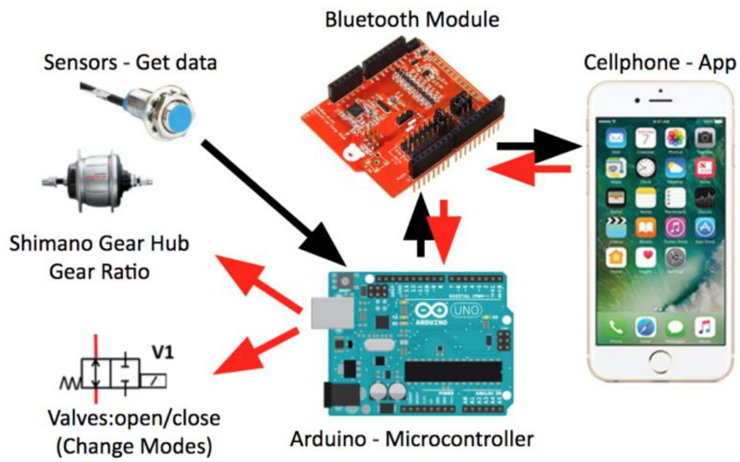


Figure 4.3.1: General Connection between Devices

4.3.1 Mobile Phone Application Development

The total functions of the application can be divided into 4 categories: Bicycle Control, Data Display, Supplementary functions and contact section. Hierarchy of smartphone functions is shown in Figure 4.3.2. The Homepage of the application is in Figure 4.3.3.

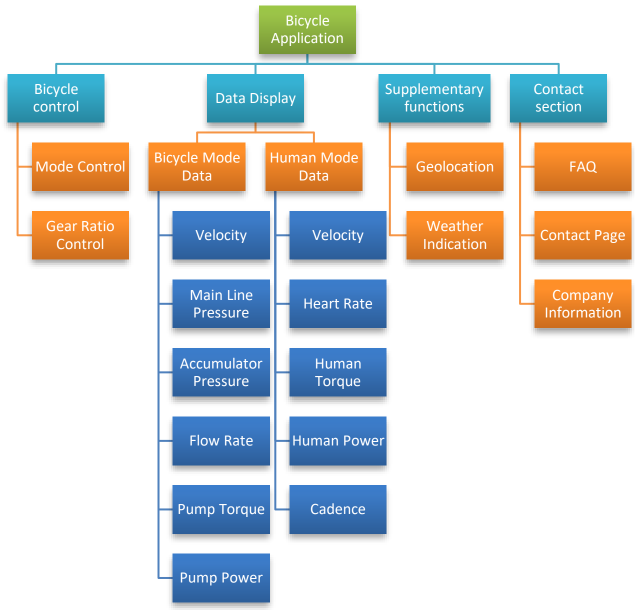


Figure 4.3.2: Hierarchy of Smartphone Functions

Both the bicycle control and data display are placed in one page shown in Figure 4.3.3. The canvas on the top includes the information for velocity, gear ratio, heart rate and efficiency. Followed by three buttons used to switch different modes. As shown in the previous chapters, four modes are developed in the hydraulic system. The pedaling, charging and boosting mode can be adjusted and the regeneration mode will be set automatically when the user brakes. The block after the buttons is used to display all the collected data, including flow rate, torque, mainline pressure and accumulator pressure. The information of gear ratio is also shown in this block. Users can change gear ratio using the buttons on the screen or simply touch the higher or lower half part of the screen, meaning adding and decreasing gear ratio, respectively. A recommend block is shown in the bottom to recommend the users to change the mood. For example, when the accumulator is full, the recommend block will tell the user to switch to the "boosting mode" to relax and use the energy stored in the accumulator.

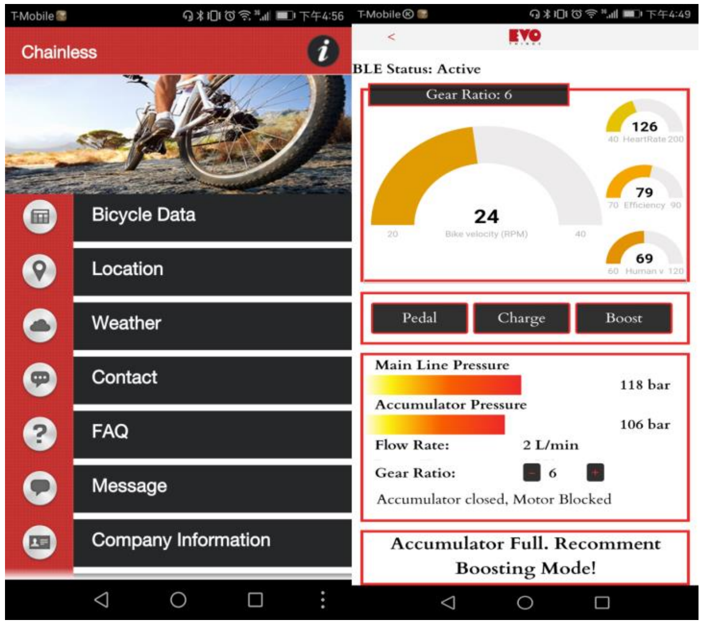


Figure 4.3.3: Homepage and Page for Data Transmission and Control

Despite the control and data display function. The application also has some supplementary functions to facilitate the use. Geolocation function is included in the application. Users can know their current location and set their favorite spots to go. The function can execute the Google map application on the smartphone use its functions like navigation. In addition, users can get the information of weather in the following hours or days. This function enables the users to choose a proper time to go out to avoid unexpected rains or other bad weather. The functions of geolocation and weather indication are shown in Figure 4.3.4.

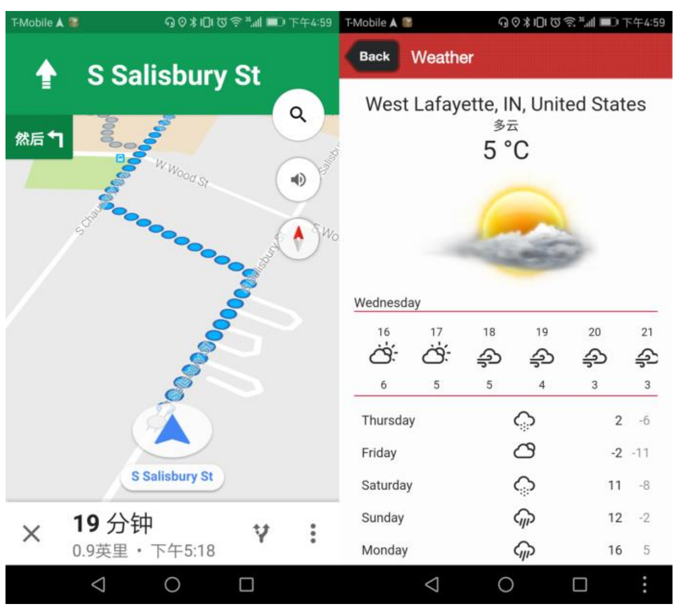


Figure 4.3.4: Geolocation and Weather Indication

Despite those functions, the application provides users quick access to answers when meeting with problems. FAQ sections are developed to show the solutions to most frequently asked problems. In addition, users can contact the team by sending the picture and description through the contact page shown in Figure 4.3.5.

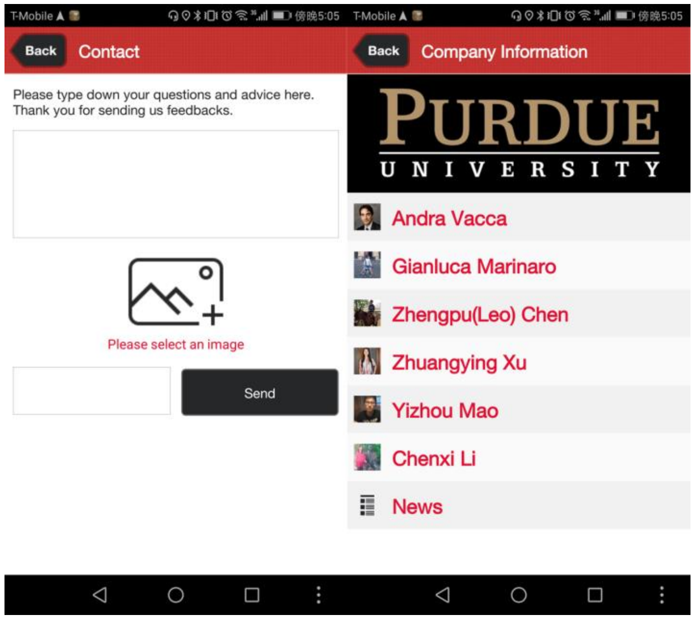


Figure 4.3.5: Contact Page of Application

In conclusion, the functions of the application include the bicycle control, data display, supplementary functions and contact section. This application can not only enable the users to know the current condition of their chainless vehicles but can also make the vehicle control more automatic and easy.

4.3.2 Hardware Interaction

The data transmission between Arduino and smartphone is bidirectional and wireless, with BLE serving as a transmitter. The setup of data transmission is shown in Figure 4.3.6.

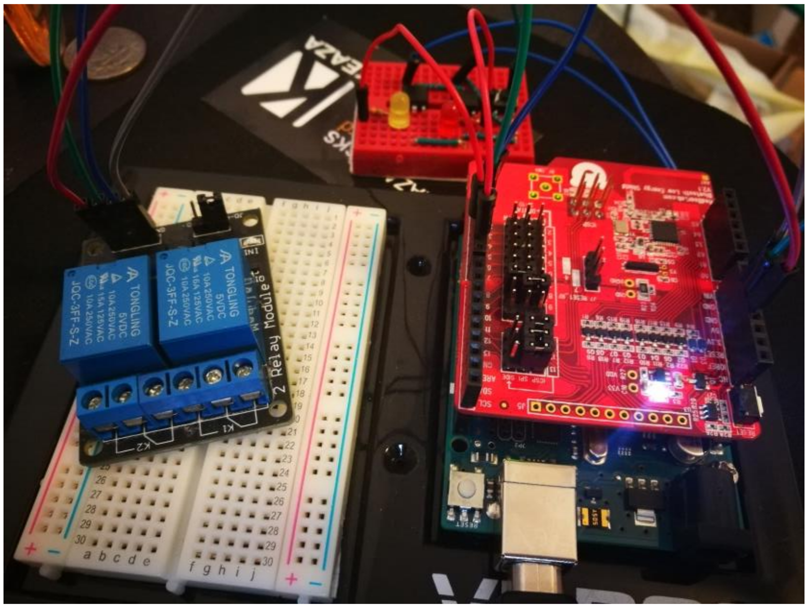


Figure 4.3.6: Setup of Data Transmission

- Data transmission and data display

For the data transferred from Arduino to a smartphone, different sensors are used to collect data of velocity, heart rate, and pressure. The detailed explanations are shown in the following chapters. To transmit the data, sensor variables are defined in variable short and are combined to be a buffer with an order for the smartphone to interpret. Specifically, a 40-byte-long buffer is declared and transmitted using the BLE embedded functions.

When receiving data on the smartphone, the programming parts include several aspects, the scanning, connection, data sorting and data display. The programming is based on JavaScript and HTML, supported by the BLE library (based on Cordova). After the BLE has been successfully connected to BLE, function in JavaScript sorts out the data by dividing the 40-byte-long buffer to pieces of four. Referring to the function of defining the variable order in Arduino, different data can be selected to display in corresponding places. The functions of each hardware are shown in Figure 4.3.7.

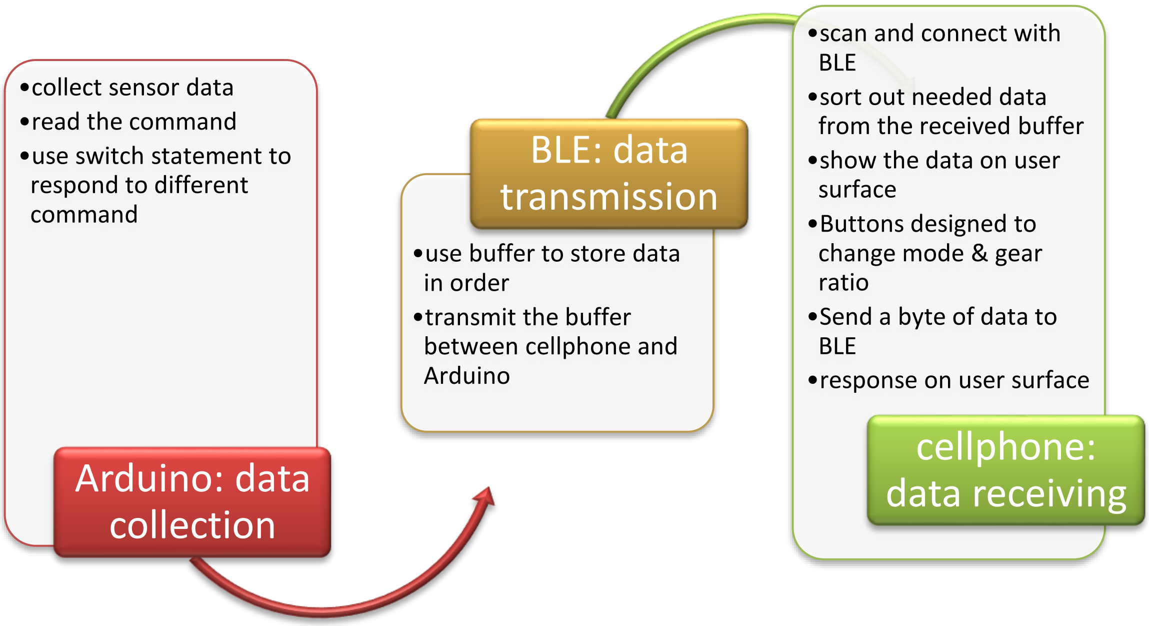


Figure 4.3.7: Functions Performed by Each Hardware

- Interpretation of command

The interpretation of command is achieved through the following procedure: transmitting command from smartphone to Arduino, distinguishing different command and executing corresponding actions.

In the part of command transmission, buttons are developed as part of the user interface. When any of the buttons is pressed, a one-byte command will be sent to the BLE. There are 5 types of command, three used for mode changes and two for gear adjustment. Functions from BLE library are called and screen response is made to indicate the readers whether the command is transmitted or not.

After getting the data, a switch statement in Arduino is used to define functions for a different command. For the command of mode change, pin voltages are changed and relays are used to control the on or off of the valves. As indicated in the former chapters, the valve close to accumulator would be closed, open and open in pedaling, charging and boosting mode respectively and the valve close to motors would be open, closed and open in these three conditions. As to the command of gear change, optoisolators are used to control the connection of the circuit. When the button on the smartphone is clicked, a voltage impulse would be generated by Arduino and enable the Shimano devices to change the gear ratios. The detailed explanations of the hardware are shown in the following chapters.

4.3.3 Hardware Explanation

Hardware apart from the ones involving wireless transmission can be divided into two categories, sensors for data collection and device for command executing. Five sensors are applied in this system, two RPM Sensor, one reporting the translational speed of the vehicle, the other determining the cadence of the rider, two Pressure Sensors, indicating the pressure within the accumulator and the main line of the hydraulic circuit, and one heartbeat sensor, monitoring the heart rate of the rider. The diagram of the placement of the sensors can be found in Figure 4.3.8.

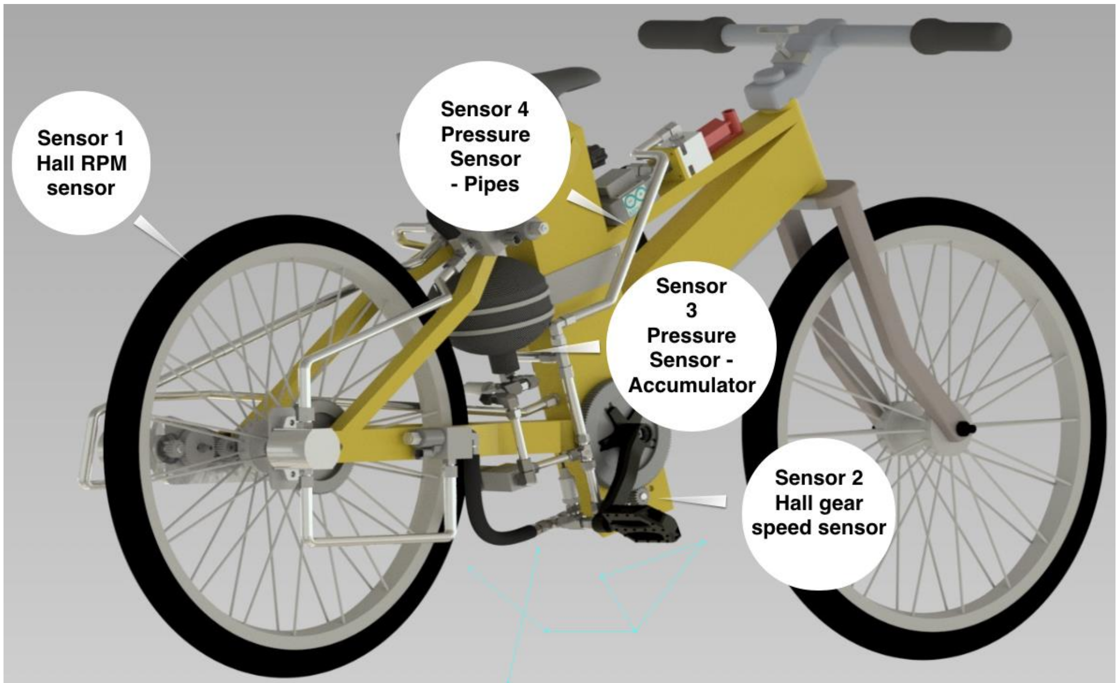


Figure 4.3.8: Placement of Different Sensors

As for the control functions, the team lightly dismantled a Shimano Alfine Di2 E-tube unit, exposing two pairs of pins which sent a signal to the gear hub to shift up or shift down when connected. The process of gear ratio adjustment is achieved according to the user input on a smartphone. Two on-off valves are placed on the vehicle to enable different three riding modes. For regeneration modes, a brake lever with diverse voltage input is used to generate distinguishable signals. By interpreting the signals in Arduino, the proportional control on the pressure of regeneration valve is realized.

- Velocity Sensor: Hall Proximity Switch Sensor

The team chose to use the hall sensor to measure the vehicle's speed of the wheels and gear. The measurement applies the principle of electromagnetic induction. A small magnet was installed on the wheel, which would rotate with the wheel. Every time when the magnet gets close enough to the sensor, it will generate a pulse which can be detected by Arduino. The micro-controller can record the interval and calculate the real RPM of the wheel and gear.

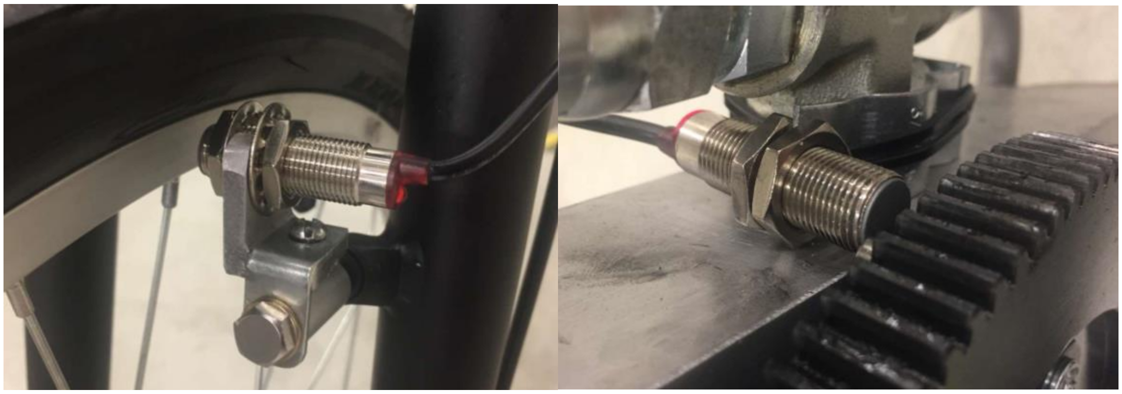


Figure 4.3.9: Hall Proximity Switch Sensor (Bike Velocity: Left / Gear RPM: Right)

- Pressure Sensor: Parker's IQAN-SP Pressure Sensor

The team chose to use Parker's IQAN-SP pressure sensor, which can measure 0 – 500bar hydraulic pressure. The pressure signal is changed into a voltage in the sensor. Then the voltage signal is transmitted to micro-controller and is processed to be displayed. The signal range is ideal for mobile equipment, being 0.5 - 4.5 VDC over the full scale of the sensor.

Figure 4.3.10: Pressure Sensor(Accumulator: Left / Main line: Right)

- Heart Rate Sensor: Pulse Sensor Amped

The Pulse Sensor Amped essentially combines a simple optical heart rate sensor with amplification and noise cancellation circuitry making it fast and easy to get reliable pulse readings. It sips power with just 4mA current draw at 5V so it's great for mobile applications. The rider can simply clip the Pulse Sensor to the finger and read the current heart rate data, which is very convenient to use.

Figure 4.3.11: Heart Rate Sensor

- Shimano Gear Ratio Control

To enable better user experience, Shimano (ALFINE S705 Series) are used for the adjustment of gear ratios. The series includes several parts and is already an integrated system for gear change. Shimano series include massive hardware, with levers (ST-S705) controlling the brake of the vehicle, shifting switch (SW-S705) collecting human kinematic input, Information display (SC-S705) showing current gear ratio, Motor unit (MU-S705) executing gear adjustment, Lithium-ion battery (SM-BTR1) providing 7.4V electricity, and junctions, battery mount, wires connecting different devices.

The team made changes to the Shimano series to combine it together with other electronic circuits. To be specific, the shifting switch is rebuilt. The cover and the mechanical button of the switch is abandoned, with the inner connection exposed. Figure 4.3.9 shows the inner structure of the switch. Point A and point B are places for gear change. When the golden places in each point are connected, a signal would be generated to change the gear ratios. To control the gear adjustment, the team connected four electronic lines to these four golden places and added an optoisolator into each of the circuits. The hardware setup and schematic for optoisolator are shown in Figure 4.3.9.

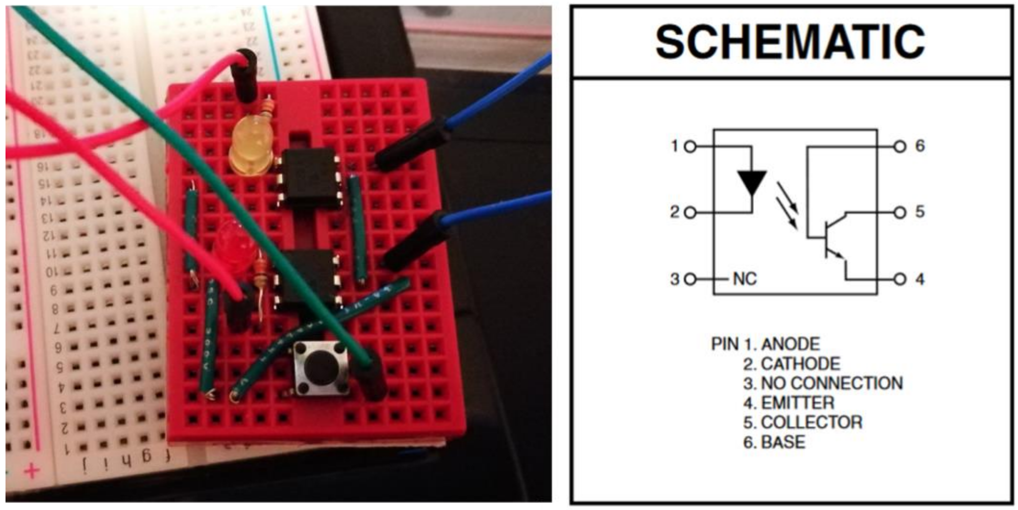


Figure 4.3.12: Hardware Setup for Gear Change and Schematic of Optoisolator

Optoisolator is one electronic part to control the second circuit by changing the voltage input in the first circuit. As shown in Figure 4.3.12, pin 1 is connected to one digital output of Arduino, pin 2 is connected to the ground, pin 5 and pin 4 are connected with the circuit involving Shimano (connected with the black and red line in Figure 4.3.12). When a command for gear change is detected by Arduino, one high voltage input would be generated in the digital output. The voltage difference between pin 1 and pin 2 makes the LED light and furtherly makes pin 5 and pin 4 connected with each other. Therefore, the second circuit is connected and the function performed by the original switch is alternated using the self-designed circuit.

- On-off Valves Controls

Apart from gear control, the electronic system also performs well on vehicle mode control. As mentioned in previous chapters, the hydraulic vehicle is able to switch between 4 different modes. Among them, the regeneration mode is executed automatically when users break, but the others can be controlled by interpreting commands on valves controls. There are two on-off valves in the hydraulic system. One is to control the flow passing through the motor (valve 1) and one is for accumulator control (valve 2). In the pedaling mode, valve 1 is open and valve 2 is closed. This structure enables human to move the hydraulic vehicle by pedaling, simulating the experience provided by traditional bicycle. In charging mode, valve 1 is closed and valve 2 is open to make the energy stored in the accumulator. In this mode, the vehicle would not move and the pressure in the accumulator will increase. By contrast, boosting mode enables users to enjoy the automatic movement of the bicycle without exerting extra human torque. In this mode, both valve 1 and valve 2 are open.

To execute the on-off valves, a battery of 12V is selected to provide enough voltage. To separate the Arduino circuit and the valve circuit and enable unidirectional control, the relay is chosen for the interaction between two circuits. The setup of the relay-involved circuit and details of the relay are shown in Figure 4.3.13.

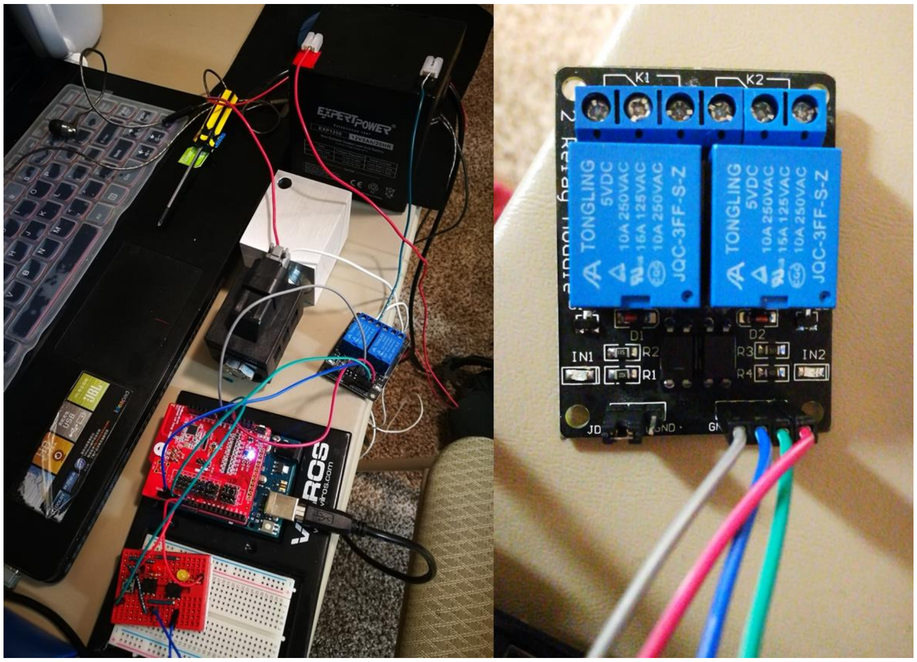


Figure 4.3.13: Setup of Circuit Involving Relay and Relay Hardware Details

The input of relay includes a power-supply pin (VCC), a ground pin (GND) and input pins (In1 & In2). As shown in the graph, pin A is connected to pin B in normal condition. But when the In1 pin is connected to a low input, pin A would connect to pin B and disconnect with B. In the electronic system, the team connect the input pins to the digital outputs of Arduino and connect the output pins to the circuit of on-off valves, with valve 1 remains normally open and valve 2 remains normally closed. In this way, the controls on on-off valves are realized.

- Proportional Relief Valve Control

A brake lever, a proportional button, and several relief valves are used to switch different modes. The brake level engages the dog gear mechanically and can switch the valves with an on-off signal. As relief valves can be set at higher pressure with a lower voltage signal, the proportional button is used to send a proportional signal to Arduino. Arduino process the signal and send certain voltage to relief valves to control the pressure. The proportional button can generate a higher voltage when being pressed by the rider. The higher voltage would be sent to Arduino as input. After being processed by Arduino, a lower voltage output would be sent to relief valve to set valve at higher pressure, which enhances the brake. The relationship between the input voltage to relief valve and the pressure is shown in Figure 4.3.14 below. In regeneration mode, the rider can pull the mechanical lever first and increase the braking by pushing the proportional button. The pictures of the relief valve and proportional button are shown in the Figure 4.3.15.

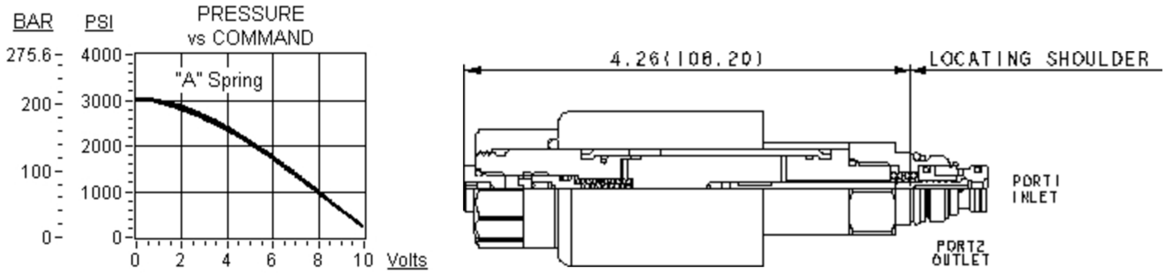
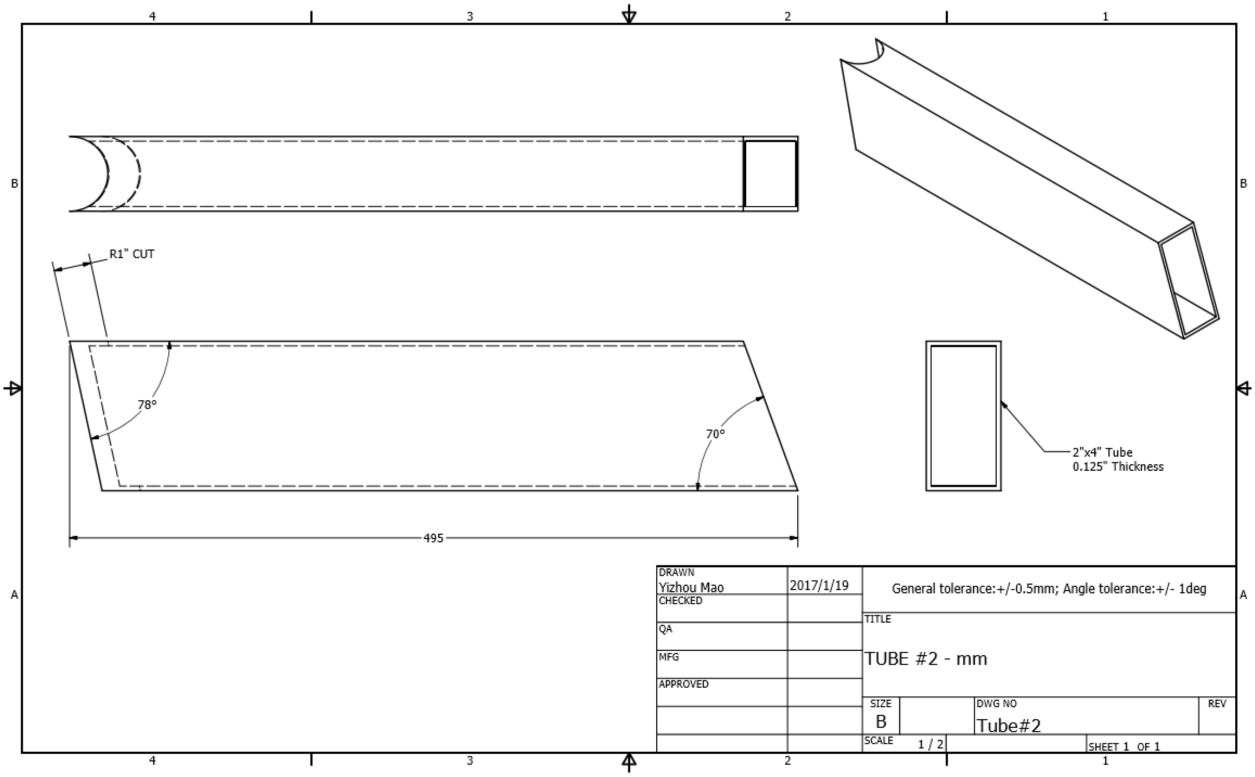


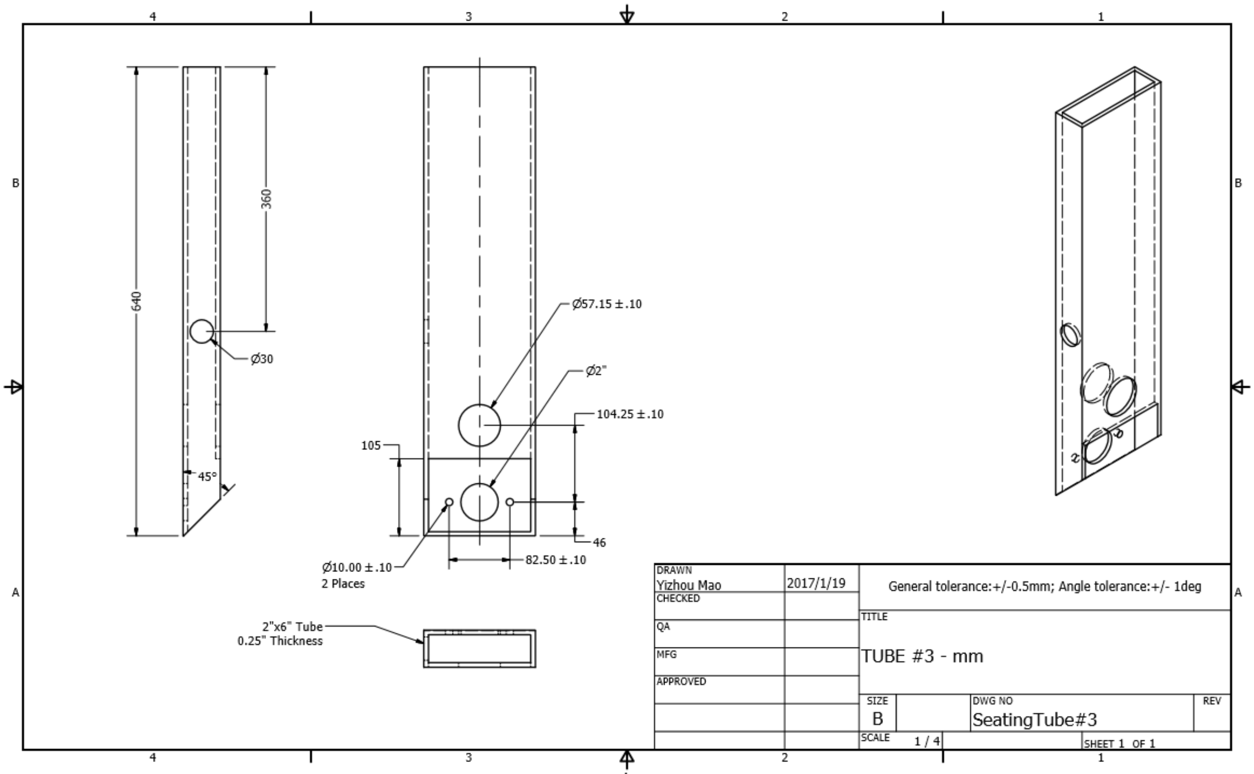
Figure 4.3.14: Relationship between input voltages and valve pressure (Left), Sketch of Relief Valve (Right)

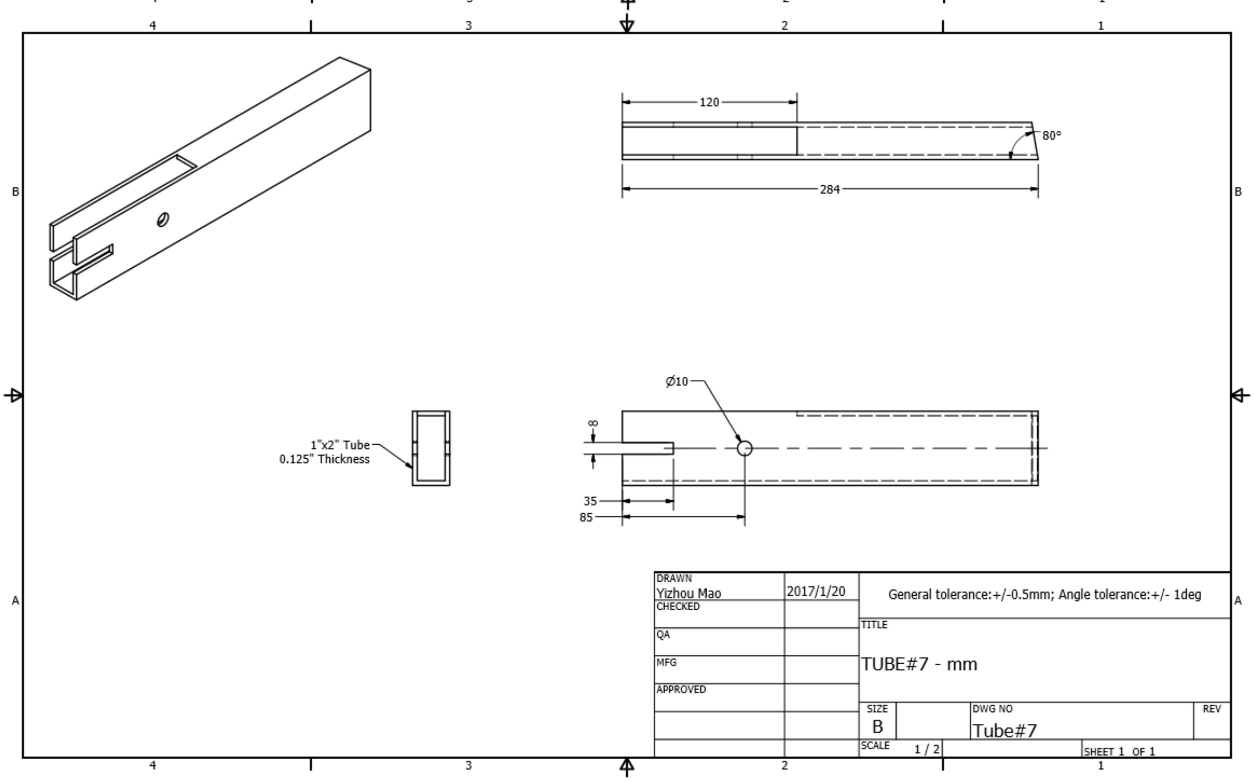
Figure 4.3.15: Relief Valve (Left) / Proportional Button(Right)

5 SELECTED DESIGN DRAWINGS

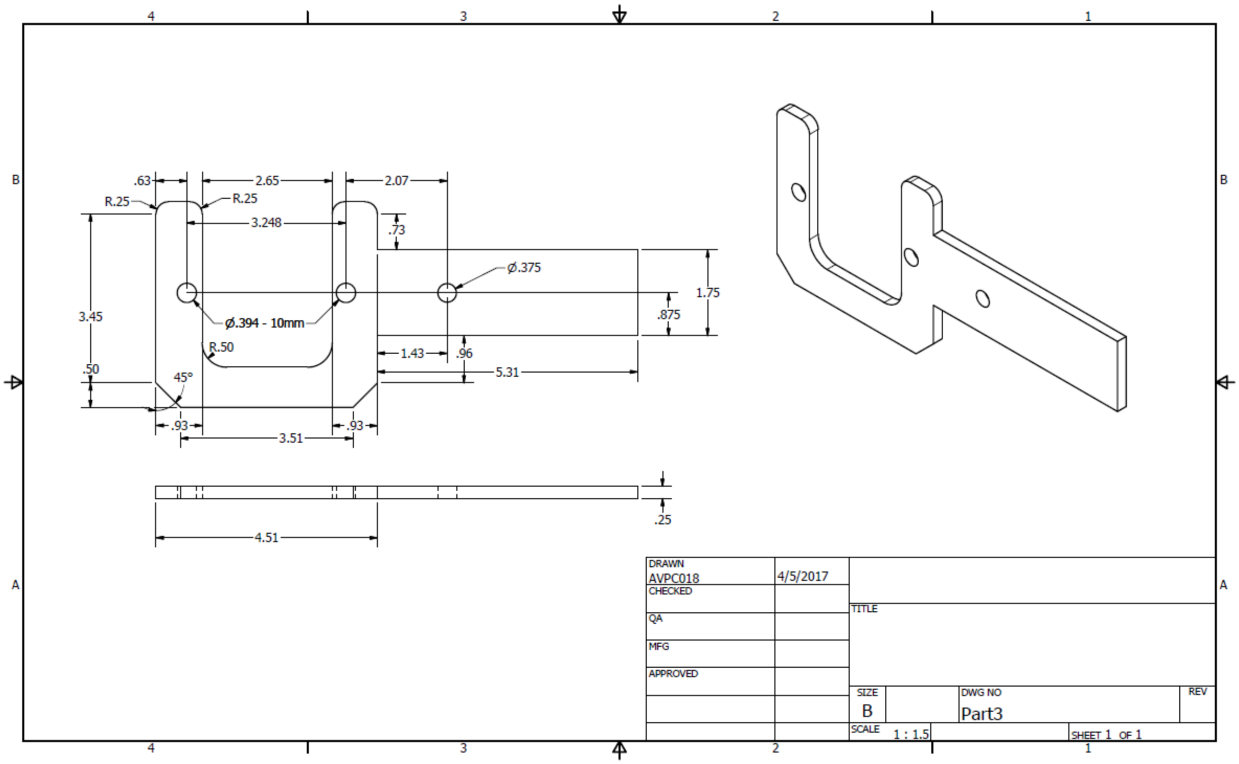
5.1 Frame (Tubes)



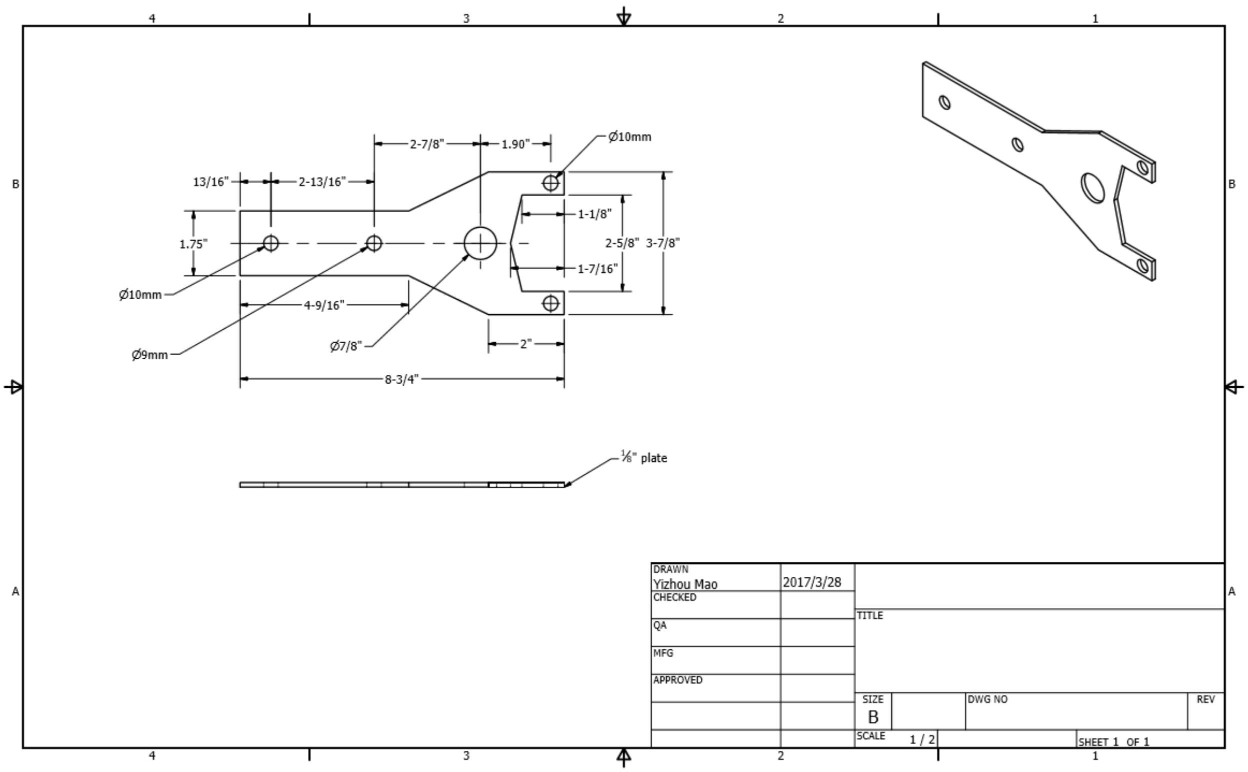

640
360
Ø30
45°
Ø57.15 ± .10
Ø2"
104.25 ± .10
105
46
82.50 ± .10
Ø10.00 ± .10
2 Places
2"x6" Tube
0.25" Thickness
DRAWN
Yizhou Mao
2017/1/19
General tolerance:+/-0.5mm; Angle tolerance:+/- 1deg
CHECKED
TITLE
QA
MFG
TUBE #3 - mm
APPROVED
SIZE
B
DWG NO
SeatingTube#3
REV
SCALE 1 / 4
SHEET 1 OF 1


120
80°
284
Ø10
8
1"x2" Tube
0.125" Thickness
35
85
DRAWN
Yizhou Mao
2017/1/20
General tolerance:+/-0.5mm; Angle tolerance:+/- 1deg
CHECKED
TITLE
QA
MFG
TUBE#7 - mm
APPROVED
SIZE
B
DWG NO
Tube#7
REV
SCALE 1 / 2
SHEET 1 OF 1

5.2 Motor Gearbox Plate



5.3 Regeneration Pump Gearbox Plate



6 COMPONENT LIST

Table 6.1: Component List

	Item	**Note**	**Quantity**
Casappa	PLP10.4 S0-30S0-LOB/OA-N-EL-C	Pump	1
	PLM10.2 D0-30S0-LOA/OB-N-EL	Motor	1
	PLP10.4D0-30S0-LOB/OA-N-A-EL FS	Regeneration pump	1
Eaton	SV3-8-O-6T-12DNS-00	On-Off Valve, NO	1
	C35315x6	Fittings	10
	C35315x6x8	Fittings	2
	C35315x8	Fittings	6
	C35515x6	Fittings	1
	C35515x8	Fittings	2
	C35705x6	Fittings	2
	C35705x8	Fittings	2
	C35955x6	Fittings	2
	C35505x6	Fittings	2

	C35505x8	Fittings	2
SunSource	1906R-5	Check Valve	1
	1908R-5	Check Valve	1
	Mobil	Oil	5gal.
Parker	SP-500 PN: 2820009	Pressure sensor	2
SunHydraulics	RBANXAN912N	Inverse relief valve	1
	DTDBXCN912N	On-Off Valve, Nc	1
SteelHead Composites	AD30CW200CA1R	Accumulator	1
Misumi	GEAHBB1.5-120-15-A-49-WDH-Q127-R127-S5-T5	Spur Gear	1
	GEAKBB1.5-19-15-A-12N	Spur Gear	1
	GEAHBB1.5-100-15-A-45-WDH-Q110-R110-S3-T9	Spur Gear	1
	GEAKBB1.5-17-15-A-12N	Spur Gear	1
	UNUTSZ6	U-Nuts	8
	SSLW6	Spring Washer	6
	RSCB6-60	Bolts	4
	RSCB6-30	Bolts	6
	RSCB4-20	Bolts	10
	SSLW4	Spring	10
	UNUTSZ4	Nuts	10
	A6061P-6F-MMA-NNS-350-300-6.35	Support Plate	1
AndyMark	am - 3568	Dog gear	1
	am - 3491	56 tooth gear	1
	am - 0186	20 tooth gear	2
	am - 0029	1/2" ID bearing	1
	am - 0030	1/2" ID ball bearing	1
	am - 0028	3/8" ID ball bearing	1
	am - 0147	Shaft (Hex)	1
Shimano	Shimano Alfine Di2 SG-S505	Internal gear hub	1
	Shimano Alfine Di2 MU-S705	Motor unit	1
	Shimano Alfine Di2 SC-S705	Display unit	1
	Shimano Alfine Di2 S705	Right Hand Flat Bar shifter	1
	Shimano Ultegra Di2 SM-JC41	Junction box	1
	Shimano Ultegra Di2 EW-SD50	Electric wire	4
	Shimano Dura-Ace Di2 SM-BTR1	Di2 battery	1
	Shimano SM-BMR2	Battery mount	1
	Shimano Di2 SM-BCR1	Battery charger	1
	Shimano Di2 for SM-BCR1	Charger cable	1
OnlineMetals	2x6x0.25	Allumin. Tube [HxWxW]	36"

	2x4x0.125	Allumin. Tube [HxWxW]	24"
	1x2x0.125	Allumin. Tube [HxWxW]	72"
	2x2x0.125	Allumin. Tube [HxWxW]	24"
	1x1x0.125	Allumin. Tube [HxWxW]	84"
	2x1.25x0.375	Allumin. Tube [ODxIDxW]	24"
	2.25x2x0.125	Allumin. Tube [ODxIDxW]	11"
Other	Bottom bracket adapter		1
	Bottom bracket cartridge		1
	Crank arm set		1
	Pedals		2
	120 tooth gear		1
	3/8"-0.5" SS pipe		3ft
	3/8"-0.5 hose		10ft
	Arduino UNO		1
	Arduino Nano		1
	Bluetooth LE Shield		1
	Shift Register		2
	Hall Sensor		2
	Back Light		1
	Proportional Lever		1
	Optoisolator		2
	Relay		1
	Battery		1
	Dopunt Wire		1
	buttons		2
	Heart rate sensor (Arduino)		1
	Brake lever (set of 2)		1
	Stands (set of 2)		1
	Fork		1
	Stem		1
	Handlebar		1
	Tire		2
	Inner tube		2
	Rim		2
	Rim tape		2
	Spokes		68
	Grips (set of 2)		1
	spacer		3

	Headset		1
	Saddle		1
	disc brake		1
	Phone holder		1
	Seat post clamp		1

7 ACTUAL TEST DATA COMPARED TO ANALYSIS

7.1 Model refinement

The experimental results can inform a set of refinements to the original model. The model will be improved the resistance calculations, specifically by changing coefficients and adding wind resistance. While including variable resistance torque caused by variable shifting would improve accuracy, the complexity it would add to the calculation is not worth the benefits to accuracy it would bring. To demonstrate that the above modifications yield a more accurate model, diagrams of the refined boost function can be found below.

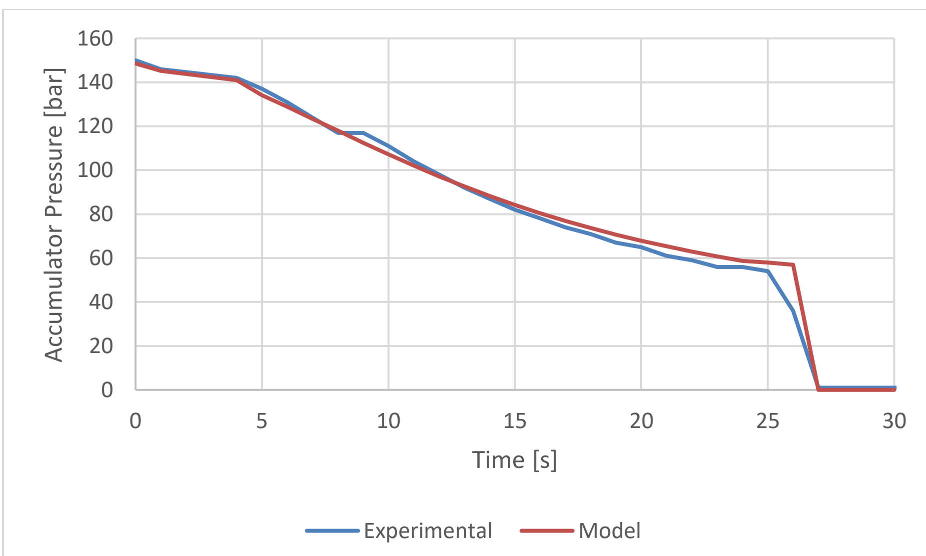


Figure 7.1.1: Accumulator Pressure: Experimental vs Model (55 bar pre-charge)

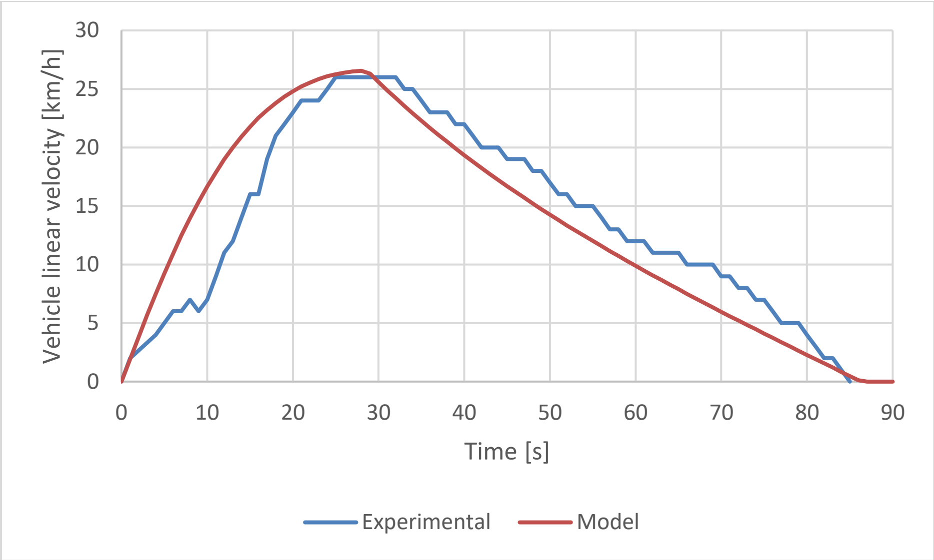


Figure 7.1.2 Vehicle linear velocity: Experimental vs Model (55 bar pre-charge)

7.2 Reoptimization

After refining the model, a new AMESim optimization function must be used to determine a new set of optimally sized hydraulic components. Due to the constraints of the competition, the team does not have the time to rebuild the prototype based on this new information. However, the new components could be applied to the mass-produced commercial iteration of the vehicle, making the commercial PurdueTracer structurally similar, but hydraulically and technically more effective than the prototype.

8 COST ANALYSIS

A good design which is successful in the marketplace not only need to have desirable functions satisfied customers' demand, but also have to be cost effective. The team strives to seek the balance between the quality and the cost of the components, in order to achieve the goal of higher quality with lower cost. In this section, a detailed cost analysis is made for the prototype vehicle as well as the production vehicle. According to the competition requirement, the labor rate is assumed to be $60 per hour and the scale of production is 500 units per year. In addition, three different versions of the vehicle with specific functions are presented. This provides customers the ability to make the selection based on their purchasing power and needs.

8.1 Prototype Vehicle

Due to the complexity of the design, the team groups the components of the prototype vehicle into several subsystems as shown in Table 8.1, including Frame, Front Gear Box, Motor Gear Box, Regeneration Gear Box, Hydraulic Circuit, Electronics, and Bicycle Part, to clearly present the cost analysis. For each subsystem, the total cost is the sum of custom parts cost, purchased parts cost and assembly labor cost. Abbreviation is used for types of machining, in which S stands for cutting, W stands for welding, M stands for milling, B stands for bending. The cost of custom parts includes the material cost and labor cost for the machining process. Then, the cost of subsystems is added up to calculated the cost of the whole prototype vehicle.

Table 8.1 Prototype Vehicle Cost Analysis

Frame					
Custom parts	**Material Cost [$]**	**Machine**	**Machining [h]**	**Labor cost**	**Total Cost [$]**
Aluminum	223.00	S, W, M	8	480.00	703.00

Front Gearbox					
Purchased Parts	**Quantity**	**Cost per 1 Ea. [$]**			**Total Cost [$]**
Pump	1	72.75			72.75
Bottom bracket adapter	1	16.25			16.25
Bottom bracket cartridge	1	17.95			17.95
Crank arm set	1	64.95			64.95
Pedals	1	18.89			18.89
Spur gear (Pedal)	1	114.87			114.87
Spur gear (Pump shaft)	1	23.28			23.28
Bolt	2	2.18			4.36
Nut	2	0.15			0.30
Washer	2	0.18			0.36
Assembly	**Hours [h]**				**Total Cost [$]**
	1				60

Motor GearBox					
Custom parts	**Material Cost [$]**	**Machine**	**Machining [h]**	**Labor cost**	**Total Cost [$]**
Support plate	48.78	S, M	2	120.00	168.78
Shimano adapter plate	15	S	1	60.00	75.00
Purchased Parts	**Quantity**	**Cost per 1 Ea. [$]**			**Total Cost [$]**

Motor	1	83.31			83.31
Spur Gear (Motor)	1	22.90			22.90
Spur Gear (Wheel)	1	103.86			103.86
Bolt	2	2.18			4.36
Nut	2	0.15			0.30
Washer	2	0.18			0.36
Assembly	**Hours [h]**				**Total Cost [$]**
	1				60

Regeneration Gearbox					
Custom parts	**Material Cost [$]**	**Machine**	**Machining [h]**	**Labor cost**	**Total Cost [$]**
Support plate (Pump)	20.00	S, M	1	60.00	80.00
Support plate (Wheel)	10.00	S, M	0.5	30.00	40.00
Engage system	10.00	S	0.5	30.00	40.00
Purchased Parts	**Quantity**	**Cost per 1 Ea. [$]**			**Total Cost [$]**
Pump	1	91.89			91.89
Dog gear	1	22.00			22.00
56 tooth gear (dog gear)	1	22.00			22.00
20 tooth gear	2	12.00			24.00
120 tooth gear	1	69.70			69.70
1/2" ID bearing	1	3.00			3.00
1/2" ID shielded ball bearing	1	2.00			2.00
3/8" ID shielded ball bearing	1	3.00			3.00
Shaft (Hex)	1	26.00			26.00
Bolt	4	2.18			8.72
Nut	4	0.15			0.60
Washer	8	0.18			1.44
Assembly	**Hours [h]**				**Total Cost [$]**
	2				120

Hydraulic Circuit					
Custom parts	**Material Cost [$]**	**Machine**	**Machining [h]**	**Labor cost**	**Total Cost [$]**
3/8"-0.5" SS pipe	30	B	2	120	150

3/8"-0.5 hose	30	S	3	180	210
Hand pump support	10	W, S, M	0.5	30	40
Accumulator support	10	S	0.5	30	40
Purchased Parts	**Quantity**	**Cost per 1 Ea. [$]**			**Total Cost [$]**
ON-OFF valve NO	1	106.5			106.50
ON-OFF valve NC	1	67.00			67.00
Relief valve	1	176.3			176.30
Hand pump	1	109.65			109.65
Accumulator	1	600			600.00
Check valve /6	1	25.76			25.76
Check valve /8	1	34.23			34.23
Fitting	30	4			120.00
Oil	5 gal.	64			320.00
Assembly	**Hours [h]**				**Total Cost [$]**
	5				300

Electronics					
Purchased Parts	**Quantity**	**Cost per 1 Ea. [$]**			**Total Cost [$]**
Arduino UNO	1	17.99			17.99
Arduino Nano	1	3.99			3.99
Bluetooth LE Shield	1	19.99			19.99
Shift Register	3	1.68			5.04
Hall Sensor	2	16.99			33.98
Back Light	1	6.98			6.98
Shimano Alfine Di2 SG-S505	1	169.96			169.96
Shimano Alfine Di2 MU-S705	1	114.11			114.11
Shimano Alfine Di2 SC-S705	1	89.99			89.99
Shimano Alfine Di2 S705	1	99.99			99.99
Shimano Ultegra Di2 SM-JC41	1	26.89			26.89
Shimano Ultegra Di2 EW-SD50	3	24.65			73.95
Shimano Dura-Ace Di2 SM-BTR1	1	24.99			24.99
Shimano Di2 SM-BCR1	1	54.44			54.44
Shimano Di2 for SM-BCR1	1	8.94			8.94

Proportional Lever	1	11.41			11.41
Optoisolator	2	0.23			0.46
Relay	1	2.99			2.99
Battery	1	33.99			33.99
Dopunt Wire	1	2.99			2.99
buttons	2	0.69			1.38
SP500 Pressure sensor	2	214.28			428.56
Heart rate sensor (Arduino)	1	2.2			2.20
Assembly	**Hours [h]**				**Total Cost [$]**
	2				120

Bicycle Parts					
Purchased Parts	**Quantity**	**Cost per 1 Ea. [$]**			**Total Cost [$]**
Brake lever (set of 2)	1	14.09			14.09
Stands (set of 2)	1	58.98			58.98
Fork	1	54.99			54.99
Stem	1	39.00			39.00
Handlebar	1	24.99			24.99
Tire	2	25.57			51.14
Inner tube	2	1.34			2.68
Rim	2	30.00			60.00
Rim tape	1	3.00			3.00
Spokes	68	1.00			68.00
Grips (set of 2)	1	8.88			8.88
spacer	3	0.50			1.50
Headset	1	14.07			14.07
Saddle	1	13.89			13.89
disc brake	1	40.00			40.00
Phone holder	1	14.99			14.99
Seat post clamp	1	7.97			7.97

The production of the prototype vehicle would not be successful without the generous donations from sponsors who greatly reduce the cost of the project. The main pump, regeneration pump and motor are provided by Casappa. The carbon fiber accumulator is provided by Steelhead Composites. Various valves and fittings are provided by Eaton. The pump gear, aluminum plate and various mechanical parts are provided by MiSUMi.

In all, the total cost of the prototype vehicle is calculated as $4237.14. The total cost without the donations from the sponsors is $6314.79.

8.2 Production Vehicle

The production vehicle cost analysis shown in Table 8.2 follows the same logic as the prototype vehicle cost analysis, which divides the whole system into subsystems. However, components and materials prices, machining and assembly time will be different from the prototype vehicle. The raw material and components prices will decrease when being purchased in bulk. The machining and assembly time will also decrease when the workers specialize in their work and the production process being optimized. These will result in a decrease of the total price of each vehicle; by analyzing prices online when possible, the price per u could be discounted from 66% to 75% of their original price when sold in high quantities, the team determined new cost assessments for the purchased components.

Table 8.2 Production Vehicle Cost Analysis

Frame					
Custom parts	**Material Cost [$]**	**Machine**	**Machining [h]**	**Labor cost**	**Total Cost [$]**
Aluminum	73.59	S,W,M	2	120.00	193.59

Front Gearbox					
Purchased Parts	**Quantity**	**Cost per 1 Ea. [$]**			**Total Cost [$]**
Pump	1	54.56			54.56
Bottom bracket adapter	1	12.19			12.19
Bottom bracket cartridge	1	13.46			13.46
Crank arm set	1	64.95			64.95
Pedals	1	14.17			14.17
Spur gear (Pedal)	1	75.81			75.81
Spur gear (Pump shaft)	1	15.36			15.36
Bolt	2	2.18			4.36
Nut	2	0.05			0.10
Washer	2	0.06			0.12
Assembly	**Hours [h]**				**Total Cost [$]**
	0.2				12

Motor Gearbox					
Custom parts	**Material Cost [$]**	**Machine**	**Machining [h]**	**Labor cost**	**Total Cost [$]**

Support plate	16.26	S,M	0.5	30.00	46.26
Shimano adapter plate	5	S	0.2	12.00	17.00
Purchased Parts	**Quantity**	**Cost per 1 Ea. [$]**			**Total Cost [$]**
Motor	1	62.48			62.48
Spur Gear (Motor)	1	15.11			15.11
Spur Gear (Wheel)	1	68.55			68.55
Bolt	2	0.55			1.09
Nut	2	0.05			0.10
Washer	2	0.06			0.12
Assembly	**Hours [h]**				**Total Cost [$]**
	0.3				18

Regeneration Gearbox					
Custom parts	**Material Cost [$]**	**Machine**	**Machining [h]**	**Labor cost**	**Total Cost [$]**
Support plate (Pump)	6.67	S,M	0.2	12.00	18.67
Support plate (Wheel)	3.33	S,M	0.1	6.00	9.33
Engage system	3.33	S	0.1	6.00	9.33
Purchased Parts	**Quantity**	**Cost per 1 Ea. [$]**			**Total Cost [$]**
Pump	1	68.92			68.92
Dog gear	1	14.52			14.52
56 tooth gear (dog gear)	1	14.52			14.52
20 tooth gear	1	7.92			7.92
120 tooth gear	1	52.28			52.28
1/2" ID bearing	1	1.00			1.00
1/2" ID shielded ball bearing	1	1.00			1.00
3/8" ID shielded ball bearing	1	1.00			1.00
Shaft (Hex)	1	19.50			19.50
Bolt	4	2.18			8.72
Nut	4	0.05			0.20
Washer	8	0.06			0.48
Assembly	**Hours [h]**				**Total Cost [$]**
	0.4				24

Hydraulic Circuit					
Custom parts	**Material Cost [$]**	**Machine**	**Machining [h]**	**Labor cost**	**Total Cost [$]**
3/8"-0.5" SS pipe	10	B	0.5	30	40
3/8"-0.5 hose	10	S	0.8	48	58
Hand pump support	3	W,S,M	0.1	6	9
Accumulator support	3	S	0.1	6	9
Purchased Parts	**Quantity**	**Cost per 1 Ea. [$]**			**Total Cost [$]**
ON-OFF valve NO	1	70.29			70.29
ON-OFF valve NC	1	44.22			44.22
Relief valve	1	116.36			116.36
Hand pump	1	109.65			109.65
Accumulator	1	396.00			396.00
Check valve /6	1	17.00			17.00
Check valve /8	1	34.23			34.23
Fitting	30	1.50			45.00
Oil	5 gal.	38.00			190.00
Assembly	**Hours [h]**				**Total Cost [$]**
	2				120

Electronics					
Purchased Parts	**Quantity**	**Cost per 1 Ea. [$]**			**Total Cost [$]**
Arduino UNO	1	9.00			9.00
Arduino Nano	1	2.00			3.99
Bluetooth LE Shield	1	10.00			10.00
Shift Register	3	0.84			2.52
Hall Sensor	2	8.50			16.99
Back Light	1	3.49			3.49
Shimano Alfine Di2 SG-S505	1	112.17			112.17
Shimano Alfine Di2 MU-S705	1	75.31			75.31
Shimano Alfine Di2 SC-S705	1	59.39			59.39
Shimano Alfine Di2 S705	1	65.99			65.99
Shimano Ultegra Di2 SM-JC41	1	17.75			17.75
Shimano Ultegra Di2 EW-SD50	3	16.27			48.81

Shimano Dura-Ace Di2 SM-BTR1	1	16.49			16.49
Shimano Di2 SM-BCR1	1	35.93			35.93
Shimano Di2 for SM-BCR1	1	5.90			5.90
Proportional Lever	1	5.71			5.71
Optoisolator	2	0.15			0.30
Relay	1	0.99			0.99
Battery	1	22.43			22.43
Dopunt Wire	1	0.99			0.99
buttons	2	0.20			0.40
SP500 Pressure sensor	2	80.00			160.00
Heart rate sensor (Arduino)	1	17.15			17.15
Assembly	**Hours [h]**				**Total Cost [$]**
	0.5				30

Bicycle Parts					
Purchased Parts	**Quantity**	**Cost per 1 Ea. [$]**			**Total Cost [$]**
Brake lever (set of 2)	1	10.57			10.57
Stands (set of 2)	1	44.24			44.24
Fork	1	36.29			36.29
Stem	1	25.74			25.74
Handlebar	1	16.49			16.49
Tire	2	16.88			33.75
Inner tube	2	0.67			1.34
Rim	2	18.00			36.00
Rim tape	1	1.00			1.00
Spokes	68	0.60			40.80
Grips (set of 2)	1	5.86			5.86
spacer	3	0.30			0.90
Headset	1	9.29			9.29
Saddle	1	9.17			9.17
disc brake	1	26.40			26.40
Phone holder	1	9.98			9.98
Seatpost clamp	1	5.26			5.26
Frame					
Custom parts	**Material Cost [$]**	**Machine**	**Machining [h]**	**Labor cost**	**Total Cost [$]**
Aluminum	73.59	S,W,M	2	120.00	193.59

Front Gearbox					
Purchased Parts	**Quantity**	**Cost per 1 Ea. [$]**			**Total Cost [$]**
Pump	1	54.56			54.56
Bottom bracket adapter	1	12.18			12.18
Bottom bracket cartridge	1	13.46			13.46
Crank arm set	1	64.95			64.95
Pedals	1	14.16			14.16
Spur gear (Pedal)	1	75.81			75.81
Spur gear (Pump shaft)	1	15.36			15.36
Bolt	2	2.18			4.36
Nut	2	0.05			0.10
Washer	2	0.06			0.12
Assembly	**Hours [h]**				**Total Cost [$]**
	0.2				12

Motor Gear Box					
Custom parts	**Material Cost [$]**	**Machine**	**Machining [h]**	**Labor cost**	**Total Cost [$]**
Support plate	16.26	S,M	0.5	30.00	46.26
Shimano adapter plate	5	S	0.2	12.00	17.00
Purchased Parts	**Quantity**	**Cost per 1 Ea. [$]**			**Total Cost [$]**
Motor	1	62.48			62.48
Spur Gear (Motor)	1	15.11			15.11
Spur Gear (Wheel)	1	68.55			68.55
Bolt	2	0.55			1.09
Nut	2	0.05			0.10
Washer	2	0.06			0.12
Assembly	**Hours [h]**				**Total Cost [$]**
	0.3				18

Regeneration Gear Box					
Custom parts	**Material Cost [$]**	**Machine**	**Machining [h]**	**Labor cost**	**Total Cost [$]**
Support plate (Pump)	6.67	S,M	0.2	12.00	18.67
Support plate (Wheel)	3.33	S,M	0.1	6.00	9.33
Engage system	3.33	S	0.1	6.00	9.33

Purchased Parts	**Quantity**	**Cost per 1 Ea. [$]**			**Total Cost [$]**
Pump	1	68.92			68.92
Dog gear	1	14.52			14.52
56 tooth gear (dog gear)	1	14.52			14.52
20 tooth gear	1	7.92			7.92
120 tooth gear	1	52.28			52.28
1/2" ID bearing	1	1.00			1.00
1/2" ID shielded ball bearing	1	1.00			1.00
3/8" ID shielded ball bearing	1	1.00			1.00
Shaft (Hex)	1	19.50			19.50
Bolt	4	2.18			8.72
Nut	4	0.05			0.20
Washer	8	0.06			0.48
Assembly	**Hours [h]**				**Total Cost [$]**
	0.4				24

Hydraulic Circuit					
Custom parts	**Material Cost [$]**	**Machine**	**Machining [h]**	**Labor cost**	**Total Cost [$]**
3/8"-0.5" SS pipe	10	B	0.5	30	40
3/8"-0.5 hose	10	S	0.8	48	58
Hand pump support	3	W,S,M	0.1	6	9
Accumulator support	3	S	0.1	6	9
Purchased Parts	**Quantity**	**Cost per 1 Ea. [$]**			**Total Cost [$]**
ON-OFF valve NO	1	70.29			70.29
ON-OFF valve NC	1	44.22			44.22
Relief valve	1	116.35			116.35
Hand pump	1	109.65			109.65
Accumulator	1	396			396.00
Check valve /6	1	17.00			17.00
Check valve /8	1	34.23			34.23
Fitting	30	1.5			45.00
Oil	5 gal.	38			190.00
Assembly	**Hours [h]**				**Total Cost [$]**
	2				120

Electronics					
Purchased Parts	**Quantity**	**Cost per 1 Ea. [$]**			**Total Cost [$]**
Arduino UNO	1	9.00			9.00
Arduino Nano	1	1.99			1.99
Bluetooth LE Shield	1	10.00			10.00
Shift Register	3	0.84			2.52
Hall Sensor	2	8.49			16.99
Back Light	1	3.49			3.49
Shimano Alfine Di2 SG-S505	1	112.17			112.17
Shimano Alfine Di2 MU-S705	1	75.31			75.31
Shimano Alfine Di2 SC-S705	1	59.39			59.39
Shimano Alfine Di2 S705	1	65.99			65.99
Shimano Ultegra Di2 SM-JC41	1	17.74			17.75
Shimano Ultegra Di2 EW-SD50	3	16.269			48.81
Shimano Dura-Ace Di2 SM-BTR1	1	16.49			16.49
Shimano Di2 SM-BCR1	1	35.93			35.93
Shimano Di2 for SM-BCR1	1	5.90			5.90
Proportional Lever	1	5.71			5.71
Optoisolator	2	0.15			0.30
Relay	1	0.99			0.99
Battery	1	22.43			22.43
Dopunt Wire	1	0.99			0.99
Buttons	2	0.2			0.40
SP500 Pressure sensor	2	80			160.00
Heart rate sensor (Arduino)	1	1.1			1.10
Assembly	**Hours [h]**				**Total Cost [$]**
	0.5				30

Bicycle Parts					
Purchased Parts	**Quantity**	**Cost per 1 Ea. [$]**			**Total Cost [$]**
Brake lever (set of 2)	1	10.57			10.57
Stands (set of 2)	1	44.24			44.24

Fork	1	36.29			36.29
Stem	1	25.74			25.74
Handlebar	1	16.49			16.49
Tire	2	16.88			33.75
Inner tube	2	0.67			1.34
Rim	2	18.00			36.00
Rim tape	1	1.00			1.00
Spokes	68	0.60			40.80
Grips (set of 2)	1	5.86			5.86
spacer	3	0.30			0.90
Headset	1	9.29			9.29
Saddle	1	9.17			9.17
Disc brake	1	26.40			26.40
Phone holder	1	9.98			9.98
Seatpost clamp	1	5.26			5.26

To better cater the needs of different consumer groups, three tiers of vehicles with specific functions are introduced by the team in the following section. For customers, like students, who focus more on the core function of the vehicle and have relatively low purchasing power the *PurdueTracer Lite* may be their best option. For professional bike riders who aim to better monitor their riding performance, *PurdueTracer Royal* will provide them detailed data on bike speed and heart rate. For people who would love to have the full function of the vehicle and customize the vehicle, *PurdueTracer Luxury* provides them the largest degree of freedom. The features of the vehicle are listed in Table 8.3.

Table 8.3: Vehicle Features

Feature	Cost [$]
Shimano Alfine 8 Speed	112.2
Shimano Alfine 11 Speed	238.92
Electronic Control System	593.45
Regeneration System	251.38
Energy Storage System	396
Customized Painting	60

PurdueTracer Lite

Feature	Cost [$]
Shimano Alfine 8 Speed	112.2

Total cost: $1977.42

PurdueTracer Royal

Feature	Cost [$]

Shimano Alfine 8 Speed	112.2
Electronic Control System	593.45
Energy Storage System	396

Total cost: $2966.87

PurdueTracer Luxury

Feature	Cost [$]
Shimano Alfine 11 Speed	238.92
Electronic Control System	593.45
Regeneration System	251.38
Energy Storage System	396
Customized Painting	60

Total cost: $3404.97

9 LESSONS LEARNED

NFPA Fluid Power Vehicle Challenge provides the Purdue Team a great opportunity to apply theoretical knowledge in solving practical problems. With the unforgettable experience of brainstorming, designing, creating, team working, assembling and debugging during in these months, the team gained important knowledge not only about specific hydraulic or electronic knowledge but also about practical abilities and cooperation spirits. A brief summary of the lessons the Purdue Team learned from this Challenge is shown below:

1. The team learned that future engineers should have the ability to teach themselves and master unfamiliar tools or software as quickly as possible.
2. The team learned that a comprehensive consideration of functions, environment, duration, economics, sustainability and user experience is the key to a good design.
3. The team learned that solving practical problems cannot only be based on theoretical simulation results. The different solution fits different situations.
4. The team learned to take advantage of different various kinds of resources provided by University like books, instructions, software to solve the problem.
5. The team learned to collect the suggestions from experts and professors to improve the previous design.
6. The team learned the importance of teamwork dynamics and cooperation spirits.
7. The team learned that the combination of individual work and pair work can maximize the working efficiency.
8. The team learned the importance of sticking to the schedule and time management.

For most of the Team member, the NFPA Fluid Power Vehicle Challenge was the first time we gained experience working on an entire project from start to finish. The lessons we learned has the important significance of guiding and will shape our efforts in future designs.

10 CONCLUSIONS

After nearly eight months of work, PurdueTracer is ready to say hello to the world. Everyone is delightful that she is not just an idea on the paper anymore. We cheered every time Tracer accomplished a test, and she is getting very close to our expectations: light, fast, efficient, and cool! She is our pride! Now that the final competition is getting closer, PurdueTracer carries the hope from every person who has contributed a share of effort. Thanks to everyone in Purdue 2017 Team, our advisor Dr. Andrea Vacca, Anthony Franklin in Maha Fluid Power, Scott Brand in Purdue ABE, and everyone who has helped!