Spring 2021 HPV Exhibition Capstone

Spr21HPV
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Capstone 476C – 2021
Project Sponsor: Perry Wood
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Disclaimer

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1 Background

1.1 Introduction

NAU has traditionally competed in the ASME sponsored Human Powered Vehicle challenge as a senior capstone design project. Our senior design team chose to forgo the competition due to scheduling conflict but remained interested in creating a human powered vehicle. Our client, Professor Perry Wood suggested building a smaller, adjustable version, catered as an exhibition for younger students 5-13 years old. This HPV design project requires us to generate different concept variants that include all traditional HPV components, including the frame, roll cage, steering, and drive systems. The team will machine and prototype the design to be fully completed when it's ready for exhibition at local schools.

1.2 Project Description

Professor Perry Wood would like an HPV that can be easily transported to local schools and allow children from 5-13 years old to ride the vehicle. Safety should be listed as the highest priority, which requires a tricycle design for stability, and some form of roll cage for protection. The vehicle should also demonstrate key engineering practices that can be used as educational anecdotes for the young students.

1.3 Original System

The 2014 NAU Senior Capstone team did exceptionally well in the HPV competition. Although our vehicle will be less competitively focused, their winning design will be researched to assist in practical application of the bicycle systems. The recumbent vehicle can be found in NAU's engineering building, and a picture is included for reference.

Figure 1 - 2014 NAU HPV

2 Requirements

2.1 Customer Requirements

The scope of the project changing from competitive to inspirational/educational caused the team to revisit prior customer requirements (CRs), engineering requirements (ERs), and quality function deployment (QFD) to fit the new project goals. Table 1 displays the new list of CRs in order of highest ranking. Regardless of working as an exhibition for younger students to gain an idea of engineering applications, safety will always be nonnegotiable as the team's top requirement. There is never a case where safety should be neglected, especially when working on a project devoted to the next generation of students.

The table of CRs were created by the team and sent to Professor Wood for approval. The original project CRs were encompassed with the competition in mind. The new table was generated with safety in mind to educate and inspire young students into pursuing an education in engineering in their future.

Table 1 - List of customer requirements

RANK	CUSTOMER REQUIREMENTS (CR'S)	DESCRIPTIONS
1	Safety	Includes seat belt integration and secure seating.
2	Stability	HPV will not tip over through a sharp turn. Will also ride upright at slow speeds.
3	Operation age (5-13 years of age)	HPV can be driven by Kindergarteners through 8th graders.
4	Educational	Includes components that students can visually learn from.
5	Ease of operation	Low difficulty to operate. Includes foot pedals/brakes and hand steering.
6	Transportable	Lightweight to transport over long commutes. Can fit in a truck bed to transport places where it cannot drive.
7	Rollover protection	3- or 4-point roll-cage to ensure safety in the case of an operator accident that tips the HPV.
8	Manufacturability	Materials used are compatible and feasible to manufacture within a college students' budget.

2.2 Engineering requirements

Stemming from the declared CRs, the team analyzed which applicable standards are necessary within the design and how they impact the direction of the project. These standards, known as engineering requirements (ERs), are applied to ensure products or systems are consistent, compatible, safe, and effective. The team declared ERs, shown in Table 2, after client and advisor approval to dive into quantifiable aspects for each of the declared CRs. The motivation behind each ER comes from the relationship between each CR and the quantifiable engineering trait. The team focused on the "*how*" and the "*why*" behind transporting a young student on the HPV. Each ER has targets and tolerances within the QFD, shown in Appendix A.

Table 2 - List of engineering requirements

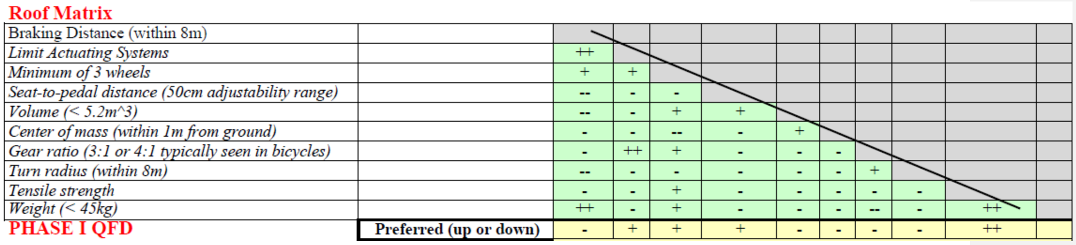
ENGINEERING REQUIREMENTS	
Braking distance (within 8 m)	Center of mass (within 1 m from ground)
Limit actuating systems	Gear ratio (3:1 or 4:1 typically seen in bicycles)
Minimum of 3 wheels	Turn radius (within 8 m)
Seat-to-pedal distance (50 cm adjustability range)	Tensile strength (250-560MPa)
Volume (no more than 5.2 m^3)	Weight (no more than 45 kg)

2.3 House of Quality

The House of Quality (HoQ) is a product-planning matrix that the team generated to show the direct relationships between the CRs and the methods used to fulfill those requirements. The methodology behind HoQ generation begins with identifying what the customer wants and how it will satisfy them. Specific product characteristics, features, and attributes are critical in customer satisfaction. Relating the how's to each other is the next step. The team took the "how do the *how's* relate to each other?" approach in fulfilling this step. Importance ratings were generated for each requirement. Based on the customer ratings, the team computed importance weights from their relationships with each other. It is important to note past project and other HPVs that currently exist. Benchmarking, or evaluating the current existing designs, tells the team how well other designs fulfill customer needs by conducting research. Performance is compared to competitors to determine the correct technical attributes needed for the scope of this project.

Below in Table 3 is the team's generated HoQ. The table evaluates the relationships between technical attributes with our customer needs. Positive relationships are shown by (+) or (++) and negative relationships are shown by (-) or (--). Double marks indicate a stronger relationship in the direction declared. The table shows our team which ERs are to be prioritized within the design to ensure our top team requirement of safety is met, with each subsequent need to be fulfilled thereafter. The entire QFD can be found in Appendix A.

Table 3 - House of Quality



Roof Matrix

Braking Distance (within 8m)											
Limit Actuating Systems		++									
Minimum of 3 wheels		+	+								
Seat-to-pedal distance (50cm adjustability range)		--	-	-							
Volume (< 5.2m^3)		--	-	+	+						
Center of mass (within 1m from ground)		-	-	--	-	+					
Gear ratio (3:1 or 4:1 typically seen in bicycles)		-	++	+	-	-	-				
Turn radius (within 8m)		--	-	-	-	-	-	+			
Tensile strength		-	-	+	-	-	-	-	-		
Weight (< 45kg)		++	-	+	-	-	-	--	-	++	
PHASE I QFD	**Preferred (up or down)**	-	+	+	+	-	-	-	-	++	

3 Design Space Research

3.1 Literature Review

3.1.1 Abel Aldape

Abel asked to be the Project Manager to step into a leadership role. As project leader his main mission is to run a successful design project that meets all deadlines and utilizes the strengths of every team member for the benefit of the group. He often will set individual assignments and milestones to be met by all team members, and delegates work proportionally and specific to people's areas of interest. Abel will also be the CAD designer for the project and will work closely with the team to create a professional and operational CAD package. This package will also allow us to perform static loading simulations to determine deflection and bending.

1) Design of Human Powered Vehicles (Textbook) [1]

   a) This textbook goes through every step of the design process for a human powered vehicle. It gives amazing broad breakdowns and milestones to achieve during the project. It also supplies exceptional graphs and equations to help determine technical aspects of the design. An example of equations to be used is an estimate on maximum power output with height and age being the independent variables. This is particularly useful for our project where short heights and younger ages will directly affect the maximum power expected to be produced.

$$Power_{men}(Watts) = \frac{(244.6 * height) - 92.1}{(1 + e^{(.038(age-77.3)})} \tag{1}$$

$$Power_{women}(Watts) = \frac{(137.7 * height) - 23.1}{(1 + e^{(.064(age-75.9)})} \tag{2}$$

2) Fundamentals of Biomechanics (Textbook) [2]

   a) The source of power for this machine will obviously be human supplied. Human forces are generated through muscles that act as loads through contraction, and joints/bones that act as pivots and levers. To better understand and compute motion studies on the pedaling of the rider the chapters about linear and angular kinetics will be used. A useful equation from the text relates acceleration as a function of time and force. Using integration equations for velocity and position as functions of time can be derived.

$$a_x(t) = \frac{F_x(t)}{m} \tag{3}$$

$$v_x(t) = v_{x0} + \int_{t_o}^{t} a_x(t)dt \tag{4}$$

$$x(t) = X_o + \int_{t_o}^{t} v_x(t)dt \tag{5}$$

3) Trike Design 101 (Peer Reviewed Article) [3]

   a) This source provides a general overview that gives advice and recommendations for all subsystems of the design. It specifically focuses on the center of gravity and steering to increase the comfortability and ride of the recumbent bicycle. The 2014 NAU HPVC group used an Ackerman Steering method, and this resource goes in depth on linkages necessary to produce the design.

4) Mechanics of Materials Eighth Edition (Textbook) [4]

   a) When designing the vehicle, the frame will need to endure the varying weights of children and ensure admissible deflection. The roll cage will also need to endure sufficient forces subject to rolling or collisions and maintain minimal deflection. For a reference when computing these bending stresses and moment diagrams, the Mechanics of Materials textbook will be exceptional. The main calculations made will be associated with the maximum bending stress, which requires the area moment of inertia of a rectangular tube.

$$\sigma_{max} = \frac{Mc}{I} \tag{6}$$

$$M = Max\ moment\ (Use\ Moment\ Diagram)$$

$$c = distance\ from\ neutral\ axis\ to\ outside\ edge\ of\ tube$$

$$I = \frac{bd^3 - hk^3}{12} \tag{7}$$

Where b, d and k are dimensions of the tube.

5) ANSI Safety and Welding Standards (Standards) [5]

   a) Professor Willy heavily suggested using a Standard as a resource due to it’s importance in designs. Manufacturing and prototyping the vehicle will require both weldments and cutting of the tubing. ANSI provides standards for safety and regulations that our team will adhere to during machining parts.

3.1.2 Preston Berchtold

Preston is the Financial Manager of the team. As a financial manager, Preston is responsible for overlooking the budget and keeping track of team expenses. Preston is also responsible for adjusting and managing the Bill of Materials, while also being the main point of contact for any budget requests that need to be approved. As budget management is not impactful in the beginning stages of the project, Preston has been helping the other team members model CAD parts, research materials for testing, or developing plans for manufacturing. Preston's focus over the course of the project has been the roll cage design and fabrication thus far.

1) ASTM Standards F2043.1497 (Classification) and F2843.26930 (Condition 0) (Standard) [6, 7]
    a. ASTM Standard F2043.1497 (Classification) outlines the standards for manufacturing bicycles in conjunction of typical use for bicycles within a selected group (child's bike, street cruiser, BMX, etc.) This standard helps identify manufacturing criteria and outlines the bicycle identification for intended uses mentioned above.
    b. ASTM Standard F2843.26930 (Condition 0) outlines the standards and criteria needed for a child size bike to be considered "safe" from failure during use. The standard states failure testing specifications and impact loading tests to determine safety of a child size bike. This ASTM standard will help the team ensure a safe and regulated product is delivered.

2) Design and Analysis of Roll Cage Chassis (Peer Reviewed Article) [8]
    a. This source outlines several common roll cage setups in all-terrain vehicles and the testing results due to impacts, torsion, and a rollover incident. As our team is building a Human Powered Vehicle, the direct correlation of these roll cages does not apply to the project. But information describing testing methods, roll cage building considerations, and common failure points will all be helpful, if not impactful for the manufacturing of the HPV roll cage.

3) NHRA & IHRA Rulebook (Handbook) [9]
    a. The NHRA (National Hot Rod Association) releases a yearly rulebook of specifications required to be involved in drag racing. Within the rulebook, specifications of roll cage thicknesses, tubing lengths, and mounting specification are explained thoroughly. The HPV will not be reaching high speeds, such as hot rods, but specifications and reasonings for roll cage designs will be helpful to the team. Some such specifications from the rulebook are head spacings, body alignment, mounting configurations, and tubing thicknesses for different speeds. The specifications for a hot rod and our HPV are going to vastly different in the sense of tubing lengths, exact mounting zones, and roll cage configurations; but will help the team be more conservative in the manner of safety, then not safe enough.

4) Shigley's Mechanical Engineering Design Ch. 8, 9, 13, & 17 (Textbook) [10]

    a. Chapter 8 within the textbook describes screws and fasteners and the selection process in which to use them. Within this section, the team will may not necessary be doing the calculations for each fastener individually but will use the section to guide them on selecting fasteners that will meet the load requirements and manufacturing criteria.
    b. Chapter 9 discusses welding and permanent joint fabrication that will be needed for manufacturing of the HPV frame. Within this section, specifications for stresses found within welded joints and the typical AWS (American Welding Society) notation needed for fabrication. This chapter will ensure that the HPV team will be able to get parts fabricated correctly, while also ensuring to the team that stresses caused within the fabrication will not cause further damage to the rest of the vehicle.
    c. Chapter 13 discusses the use of gears and gear ratios. This section will be the most helpful to the team in determining correct gear and sprocket ratios for our child size HPV. As the HPV team is designing a child size bike, the forces needed to pedal and continue speed forward will be vastly different from our age (20-24). Therefore, this section will be the most helpful in determining the exact gear and sprocket specifications for a child between the ages of 5-13. This section will also help the team in determining manufacturing methods or “off-the-shelf parts.”
    d. Chapter 17 will be used closely with chapter 13 as the use of gear on an HPV will be useless without a chain. Therefore, understanding and using the calculations presented in chapter 17 for roller chains will be the part of the driving force to correctly manufacture a reliable drivetrain system. The HPV is inclined to use a rear wheel drive, therefore a longer roller chain will be needed to connect the pedals in the front to the rear wheels; meaning slipping, chain breakages, and stress fractures are more likely to occur throughout our system.

5) Electronic Code of Federal Regulations – Title 16, Part 1512 (Standard) [11]
    a. This regulation outlines the manufacturing, safety specifications, and federal regulations for any 2- or 3- wheeled bicycles. Therefore, this standard will help outline to the team manufacturing specifications, but more importantly safety specifications such as reflectors specifications, failure testing procedures, and structure integrity determinations.

3.1.3 Martin Dorantes

Martin is carrying the roles of Test Engineer and Logistics Manager. As Logistics Manager, it is Martin’s duty to manage all internal and external communications. He is the main point of contact between the client and team. He also documents meeting minutes and agendas to upload on the team website. Managing facility and resource usage is another responsibility of being Logistics Manager. As the Test Engineer, it is Martin’s responsibility to oversee experimental design and testing portions of the project.

He plans testing procedures, acquires necessary equipment, sets up apparatuses, and manages all tests on the team's behalf. Martin is also responsible for coding the team website to be displayed on NAU's public domain. He is responsible for collecting all pictures, information, and documents to upload the progression of the project to the HTML website using Dreamweaver and Bootstrap extension plug-ins.

1) *Aerodynamics* by Tony Foale [12]
    a. This article focuses on general aerodynamic properties. Specifically drag, lift, and both basic & dynamic directional stability are the main points Foale discusses. He wrote about the biggest problems that come with each of the main points, along with how to correctly analyze them to yield better performing bikes.

2) *Fundamentals of Vehicle Dynamics* [13]
    a. This textbook contains a section on rolling resistance. This will aid the tea [7]m in designing the wheels correctly to prevent rollovers. Rolling resistance is important to note because it is present from the instant the wheels begin to turn. There are 7 mechanisms responsible for rolling resistance: energy loss due to tire sidewall, energy loss due to deflection of tire tread, contact patch scrubbing, tire slip, road surface deflection, air drag on tires, and energy loss on bumps. The total rolling resistance, R_x, is the sum of resistances seen in Equation 8 below.

$$R_x = R_{xf} + R_{xr} = f_r W \tag{8}$$

R_{xf} = Rolling resistance of front wheels

R_{xr} = Rolling resistance of rear wheels

f_r = Rolling resistance coefficient

W = Weight of vehicle

3) Matador N.E.D. 1.0 – Final Design Report [14]
    a. Biomechanics is an important aspect of operating an HPV. This capstone group combined the biomechanics and biological systems on the physical human interactions with the device. The team can use the same process that this group did to find power output results via a PowerTap device. Specific measurements are taken from a PowerTap from each team member to design the HPV around the dimensions. It can be taken a step further and test with students between the ages of 5 to 13 years to grasp more accurate data to produce an HPV with maximum efficiency for each rider in mind.

4) *2011 HPVC Design Report* – NAU ASME Human Powered Vehicle (The Orka) [15]
    a. The 2011 NAU HPVC group performed a fairing analysis to overcome drag as the biggest obstacle for a faster top speed. The group found that having a full fairing on the HPV would yield minimal drag force. The fairing has two air ducts in the frontal area and low-pressure back end to ventilate the inside of the fairing. This implementation can be

        useful in keeping the driver cool during operation and prevent overheating, which would limit muscle energy and output power.

5) 6061 Aluminum: Get to Know its Properties and Uses [16]
    a. Gabrian breaks down the pros and cons of 6061 aluminum. Comparisons are also drawn between other similar alloys to visually see which can be used for any intended application. Material properties are listed and provides a downloadable PDF for all 6061 aluminum properties. It is important to note that 6061 is generally used as a structural aluminum, implying that our HPV application will be a perfect fit for supporting young students.

6) Lightning F-40 [17]
    a. At the time, the Lightning F-40 was built, it was the world's fastest production bicycle. The lightweight design was something ahead of its time that set it apart from other HPV designs, while breaking records held from other HPVs.

3.1.4 Trent Todd

Trent is carrying in charge of manufacturing and has overseen much of the design process for both system and subsystem levels. It is his responsibility to understand all physical components of the design and ensure that all proposed manufacturing is feasible, along with Abel he is currently signed up for machine shop training. Currently he is overseeing the CAD model and working with team members to help implement subsystem ideas together. He was suited for this position based off his mechanical experience and understanding, while having some experience with metal working and operating shop equipment, and with having a background in bicycle riding and racing.

1) ANSI Standard Z49.1 :2012 - Safety in Welding, Cutting, and Allied Processes [18]

    This standard covers all aspects of safety and health in the welding environment which will come in handy as the team is beginning to design for manufacturing and will soon be manufacturing themselves. This goes over in-depth all the safety aspects to welding, including oxygen, gases and other fume safety, ventilation, personal protection equipment, and other precautionary information.

2) AWS D1.2/D1.2M :2008 - Structural Welding Code—Aluminum [19]

    This American National Standard covers the welding requirements for any type of structure made from aluminum alloys. Which walks through topics including, general requirements, design connections, fabrication, and repairing existing structures.

3) Recumbent Bike Forum [20]

    This is a large public forum solely dedicated to dedicated to recumbent bikes and ASME HPV racing. A large variety of information is available here including what systems or subsystems have been the most successful, manufacturing advice, even standards and other technical documents. Which can save the team a lot of time, by evaluating what ideas have already been tested and don't work, or common mistakes made by teams.

4) Human Powered Vehicle Challenge (HPVC) Competition Group [21]
   This is another large public participant created group dedicated to the Human Powered Vehicle Challenge (HPVC) Competition. It provides a forum for member to post their own topics, along with links to rules, past winners and their reports. Which will provide an excellent way to find the best HPV's for benchmarking.

5) BIKECAD – Bicycle design software and forum [22]
   This is a unique website that has an online based CAD program for designing bikes, with an optional professional level download. Also included are online forums which offer a ton of help for the design process, there is also a design archive of other people designs. Which may be a useful tool for testing or rough prototyping.

3.2 Benchmarking

After evaluating the developed ERs, the team generated measurable parameters and conditions for each. The ERs must target, hit a design-to mark, or be quantifiable conditions to exist. The justifications behind verifying an ER revolve around the generated CRs. The measured or quantifiable conditions were generated with safety, education, and inspirational in mind. The team conducted research to gather information from existing HPVs that prioritize the same ERs and measure internal performance. Measuring the performance of the device is a part of the benchmarking process. The goal of benchmarking is to identify internal improvement for future applications. It helps the team visually see which traits of some existing designs can be applied to the one generated from this project. Our team divided benchmarking into two sections: system level and subsystem level.

3.2.1 System Level

Three existing HPV designs have been selected for system level benchmarking. The Lightning F-40, 2014 NAU HPV, and N.E.D. 1.0 are shown in Figures 2, 3, and 4, respectively. Along with each figure is a short description analyzing some of the positive and negative aspects of each concept, in reflection with the generated ERs.

Figure 2 - Lightning F-40 [17]

At the time of its construction in the early 1990s, the Lightning F-40 was considered the world's fastest production bicycle. The 4130 Chromoly steel tubing made for a robust central frame to support a variety of operators. The lightweight design and fairing combination averaged a 10-mph speed gain from the average HPV. The F-40 secures the driver in the vehicle, preventing fallouts during crashes. This bike also includes a transparent headlight window, to incorporate usage at night.

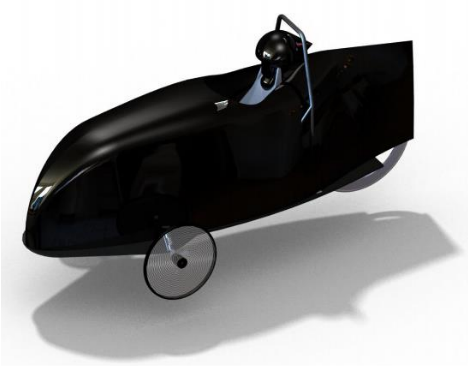


Figure 3 - N.E.D. 1.0 [14]

The N.E.D. 1.0 HPV was designed and built in 2010 by the students at California State University, Northridge. The design is made of a carbon fiber composite with honeycomb core and a carbon fiber with Kevlar fabric fairing yielded a design achieving light weight, robust, and speed requirements. This HPV had a calculated top speed of 44.7-mph. The design in Figure 3 shows the team that aesthetics is critical. It creates pride within work. If the goal is to educate and inspire future engineering students, the

HPV should be designed with an aesthetic appearance, given by the fairing. The fairing can also be used as an educational outlet by teaching the basics of aerodynamics.

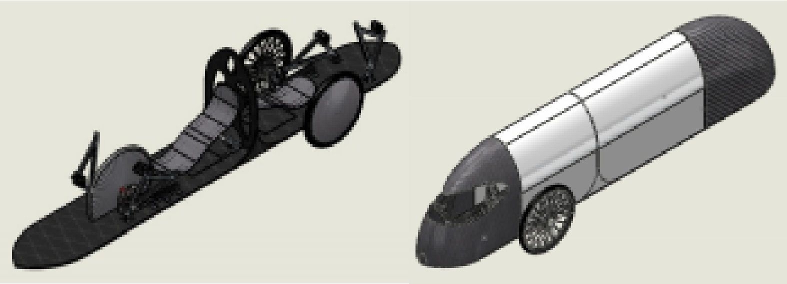


Figure 4 - 2011 NAU HPV [15]

The 2011 NAU HPVC capstone group generated the HPV shown in Figure 4. This design is relevant because it incorporates two operators to produce more human power output. The front-facing driver pedals and steers, while the rear-facing driver only pedals the vehicle. The roll cage was designed to exceed the 2011 HPVC rules for safety. The air ducts within the fairing prevent overheating in the vehicle. The ventilation is aimed to keep drivers cool to ensure their muscles do not overheat, resulting in lower human muscle output. The frame is made from an aluminum honeycomb tube and the fairing is made from a carbon fiber composite and stretch fabric. This design is heavier in weight at 80lbs but is alleviated by the two-operator design. Its top speed is projected to be at 45-mph with both drivers and fairing.

3.2.2 Subsystem level

For subsystem benchmarking, the team examined three different subsystems to benchmark against. Therefore, this section will layout three different subsystems: steering, roll cage safety, and drivetrain, and provide an example for each showing the strengths and weaknesses. Each example shown will either be an “off-the-shelf" product or a subsystem design taken from a full system HPV.

To start, Ohio University’s HPV [23] was a well-designed tadpole style trike closely related to our HPV project. Therefore, the steering configuration outlined by their design will be useful in guiding and outlining steering angles that would be needed. The castor angle, defined in the figure below, helps the bike recenter wheels after a turn and improves stability at high speeds. Therefore, the team should optimize the castor angle to be within 7-10 degrees for the best steering re-centering; with 10 degrees being the most optimal. The negative camber angle, described in the figure below, establishes a better stability for corners due to body roll. Therefore, an angle of negative two degrees will counteract the body roll during a corner and provide a better tire footprint during turns. Lastly, the kingpin should be in line with the bottom of the wheel to provide a stable and reliable turning system with no “steering gaps”.

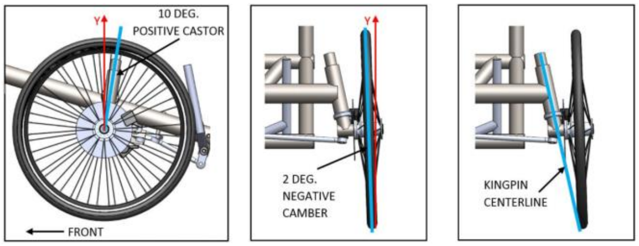


Figure 5: Castor, Camber, and Kingpin Angles [23]

Secondly, the team benchmarked against the California State University (CSU) Northridge HPV for safety standards, more specifically roll cage deflection. ASME defines two deflection tests within the HPV rulebook: a top point load of 2670N applied 12 degrees from the aft and a 1330N force applied to the sides at shoulder height. Both tests require a deflection less than 5.1cm and 3.8cm, respectively. Therefore, CSU's roll cage was selected to benchmark as the results of the deflection was very minimal, with a deflection of 2cm and 0.018cm, respectively [24]. CSU's minimal reflection from the tests netted a factor of safety for the frame of 2.54 for the top load and a factor of safety of 21 for the side loads [24]. Our team's main priority for the child size bike is safety and using CSU's safety benchmarks will help the team to ensure a safe and reliable design.

Lastly, the team benchmarked against an off-the-shelf internal gear system. As the child size HPV will be used with kids from the ages of 5-13, having a complex manual shifter can lead to multiple problems of user errors, chain slip, or derailleur malfunctions. Thus, the team would like to have a reliable single gear-to-gear system where no chain slippage or derailing occurs. Therefore, the team selected an internal gear system to benchmark gear ratios against to find an optimal performance. The Shimano Inter-3 Gear system was reviewed for its simplicity and gear ratios. The Shimano system, as seen below, is an all-in-one gear system designed for easy shifting, with gear ratios of 0.733, 1.0, and 1.36 [25]. Therefore, allowing riders to be able to have torque on the low end and speed on the high end, while being simplistic and easy to manipulate.

Figure 6: Shimano 3-Speed Gear System [25]

3.3 Functional Decomposition

Functional decomposition was created to further help the team analyze and break down subsystems of the HPV project. Therefore, the team started with a simple Blackbox model to understand basic inputs and outputs. The basic Black Box model helped the team understand the basis for the full decomposition. Furthermore, the basic Black Box also helped the team to “take a step back” and see the bigger picture and overall direction of the project.

Figure 7: Basic Black Box

From this point, the team continued to break down the model into a full subsystem decomposition shown below. The full decomposition helped the team to determine where subsystems would be linked, while also realizing where subsystems would be independently working within the system. Within the decomposition we can see that the subsystem to move the bike (input feet, rotate pedals, rotate wheels, etc.) and the hands to actuate steering are connected but do not impact each other’s subsystem directly, but instead, impacts the result of kinetic energy and displacement.

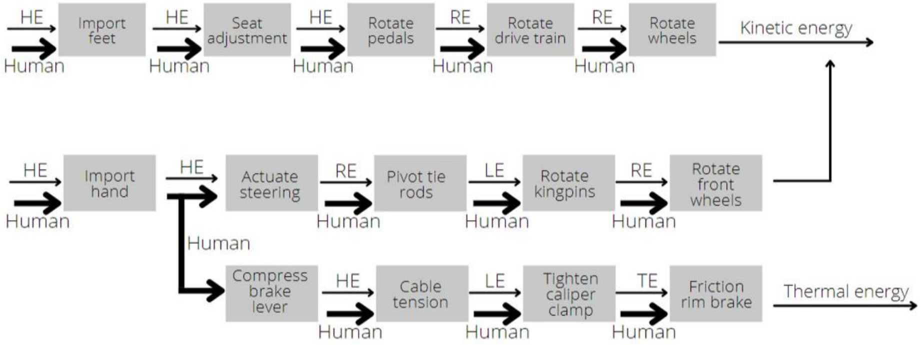


Figure 8: Full Functional Decomposition

4 Concept Generation

The team began concept generation by investigating existing HPV systems and components as this information is easily found and commonly shared. This allowed the team to save time and resources by finding out what systems have worked, and which have common issues. With the current scope of the project being shifted towards building a child size HPV, the evaluations of the full system and subsystem components have shifted accordingly. For example, top speed and competitive performance are not the priority when compared to safety and stability for this child size model, changing how the HPVC project is conventionally approached.

4.1 Full System Concept

To start first the full the overall general HPV layouts were researched and evaluated keeping in mind the new Customer requirements. These requirements include having a design with a minimum of 3 wheels, so automatically any 2-wheel systems were thrown out of consideration. Some of the biggest considerations when developing full system concepts include, the vehicle must be safe, must be easy to operate, and must accommodate riders of ages 5-13 roughly.

4.1.1 4-Wheel concept

To begin, one concept is a 4-wheel recumbent HPV which can be seen in (Fig. 9), note that the specific subsystems shown on the figure are not being evaluated, only the fundamental 4-wheel layout. Some of the benefits to this layout include having the best stability, at least at lower speeds. It also provides a fairly adaptable layout as many different sub-systems could be implemented. However, this would likely be much heavier than its 3-wheel competitors and considering the range of riders a 5-year-old could have a hard time getting this heavier concept to move. Also, this layout would be more mechanically complex when compared to other concepts.

Figure 9: 4-Wheel concept [26]

4.1.2 Delta concept

The next concept generated is a Delta layout HPV (Fig. 10) which utilizes one wheel in the front and two in the back. One of the largest benefits to this layout is the high maneuverability and lower speeds, many utilize front wheel steering which allows the front wheel to turn up to 90 degrees, creating a much smaller turning radius. Delta trikes can allow for better ergonomics and better accessibility, as they tend to have a seat higher off the ground. Also having less obstacles on the front of the trike to step over when seating, when compared to the tadpole layout which often has the wheels close to the seat. Another benefit to this design is the adaptability, when certain subsystems are paired correctly this bike provides some unique advantages. Looking at the construction of (Fig. 10) which utilizing the front wheel to drive and the rear to steer, allowing for adjustability of the frame [27]. Which is nice considering the steering actuator can adjust to riders with the seat.

However, the Delta concept does have its flaws, a big one being stability. Due to only having one front wheel they are prone to poor handling at higher speeds, namely tipping over when corning which is a huge drawback considering it will be operated by elementary to middle school students and safety is the priority. Another flaw is complexities when trying to pair with a rear-wheel-drive system, as either some sort of differential would be needed to power both rear wheels as only one powered wheel would cause the bike to pull to one side.

Figure 10: Delta Concept [27]

Commented [TMT1]: "Mobo Triton Pro Adult Three-Wheeled Cruiser - Adult Recumbent Trikes," www.mobocruiser.com. [Online]. Available: https://www.mobocruiser.com/MoboTritonPro-p/tri-501.htm. [Accessed: 22-Feb-2021].

4.1.3 Tadpole concept

The Tadpole layout utilizes two wheels in the front and one in the back (Fig. 11), the main benefit to this design is stability. With having two wheels in the front which provide extra grip and stability which helps prevent the bike from tipping over when maneuvering corners. Tadpole trikes also tend to be smaller and lighter than the 4-wheel and Delta layouts, making their transportation a bit easier which is a bonus as this HPV will be transported to different schools. This layout also tends to offer a lower center of gravity due the lower seat higher, creating better handling and a sporty feel.

However, some downfalls of this layout include, such as a larger turning radius. Commonly this layout uses front wheel steering, but due to having the two front wheels their range of motion is limited, by both the physical components of the bike and the rider. Also depending on design, the Tadpole trikes can be harder to get in, due to the lower seat height, location of the front wheels and steering components.

Figure **11**: Tadpole Concept [28]

Commented [TMT2]: D. Hipwood, “Human Powered Vehicle (Sr. design) - Daniel Hipwood's Digital Portfolio,” Google Sites, 2008. [Online]. Available: https://sites.google.com/site/dhipwooddigitalportfolio/projects/human-powered-vehicle. [Accessed: 22-Feb-2021].

4.2 Subsystem concepts

After generating concepts for the general layout of the bike the individual subsystems could be evaluated. These were discussed as a group and broken up into the following material selection, drivetrain, steering, braking, roll cage, ergonomics, and fairing. Then based off each team members strengths and experience subsystems were assign accordingly to be investigated.

4.2.1 Material selection

4.2.1.1 Carbon Fiber

The first material investigated for the frame/roll cage was carbon fiber, which would be the lightest material to use for the HPV construction. When manufactured corrected it can also be incredibly strong, but these manufacturing processes can be quite expensive and complex. Carbon fiber is also directionally dependent which would complicate the design process, it is also less durable making it prone to damage when handled incorrectly, along with general reliability issues.

4.2.1.2 Chromoly Steel

The next material was 4130 chromoly steel, which is a chrome-alloy steel with a medium carbon content. Chromoly steel is durable, and less brittle compared to carbon fiber or aluminum, allowing them to take a beating. If something does brake, steel is easily repairable as steel is easy to weld and bend. However, steel frames are heavier than aluminum or carbon fiber as steel is about 2.5 times denser than aluminum. Steel is less efficient for an HPV as its less rigid, there is more deflection in the frame causing energy to be wasted, however this can provide a more comfortable ride.

4.2.1.3 Aluminum

Lastly Aluminum 6061 alloy was evaluated, which is a 061 is a hardened aluminum alloy containing magnesium and silicon. Aluminum is a good middle ground between carbon fiber and steel, its lighter than steel, but cheaper and easier to manufacture than carbon fiber. It is also stiffer and more rigid, making it more efficient for an HPV but at the cost of less shock absorption. Aluminum would be fairly easy to manufacture with the exception of requiring TIG welding which no team members have experience with, which also hurts its repairability. A unique advantage of aluminum is its weather resistance as it does not rust. However, aluminum is prone to fail in unpredictable ways, and is prone to fatigue failure.

4.2.2 Drivetrain

The components and layout which make up a drivetrain can get complex, as there are a lot of possible systems and combinations. Such as drive wheel, power delivery system, gearing, vehicle layout, wheelbase, and crank size. To start front wheel drive (FWD) and rear wheel drive (RWD) systems were investigated, a FWD setup provides some benefits such as allowing for a larger front wheel and has a shorter more efficient chain line. However, it has some big disadvantages such as steering complications, instability when pedaling, lack of wheel traction due to weight distribution, and its general more complex. While RWD systems provide better stability, better traction, and is generally less complex. Yet suffers from longer chain placement, making a less efficient chain line. Note these pro's and con's can vary depending on the general bike layout and the subsystems its paired with.

Another component which was investigated was the power delivery system, meaning how is the power transferred from the crank to wheel. A unique solution would be to use a driveshaft, although this seems to be prone to complications, is heavier than a chain, and would be difficult to implement to a recumbent style bike. Another option is using a direct drive system, where the crank is connected directly to the wheel. This would be more beneficial with the Delta concept as there is only one front wheel, however this eliminates the possibility for multiple gears, and can be hard to pedal up a hill. Realistically a chain with multiple speeds would be the choice, this is a proven design and is pretty much standard for all bicycles. Chains are compatible with almost and design, are compatible with derailers making changing speeds easy, and can easily be adjusted.

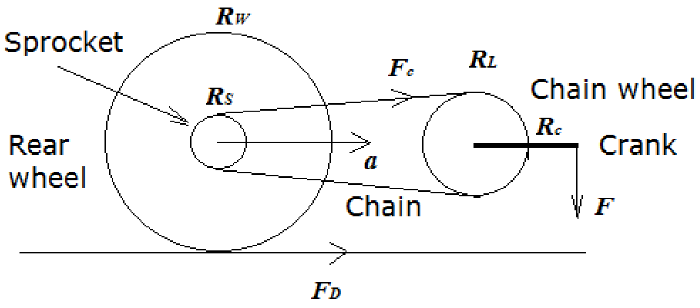


Figure **12**: Chain drive [29]

4.2.3 Steering

The steering subsystem is very broad and very dependent on the layout it is paired with. There are several factors that come into play such as, alignment geometry, indirect vs direct, front wheel (FWS) vs rear wheel steering (RWS) vs tilt steering or a combination of. A FWS system is much more common, due to its superior stability, handling, when compared to a RWS system. While a RWS system can make the front of the bike less complex and offer clean aerodynamics, rear steering causes crashes at high speed, and unusual turning at low speeds.

Direct steering which is when the steering bars (or other actuator) are connected directly to wheel fork and pivot about the same axis, this offers more precise steering and mechanical simplicity. With the tradeoff being instability at higher speeds, its more prone to vibrations, and limited design possibilities. While indirect steering allows for the handlebars to be moved around, which can be used to solve interference issues, it also provides adjustable steering ratios and better ergonomics. With the tradeoff being mechanical complexity, and less precision in turning at lower speeds.

Two Strong concepts that emerge from the indirect steering category include, a joy stick system mounted directly to the kingpins and kept aligned with a track arm (Fig. 13). This design offers a very lightweight and compact steering package, also its unique and the kids riding in this might be intrigued. Its flaw include limited adjustability to riders, as they won’t be able to adjust with the large range of riders, and there could be interference with riders legs. The second concept is a standard kingpin linked to handlebars or wheel like seen in (Fig. 14), similar in complexity to the joy stick concept, not likely as cool. However, this offers the possibility to have an adjustable steering wheel, if angled and setup correctly the steering column could adjust with the rider, using a splined shaft of similar method.

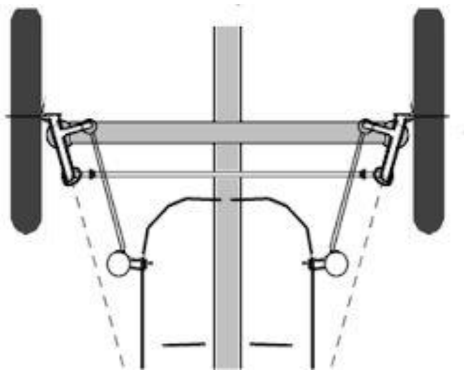


Figure 13: Joystick steering [20]

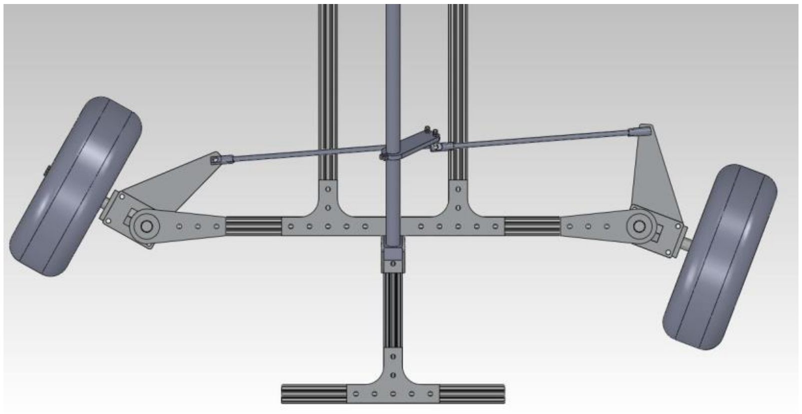


Figure **14**: Handlebar steering [20]

4.2.4 Braking

The braking subsystem is one of the most important to ensure a safe human powered vehicle. Three main concepts where generated based on the industry standards, which are caliper brakes (Fig. 15), cantilever brakes (Fig. 16), and disk brakes (Fig. 17). On paper disk brakes provide the best performance in terms of braking, however there is concern due to the layout of the tadpole style trike that these might over preform and cause the bike to tip forward under heavy braking. Disk brakes can be powered by hydraulics or cables, and tend to be the more costly option, but offer the ability to be mounted direct at the wheel hub eliminating the need for any external frame around the wheel for mounting. Which also allows braking to be unaffected if the wheel is out of true, unlike the rim-based braking methods.

Caliper and cantilever are both rim-based braking with very similar performance between the two with cantilever being slightly better due to the larger amount of force they can provide. However, Cantilever brakes are a bit more complex and need two mounting locations one on either side of the wheel, they also cost a little bit more then the caliper style. The Caliper brakes are the cheapest of all three, are easier to mount then the cantilever, and would likely be the best when paired on the front wheels of the tadpole styler trike and could be mounted off the kingpin of the joystick steering setup.

Figure 15: Caliper brakes [30]

Figure 16: Cantilever brakes [30]

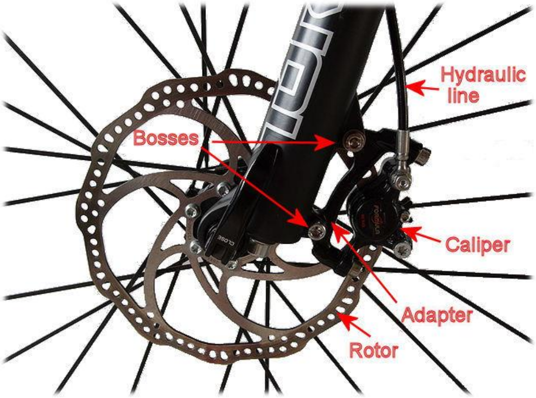


Figure 17: Hydraulic disk brake [30]

4.2.5 Roll cage

The roll cage is a necessary component given by the customer requirements, with the purpose of protecting the rider in case of a rollover. There are countless possible designs which the team has narrowed down to two general designs, a four-point cage (Fig. 18), and a wrap-around cage that can serve as a structural part of the frame (Fig. 19). The 4-point cage would likely be the lighter and more simplistic of the two, while offering excellent performance, reviewing previous HPVC teams it also seems to be the most common. Sure, it is heavier than the 3-point and 2-point cage designs but is the better choice as our design prioritizes safety or performance. Likely this cage would start off the frame located next to the seat then branch backwards and connect next to the rear wheel much like is seem in the tadpole concept (Fig. 10). The wrap around cage would likelier be heavier than the 4 point, put could offer the most protection, and if designed correctly could become a structural member of the HPV frame itself providing a safer and more rigid design, but could be difficult to get in and out of.

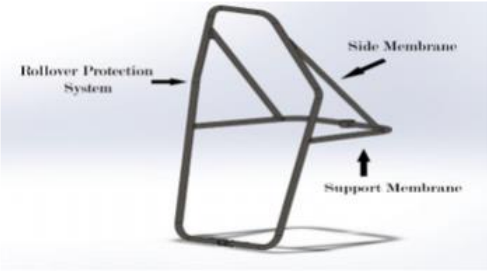


Figure 18: 4-point cage [31]

Figure 19: Wrap-around cage [31]

4.2.6 Ergonomics

At this point in the project ergonomics focused mostly on seat positioning, although many other factors will be taken into consideration as this project progresses, such as seat design, and placement of controls. Hip orientation angle (HOA) and body configuration angle (BCA) were investigated, which can be seen illustrated on (Fig. 20). It was discovered that a BCA of 130-140 degrees would be optimal, paired with either a -15 or +5 degree HOA. The -15 HOA provides the most efficient power delivery, as less power is required to ride the HPV as speed progresses when compared to the +5 HOA as seen on (Fig. 21), however the +5 HOA is the more aerodynamic. The -15 HOA also provide better stability as the rider can be sat lower on the HPV.

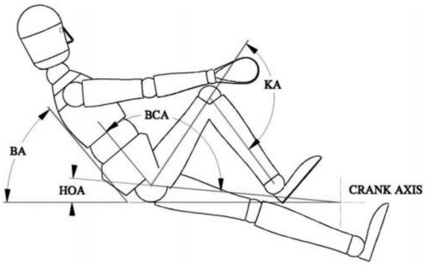


Figure 20: Ergonomic angles [3]

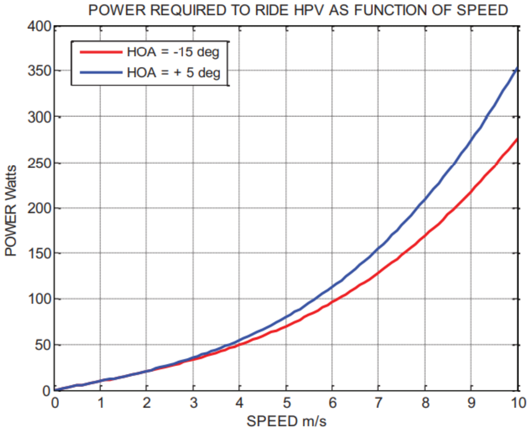


Figure 21: HOA performance [3]

4.2.7 Fairing

The final subsystem evaluated was the fairing component, as this HPV won't be used in competitions and isn't designed for high speeds as children will be the target audience a fairing would really only be used for aesthetics and to be interesting for the children using the HPV. Several fairing styles were generated including a tear drop, Kamm tail, Ellipse, U-shape, or any partial fairing of the styles, or no fairing at all. A tear drop shaped fairing is expected to offer the best performance, but there is concern about using a full fairing. As the large range of adjustability required would make the fairing design less efficient, also the HPV likely won't be reaching speeds in which a fairing would become very affective. Other concerns include durability, visibility, and accessibility for the children's operators. A good middle ground would be to use a partial clear fairing like seen in (Fig. 10), which would provide easier access into the HPV and would provide better visibility to the operator. Also, children can be destructive, a full fairing, especially any high performance light weight fairings would likely get easily broken.

5 Designs Selected

5.1 Technical Selection Criteria

This portion of the report will relate technical information and calculations to the CR's and ER's to justify design selections.

5.1.1 Layout

With a customer constraint of minimum of three wheels for stability, the layout of the bicycle was limited to two options, the tadpole design and delta trike design. The Trike Design 101 article provided the technical information necessary to decide which of the two designs to use.

Delta Configuration (One front wheel)	**Tadpole Configuration (Two Front Wheels)**
Easy to design	Offers excellent braking
Lower manufacturing costs, standard components	Excellent handling
Can cause excessive roll	Steering systems are more complicated and need unique parts to be designed
Braking compromised due to one forward wheel	Design is complicated

Table 4: Layout evaluation

The delta configuration offers easier to design components, but has safety drawbacks, which is not possible considering our customer requirements. For this reason, the tadpole configuration is chosen for its increased stability and braking capabilities. It is a more difficult design process, but necessary to provide the best safety considerations to the riders.

5.1.2 Ergonomics

Ergonomics relates to the stability and ease of operation customer requirements. The placement and angle of seating drastically affects center of gravity and maximum power output. The Design of Human Powered Vehicles textbook provides optimum angles for the Body Configuration Angle (BCA) and Hip Orientation Angle (HOA), seen in Figure 15 above. The following graph represents the benefit of the -15-degree HOA.

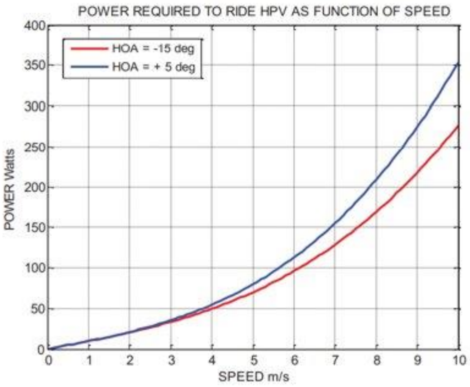


Figure 22: Benefit of HOA [3]

The lower angle helps to reduce drag and necessary power output. This is beneficial when the drivers will be children with limited ranges of muscle strength.

5.1.3 Braking

Braking is related to the safety, ease of operation, and manufacturability customer requirements. These criteria ultimately lead us to the caliper disk brakes. It is an extremely reliable system that allows for easy installment in the vehicle. To ensure the vehicle can stop within 8 meters both front wheels will have brakes.

5.1.4 Roll cage

The roll cage is tied to the safety and rollover protection customer requirements. The main concept variants deal with how many points of contact the system has with the more points being safer for the rider. The only drawbacks of having a larger roll cage are the additional weight it adds to the vehicle. Seeing as the vehicle weight will be lower due to the small size and small passengers, the four-point roll cage outperforms the other concept variants.

5.2 Rationale for Design Selection

Design selection was determined based of research, how parts interact with each other and a few calculations. To begin a Pugh charts were created for the general layout and each subsystem which will be listed off below beginning with general layout (Table. 6). Which results in the Tadpole style bike scoring the highest, which also aligned with the team's expectations as it stability and a more adaptable layout. Note the asterisk on the 2-wheel section is due to an updated customer requirement invalidating and design with less then 3 wheels.

Table 5: Layout Pugh

		2 Wheels *			3 Wheels		4 Wheels
Criteria	**Weight %**	**Upright**	**Prone**	**Recumbant**	**Delta**	**Tadpole**	**Quad**
Stabilty/ safety	25.0%	5	4	3	6	9	10
Performance	15.0%	7	6	6	5	6	3
Weight	10.0%	9	9	7	5	5	2
Ease of operation	20.0%	6	2	4	8	9	7
Braking	15.0%	6	3	5	7	7	6
Aerodynamics	5.0%	8	9	7	6	6	3
Complexity	10.0%	8	7	6	5	5	3
Total	1	6.5	4.8	4.85	6.2	7.3	5.9

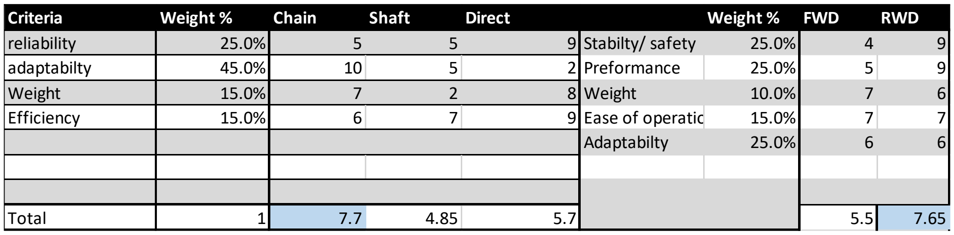
Next the steering subsystem was evaluated through 2 different sections, front wheel (FWS) vs rear wheel steering (RWS), and direct vs indirect vs tilt steering. Note tilt steering can be paired in combination with direct or indirect steering, at either wheel or both. As expected FWS scored much higher than RWS due to RWS poor handling and stability, and in-direct steering took the lead due to its stability, and adaptability.

Table 6: Steering Pugh

	Weight %	FWS	RWS	Direct	In-direct	Tilt*
Stabilty/ safe	25.0%	10	5	5	7	4
Preformance	25.0%	8	5	6	6	6
Weight	10.0%	7	5	7	5	5
Ease of oper	15.0%	7	5	4	8	3
Adaptabilty	25.0%	6	6	5	7	2
Total	1	7.75	5.25	5.3	6.7	3.95

For the drivetrain subsystem (Table. 8), components were broken into power delivery method Chain vs Shaft vs Direct, and front wheel drive (FWD) vs rear wheel drive (RWD). The chain system provided unmatched adaptability at a low weight compared to the shaft, and direct drive suffered from adaptability as its dependent on being mounted to the front wheel in a recumbent design. Also RWD was the clear winner due to its superior stability and performance, but will limit some other design features such as an adjustable frame.

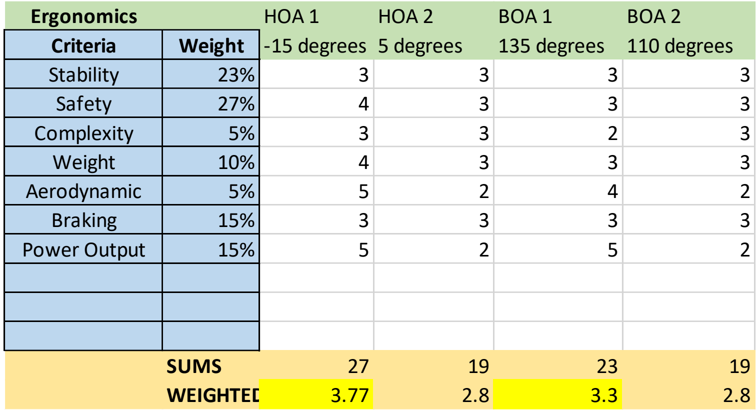
Table 7: Drivetrain Pugh



Criteria	Weight %	Chain	Shaft	Direct		Weight %	FWD	RWD
reliability	25.0%	5	5	9	Stabilty/ safety	25.0%	4	9
adaptabilty	45.0%	10	5	2	Preformance	25.0%	5	9
Weight	15.0%	7	2	8	Weight	10.0%	7	6
Efficiency	15.0%	6	7	9	Ease of operatic	15.0%	7	7
					Adaptabilty	25.0%	6	6
Total	1	7.7	4.85	5.7			5.5	7.65

Ergonomics was evaluated at the two top HOA and BOA angles, note this Pugh cart (Table. 9) ratings are out of /5. This Pugh cart outlines the -15 HOA and 135 BOA as superior mainly their power efficiency outputs, which pairs nicely with the tadpole layout trike. Future ergonomic evaluations include seat design, seat positioning in reference to pedals and steering/ braking actuators.

Table 8: Ergonomics Pugh



Ergonomics		HOA 1	HOA 2	BOA 1	BOA 2
Criteria	Weight	-15 degrees	5 degrees	135 degrees	110 degrees
Stability	23%	3	3	3	3
Safety	27%	4	3	3	3
Complexity	5%	3	3	2	3
Weight	10%	4	3	3	3
Aerodynamic	5%	5	2	4	2
Braking	15%	3	3	3	3
Power Output	15%	5	2	5	2
	SUMS	27	19	23	19
	WEIGHTED	3.77	2.8	3.3	2.8

Braking was evaluated for the caliper, cantilever, drum, and disk concepts. Of which the caliper brakes came out on top, followed by disk brakes, as caliper brakes are the cheapest, least complex, and are safer considering the risk of forward tipping depending on the weight distribution of the bike. An idea for the braking system is to have the front to wheels using caliper brakes and the rear brake being a disk, it would also be beneficial to have an auxiliary brake lever on the rear of the bike in case the children operators need to be stopped by instructors.

Table 9: Braking Pugh

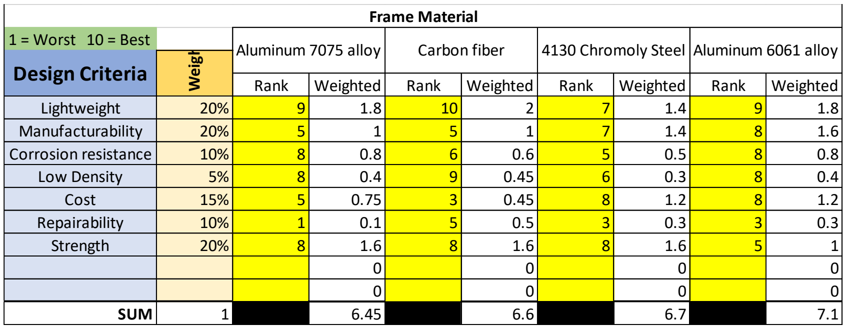
Braking		Design 1	Design 2	Design 3	Design 4
Criteria	**Weight**	Caliper	Cantilever	Drum	Disk
Safety	25%	5	4	3	4
Reliability	20%	3	3	3	4
Complexity	15%	4	3	3	2
Price	15%	5	4	3	2
Performance	25%	3	3	3	5
	SUMS	20	17	15	17
/5	**WEIGHTED**	3.95	3.4	3	3.65

The roll cage subsystem was evaluated by general roll cage layout and its material (Table 11). For layout, the 4-point cage took the lead followed by the wrap-around cage as they both offer the highest protection, even though they would be the heaviest since safety is the priority. Aluminum was rated the highest for the material as it offers a good middle ground of price vs performance which also supports the ideal frame material being aluminum seen in (Table 12) which is the Pugh cart for frame material. Aluminum 6061 came out on top as the frame material, due to its well balance of performance and cost. In second place is 4130 chromoly steel which offers easier manufacturing as it does not require TIG welding, and still balances cost and performance well.

Table 10: Roll cage Pugh

Roll Cage		**SCALE [1-5]**		**[HIGH SCORE = BETTER]**		**MATERIAL**		
Criteria	**Weight**	2-point	4-point	3-point	Wrap-around	Steel	Aluminum	Carbon Fiber
Weight	15.0%	4	3	3	2	3	4	5
Protection	30.0%	2	4	3	4			
Drag Coeff	10.0%	2	2	2	3			
Deflection	30.0%	1	4	3	3	3	4	3
Price	15.0%					4	4	1
Resistant to Cracks	15.0%					4	3	1
Manufacturing	15.0%	4	3	3	3	4	3	2
SUM = 1 ->	100.0%							
	SUMS	13	16	14	15	18	18	12
	Weighted SUMS	2.3	3.5	2.9	3.15	3.15	3.3	2.25

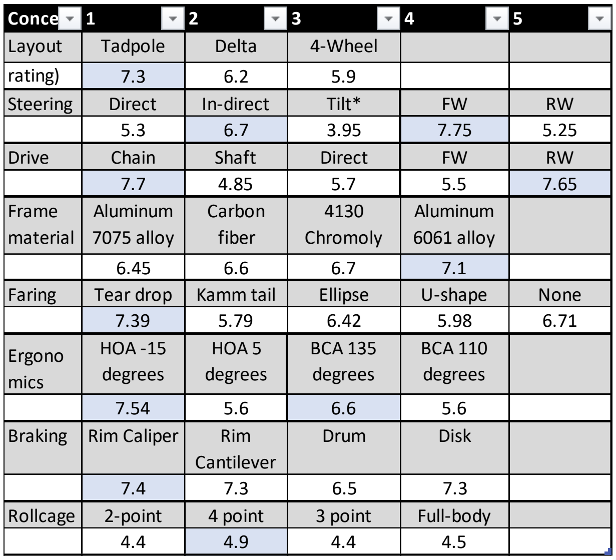
Table 11: Frame material Pugh



1 = Worst 10 = Best		Frame Material							
Design Criteria	**Weigh**	Aluminum 7075 alloy		Carbon fiber		4130 Chromoly Steel		Aluminum 6061 alloy	
		Rank	Weighted	Rank	Weighted	Rank	Weighted	Rank	Weighted
Lightweight	20%	9	1.8	10	2	7	1.4	9	1.8
Manufacturability	20%	5	1	5	1	7	1.4	8	1.6
Corrosion resistance	10%	8	0.8	6	0.6	5	0.5	8	0.8
Low Density	5%	8	0.4	9	0.45	6	0.3	8	0.4
Cost	15%	5	0.75	3	0.45	8	1.2	8	1.2
Repairability	10%	1	0.1	5	0.5	3	0.3	3	0.3
Strength	20%	8	1.6	8	1.6	8	1.6	5	1
			0		0		0		0
			0		0		0		0
SUM	1		6.45		6.6		6.7		7.1

Last all main subsystems and their corresponding Pugh rating were inputted into a large decision matrix seen below (Table 13). With all values be converted to be out of 10, this provided an easy way to generate complete concepts based off their rating. However, some lower rated systems can be improved depending on what they are paired with, such as direct FWD paired with rear wheel steering create a strong concept due to the ability to be adjusted at the frame. Based off this matrix a Tadpole style trike, using front wheel indirect steering, rear wheel chain driven, aluminum frame, with a 4-point roll cage is the theoretical ideal setup. A rough 3D model was created using these systems, seen as figure 23.

Table 12: Decision Matrix



Conce	1	2	3	4	5
Layout	Tadpole	Delta	4-Wheel		
rating)	7.3	6.2	5.9		
Steering	Direct	In-direct	Tilt*	FW	RW
	5.3	6.7	3.95	7.75	5.25
Drive	Chain	Shaft	Direct	FW	RW
	7.7	4.85	5.7	5.5	7.65
Frame material	Aluminum 7075 alloy	Carbon fiber	4130 Chromoly	Aluminum 6061 alloy	
	6.45	6.6	6.7	7.1	
Faring	Tear drop	Kamm tail	Ellipse	U-shape	None
	7.39	5.79	6.42	5.98	6.71
Ergonomics	HOA -15 degrees	HOA 5 degrees	BCA 135 degrees	BCA 110 degrees	
	7.54	5.6	6.6	5.6	
Braking	Rim Caliper	Rim Cantilever	Drum	Disk	
	7.4	7.3	6.5	7.3	
Rollcage	2-point	4 point	3 point	Full-body	
	4.4	4.9	4.4	4.5	

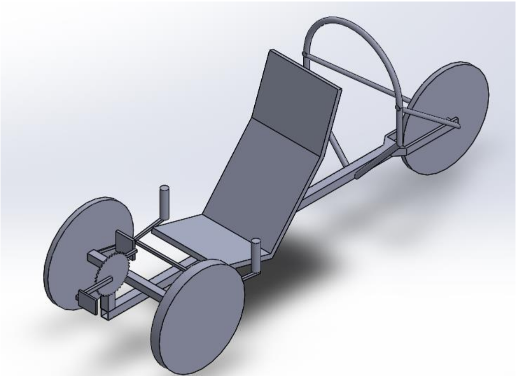


Figure 23: Solidworks model

6 Conclusions and Future Work

The scope of the project still has work to be completed. Everything included in this report will lead the team to a successful prototyping start. The next immediate steps are to complete a fully rendered SolidWorks model start looking for affordable vendors to supply the materials for the HPV. Once all materials are in-hand the team can begin building the first prototype, based on dimensions calculated from the CAD drawing, and test upon completion. In between wait times for materials to be attainable, the team will also be working on the public website, updating all documents, pictures, and milestones achieved.

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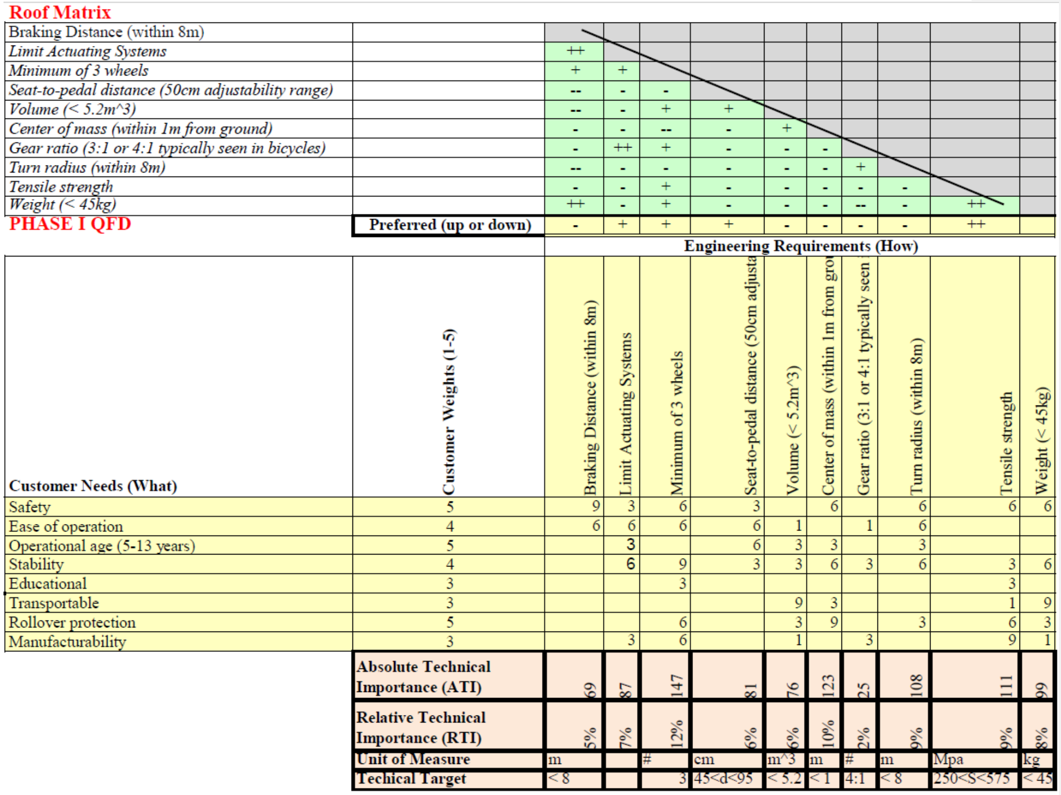
Appendices

Appendix A

Table 13 - QFD



Roof Matrix

Braking Distance (within 8m)											
Limit Actuating Systems		++									
Minimum of 3 wheels		+	+								
Seat-to-pedal distance (50cm adjustability range)		--	-	-							
Volume (< 5.2m^3)		--	-	+	+						
Center of mass (within 1m from ground)		-	-	--	-	+					
Gear ratio (3:1 or 4:1 typically seen in bicycles)		-	++	+	-	-	-				
Turn radius (within 8m)		--	-	-	-	-	-	+			
Tensile strength		-	-	+	-	-	-	-	-		
Weight (< 45kg)		++	-	+	-	-	-	--	-	++	
PHASE I QFD	**Preferred (up or down)**	-	+	+	+	-	-	-	-	++	

Engineering Requirements (How)

Customer Needs (What)	**Customer Weights (1-5)**	Braking Distance (within 8m)	Limit Actuating Systems	Minimum of 3 wheels	Seat-to-pedal distance (50cm adjusta	Volume (< 5.2m^3)	Center of mass (within 1m from gro	Gear ratio (3:1 or 4:1 typically seen	Turn radius (within 8m)	Tensile strength	Weight (< 45kg)
Safety	5	9	3	6	3		6		6	6	6
Ease of operation	4	6	6	6	6	1		1	6		
Operational age (5-13 years)	5		3		6	3	3		3		
Stability	4		6	9	3	3	6	3	6	3	6
Educational	3			3						3	
Transportable	3					9	3			1	9
Rollover protection	5			6		3	9		3	6	3
Manufacturability	3		3	6		1		3		9	1
	Absolute Technical Importance (ATI)	69	87	147	81	76	123	25	108	111	99
	Relative Technical Importance (RTI)	5%	7%	12%	6%	6%	10%	2%	9%	9%	8%
	Unit of Measure	m		#	cm	m^3	m	#	m	Mpa	kg
	Techical Target	< 8		3	45<d<95	< 5.2	< 1	4:1	< 8	250<S<575	< 45