Spring 2021 HPVC Exhibition Capstone

Final Report

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DISCLAIMER

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EXECUTIVE SUMMARY

Northern Arizona University requires all senior mechanical engineering students to undergo a yearlong Capstone Design program. This final design course utilizes all the skills and techniques taught in the first three Design4Practice programs. Our team of four were selected to take part in the Human Powered Vehicle competition, which has been a well-established capstone team managed by our client, Professor Perry Wood. In 2014, Professor Wood helped the capstone team design a competitive award-winning recumbent tricycle.

Figure 1: Final Child-Sized HPV

Due to scheduling conflicts with the HPV competition, our client decided upon a new direction for our design. The human powered vehicle would now be designed for the use of children from the age ranges of 5-13 years old. This vehicle would be taken to neighboring schools and allow kids to ride around and experience a fully developed project. When designing the device, customer requirements like safety, stability, ease of operation, adjustability, and transportability were referenced heavily in decision making. The client also established multiple constraints including a three-wheel design, and the inclusion of a roll cage for safety purposes. Through benchmarking, decomposition models, and concept generation and evaluation, our team finalized our six major subsystems decisions. Which lead our team to build the HPV seen about (Figure 1) which is a recumbent tadpole tricycle (two wheels in front one in back) with indirect steering, a rear-wheel-drive chain system, three caliper breaking devices, a four-point roll cage, and ergonomic values that determine the angles at which the body is oriented within the device to make it ideal for children.

Figure 2: Current CAD

This final report encompasses all the design decisions and calculations to validate the design process, as well as the Failure Mode and Effect Analysis. Along with a thorough walk through of the final product and its performance validated through testing procedures. As well as touching on all the technical details and areas that could be improved upon if a future team wanted to try and improve the product.

ACKNOWLEDGEMENTS

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- David Willy - Capstone advisor, senior ME lecturer
- Paul Howitz - Machine Shop supervisor
- Wyatt Watson - Machine Shop supervisor

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1 BACKGROUND

1.1 Introduction

Northern Arizona University (NAU) has traditionally competed in the American Society of Mechanical Engineer's (ASME) sponsored Human Powered Vehicle (HPV) competition. 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 vehicle to be fully completed when 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 young students. Therefore, the focus of the project was shifted from a competition style bike, needing high speed and strong reliability, to a child friendly bike, requiring safety and adjustability.

2 REQUIREMENTS

The following section will outline the list of Customer Requirements (CR's) and Engineering Requirements (ER's) the team has fulfilled during the project. This section will also outline the change of scope from competition HPV to a safety and inspiration drive HPV. Lastly, this section will also outline criteria and justification for the Engineer Requirements obtained.

2.1 Customer Requirements (CRs)

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. 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: 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 8^{th} 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 (ERs)

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 C.

Table 2: 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 $m3$)	Weight (no more than 45 kg)

Many of these engineering requirements stemmed from either the customer requirements directly, such as the seat-to-pedal distance, or taken from the ASME competition for reference. Other engineering requirements, such as turning radius, were used by the team to keep the bike about the original project through ASME. Therefore, the team felt that these engineering requirements were to help guide though undefined or undefined areas within the project.

2.3 Functional Decomposition

A functional decomposition, in a full form or simple black box, helps design teams focus on the importance of functionality in a product. Therefore, our Human Powered Vehicle (HPV) team started with a simple black box model to help shift focus to a child sized from the original ASME HPV competition. This change shifted several key concepts, such as speed and endurance, from a competition expectation to more of a safety focused project. Furthermore, the team took time to re-investigate the original black box and shifted its functionality from “speed and reliability” to “safety and inspiration.”

2.3.1 Black Box Model

Functional decompositions, in all forms, 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 and, furthermore, to “take a step back” and see the bigger picture and overall shift of the project from competition to safety.

Figure 3: Black Box Model

Moving into the second semester, the team reflected on how safety and simplicity should continue to be the focus of the design. The simple Black Box model did not change throughout the manufacturing process.

2.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

From the black box model, 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. Furthermore, during manufacturing the team decided to add additional drivetrain components for the bike.

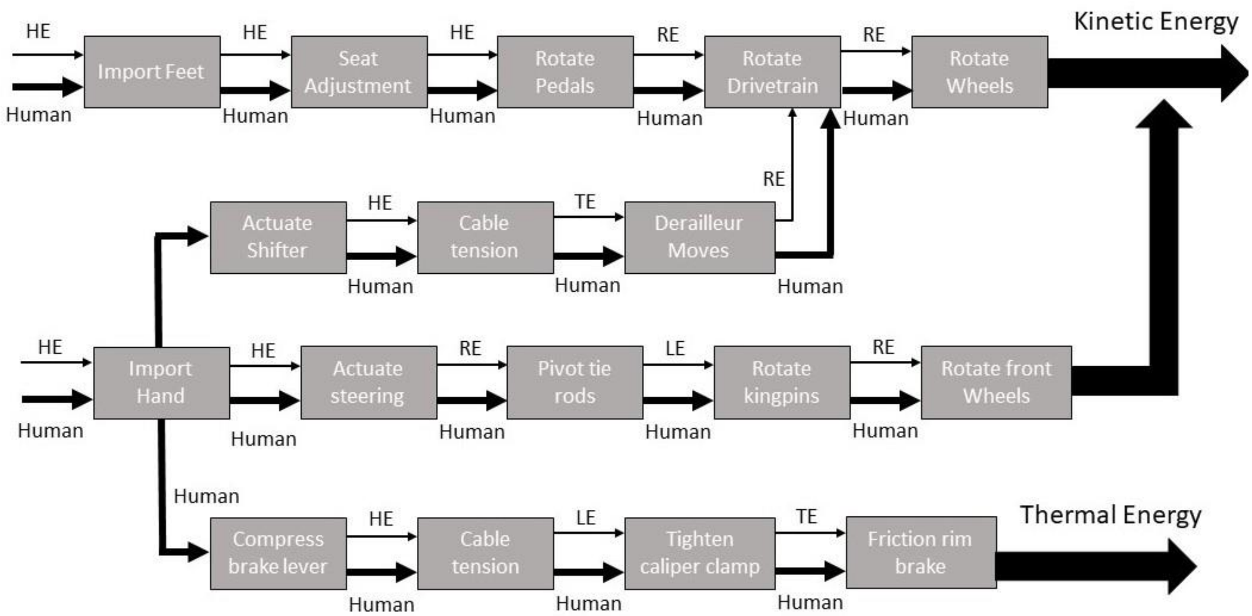


Figure 4: Functional Decomposition

2.4 House of Quality (HoQ)

The House of Quality (HoQ) is a product-planning matrix that the team generated to show the direct relationships between the customer requirements (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 5 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 C.

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)**	-	+	+	+	-	-	-	-	++	

Figure 5: House of Quality

2.5 Standards, Codes, and Regulations

The HPV team examined several different standards for current use within the design or for use within manufacturing. These standards will help the team ensure safe manufacturing specifications (protecting all team members while manufacturing), while also outlining standards set in place for a safe product for the consumer.

Table 3: Standards of Practice as Applied to this Project

Standard Number or Code	**Title of Standard**	**How it applies to Project**
ASTM F2043.1497 [1]	Standard Classification for Bike Usage	ASTM F243.1497 identifies manufacturing criteria and outlines the bicycle identification for intended uses (child, road use, BMX, etc.)
ASTM F2843.26930 [2]	Standard Specification for Condition 0 Bicycle Frames	ASTM F2843.26930 identifies criteria needed for a child size bike to be considered "safe" from failure during use (stress and impact specifications)
ANSI Z49.1:2012 [3]	Safety in Welding, Cutting, and Allied Processes	ANSI Z49.1 outlines safety and standard practices for welding. This will be helpful for manufacturing within the team to ensure our product is safe for the consumer.
ASTM Y14.5 [4]	Dimensioning and Tolerancing	ASTM Y14.5 outlines the standards for dimensioning and tolerancing various parts and assemblies.

3 DESIGN SPACE RESEARCH

Within any project, fundamental research should be conducted to outline basic principles and specifications. The HPV team conducted many terms of research through literature review and benchmarking to further understand the project. Furthermore, the team wanted to understand fundamental mistakes, errors, and designs that mitigated these mistakes to not "*reinvent the wheel.*" This also came to the team's aid when recycling old parts to better understand efficient designs.

3.1 Literature Review

To start the team broke up the project into subsystems to research. These sections were broken into the following: ergonomics and layout, frame and fairing, steering, and drivetrain. Every team member took the time to research their topic and provide evidence of their findings. Abel addressed the ergonomics and layout of the HPV. Through his research, Abel researched through *Design of Human Powered Vehicles* [5] textbook outlining general specifications for HPVs. Furthermore, Abel identified the hip orientational angle (HOA) of 15 degrees and the stronger reasoning for the tadpole design selected. Martin underwent research for frame and fairing. Martin provided evidence for the use of 6061-T6 aluminum for the frame. Furthermore, Martin took a deep dive into the *Durability of Carbon Fiber Reinforced Polymer* [6] and other HPVs with fairings, such as the Lightning F-40. The team decided that a fairing was unnecessary during the manufacturing phase of the project. Trent researched the steering aspect of the project and used several online outlets, such as *The Recumbent Bicycle and Human Powered Vehicle Information Center* [7]. Theses outlets helped gain further understanding of Ackerman steering and different steering types, such as indirect or tilt steering. Lastly, Preston researched the drivetrain and its components mainly sprockets and chain. *Shigley's Mechanical Engineering Design* [8] was used primarily in understanding gear ratios, chain lengths, and sprocket dimensioning, while also helping the team in identifying fasteners and screws needed.

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 Benchmarking

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.

3.2.1.1 Existing Design #1: Lightning F-40

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 6: Lightening F-40 [9]

3.2.1.2 Existing Design #2: N.E.D. 1.0

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 7 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.

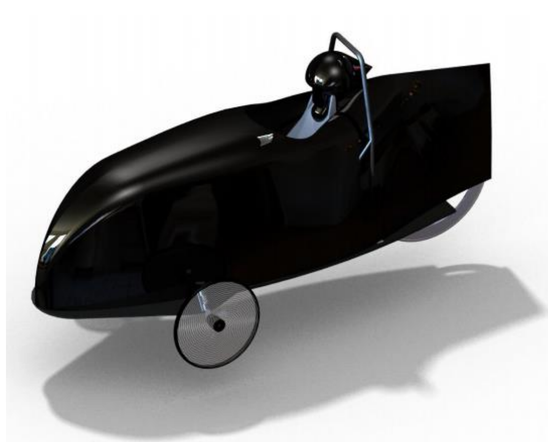


Figure 7: N.E.D. 1.0 [10]

3.2.1.3 Existing Design #3: 2011 NAU HPVC

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

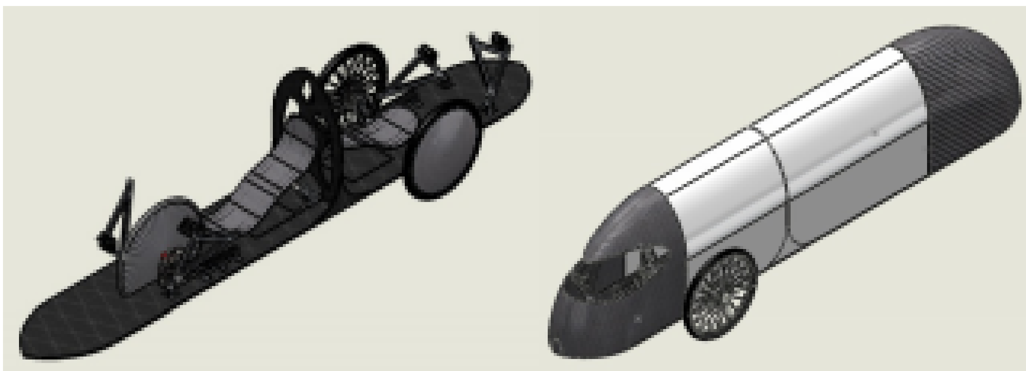


Figure 8: 2011 NAU HPV [20]

3.2.2 Subsystem Level Benchmarking

The team investigated and benchmarked against several different subsystems to understand advantages, disadvantages, and common errors or mistakes within each system. The team started with drivetrain systems and investigated the most common systems on the market and widely available to all consumers. From drivetrain, the team moved into steering systems and common manufacture styles and geometry. Lastly, the team investigated braking system, as this is the most critical subsystem for safety within the HPV. Within each subsystem, a discussion of different systems and their advantages/disadvantages will be outlined.

3.2.2.1 Subsystem #1: Drivetrain

The team benchmarked against other drivetrain systems to have a general idea of different systems. These systems are all relatively similar, but do vary slightly in operation, setup, and user interface. The following benchmarks will be against a normal kids bike chain setup, an adult bike chain setup, and lastly, an uncommon internal gear arrangement. Within each section, the advantages and disadvantages of each setup will be outlined.

3.2.2.1.1 Existing Design #1: Simple Gear Setup

On a standard bike manufactured for children, a direct chain system consisting of two sprockets and a chain are typically used. This system is the simplest form of a bike drivetrain and is generally easy to operate, maintain, and adjust. The disadvantages of this system are the lack of adjustability to the sprockets and the set gear ratio when assembling the system. This would be the most viable for a general bike but struggles to accommodate various users and a heavy bike, such as the HPV.

3.2.2.1.2 Existing Design #2: Guide and Derailleur

The use of a guide and derailleur applies to the previously mentioned simple gear setup. The system involves stacking sprockets of different sizes on both the front and rear wheel. The use of a derailleur and guide (front derailleur) help shift the chain horizontally and vertically to align with the next sprocket. This system allows for multiple gear ratios and is generally easy to maintain and operate. The disadvantages of this system consist of being more complex, requires slightly more maintenance, and requires user input for gear selections. This system is the most ideal for HPV as it can accommodate various users and will help start moving the heavy bike for younger children. The user interface created a disadvantage for the team, as we believed the complexity of a shifter could create problems for the children riding.

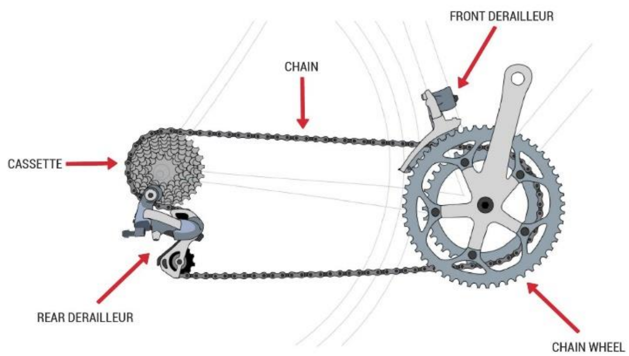


Figure 9: Complex Drivetrain Schematic

3.2.2.1.3 Existing Design #3: Internal Gear Setup

Lastly, the team investigated a not-common internal gear system. The gear system consists of sprockets being contained within the gear box and a single front sprocket with a chain. The internal gear box would shift for the user depending on speed of the bike and crank speed. The disadvantage of the system is lack of reliability, difficulty of maintaining, and pre-set gear ratios. Furthermore, the team believed that if the internal gear system was unreliable and could not be maintained, multiple internal gear systems would need to be repurchased.

3.2.2.2 Subsystem #2: Steering

The steering subsystem is vital for controlling directions of speed and ensuring a safe ride in the correct direction. Furthermore, the team investigated several different steering systems, such as direct, indirect, and tilt. Each system has advantages and disadvantages towards user interface, reliability, and stability.

3.2.2.2.1 Existing Design #1: Direct Steering

A viable option for the team would be a direct steering system. The system has user handles connected directly to the kingpins on each wheel to control the direction of speed. Typically, a trackbar connects each wheel keeping alignment between the pair. This system is very simple and requires less material, while also being easy to maintain and operate. As a drawback, the system is usually prone to feedback through the handles during bumps or rough terrain (bump steer) and can fail easily during small collisions or opposing direction forces in the wheels. This was a main concern for HPV as safety and reliability are the focus of the project.

3.2.2.2.2 Existing Design #2: Indirect steering

Another viable option for the team would be an indirect steering system. Indirect steering is very similar to the previous mentioned system but involves more parts and the handles being separate from the kingpins. On an indirect steering system, the user handles are connected to a drag bar or steering bar. From the drag bar, linkages are arranged to connect to the kingpins for steering and accompanied with a trackbar for alignment. This system is typically better for users as bump steering is mitigated and drag bars can moved forward or rearward for better ergonomic design. Indirect steering does suffer from the need for more space and volume, more parts prone to failing, and more maintenance required. The HPV favored heavily towards this design as a reliable and user-friendly way of directing speed.

3.2.2.2.3 Existing Design #3: Tilt steering

The last option HPV investigated was tilt steering. Tilt steering is more complex in terms of system geometry, but also more intuitive and friendly for the user. The system makes use of a knuckle for each wheel and connects two trackbars to a center pivot point on the frame. As the user rides the bike and leans to one side, the weight shift would rotate the wheels at an angle causing the tire to ride on the outer/inner radius of the tread and thus creating the turn. This system is very complex to build as geometry becomes critical for system function but generally requires the same number of parts as an indirect system. Furthermore, failure of the system, such as a broken trackbar, can lead to catastrophic failure of the frame being stuck to one side or steering in opposing directions. The HPV team believed this would be the most exciting for the kids to ride, but also very dangerous during a failure.

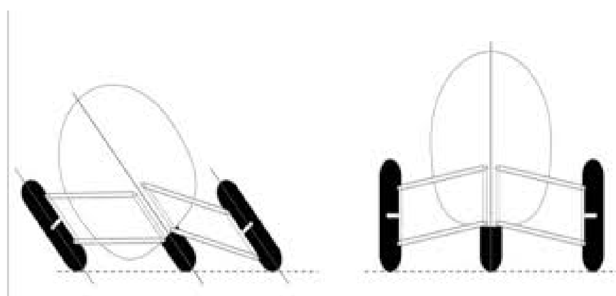


Figure 10: Tilt Steering Diagram [11]

3.2.2.3 Subsystem #3: Brakes

The team benchmarked against several different braking systems to ensure a safe ride for our users. Furthermore, the brake system is fundamentally the most important subsystem to ensure safety for the users and failure of the system could create catastrophic failures or crashes. Thus, three different style braking systems were investigated and analyzed for their advantages: the caliper brake, V-brake, and disc brakes.

3.2.2.3.1 Existing Design #1: Caliper Brake

Caliper style brakes are the most common brake style on bikes and was investigated first by the team. The system composes of a single mounting point for the brake pads to meet against rim actuated by a steel cable for the user to pull on via a brake lever. This system is fundamentally the easiest and least complex to manufacture or maintain for the user. The system does suffer from the single mounting point and starts to lose its mechanical advantage as tires get wider or deeper. Furthermore, if the tires begin to get wet or dirty around the rim, the pads will be less effective at creating friction to stop. The HPV team was interested in this system as it is the easiest and generally cheapest for a brake system, while also carrying a general strong reliability.

3.2.2.3.2 Existing Design #2: V-Brakes or Linear Pull

V-Brake or Linear Pull brakes are very similar to the previous mentioned caliper brake. The brake system requires two mounting points and two lever arms for actuation. With each side being tensioned at the bottom, a brake cable is threaded through the top for actuation. When tension is applied to the brake cable, the two levers move inward towards the wheel causing the brake pads to contact the rim and slow the bike down. Furthermore, this system is also very simple to maintain and manufacture but struggles with wet or dirty rims like the caliper system. The system does contain a higher mechanical advantage and, therefore, works more effectively and reliably than caliper brakes. The HPV team believed this system was a solid upgrade from the caliper system but were still disappointed with the rim style brake.

3.2.2.3.3 Existing Design #3: Disc Brake

The team investigated disc brakes as another alternative to the HPV. Disc brakes are composed of the same principle of caliper and v-brakes with a steel cable applying tension to a pad actuated by the brake lever. Disc brakes have an advantage of relying on an external rotor for friction to slow down instead of the rim. This difference eliminates the problems occurring with a wet or dirty rim being less effective. Furthermore, disc brakes are more complex to manufacture and maintain, but are more reliable and stronger than the previous mentioned systems.

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 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. 11), 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 an 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 11: 4-Wheel concept [12]

4.1.2 Delta concept

The next concept generated is a Delta layout HPV (Fig. 11) 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. 11) which utilizing the front wheel to drive and the rear to steer, allowing for adjustability of the frame [12]. 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 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 12: Delta Concept [12]

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 13: Tadpole Concept [13]

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

Below includes a concise outline of each material considered for the project application.

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 generally 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 advantages and disadvantages 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.

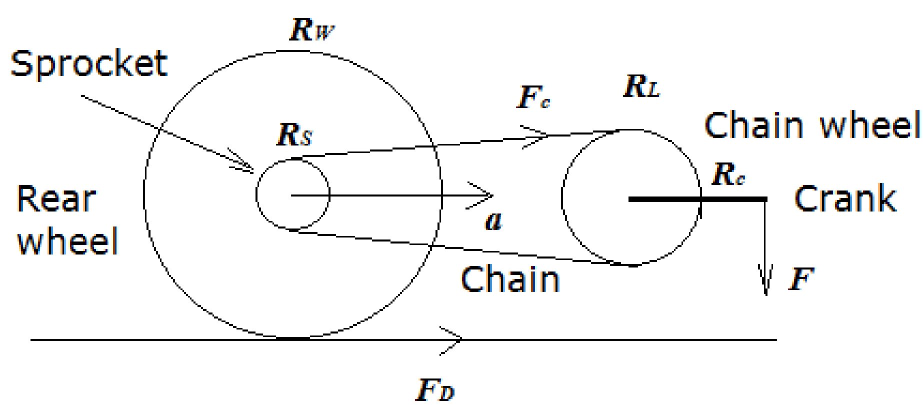


Figure 14: Chain drive [14]

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 joystick 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 includes limited adjustability to riders, as they won't be able to adjust with the large range of riders, and there could be interference with rider's legs. The second concept is a standard kingpin linked to handlebars or wheel like seen in (Fig. 14), similar in complexity to the joystick 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.

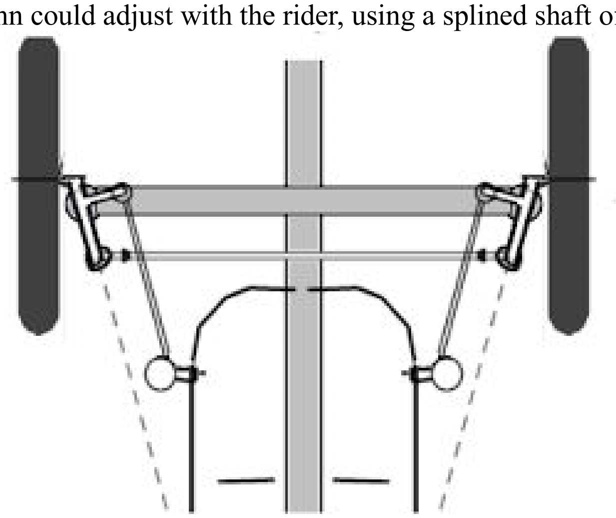


Figure 15: Joystick steering [15]

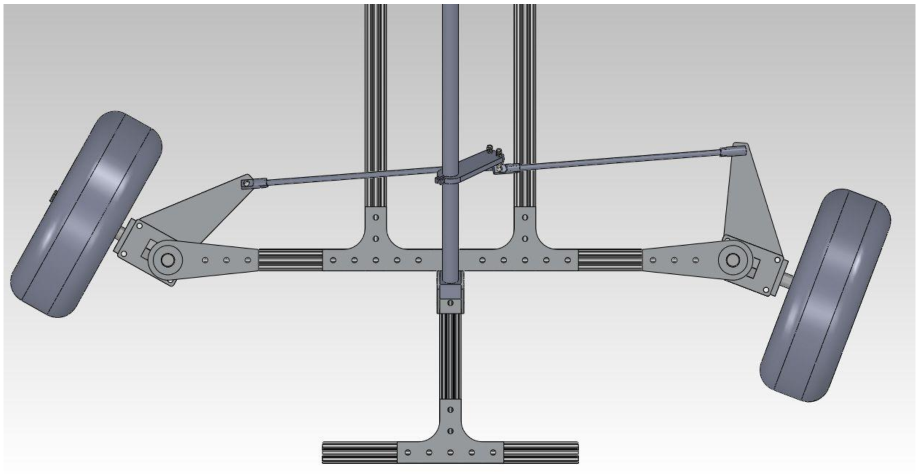


Figure 16: Handlebar steering [15]

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. 18), cantilever brakes (Fig. 19), and disk brakes (Fig. 20). 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 perform 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 than 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 17: Caliper brakes [16]

Figure 18: Cantilever brakes [16]

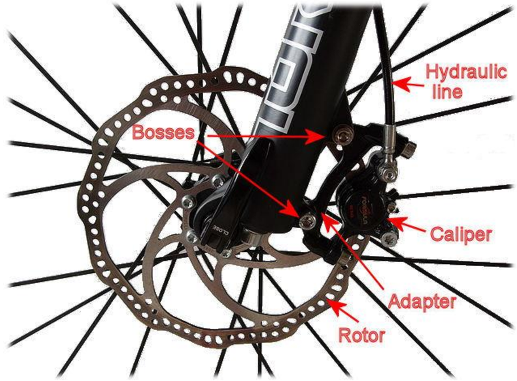


Figure 19: Hydraulic disk brake [16]

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. 21), and a wrap-around cage that can serve as a structural part of the frame (Fig. 22). 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. 14). 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.

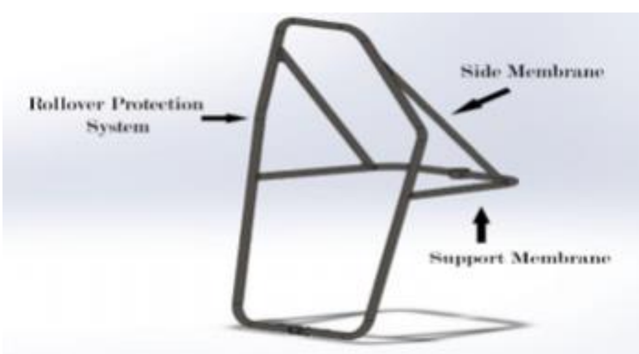


Figure 20: 4-point cage [17]

Figure 21: Wrap-around cage [17]

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. 24), 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.

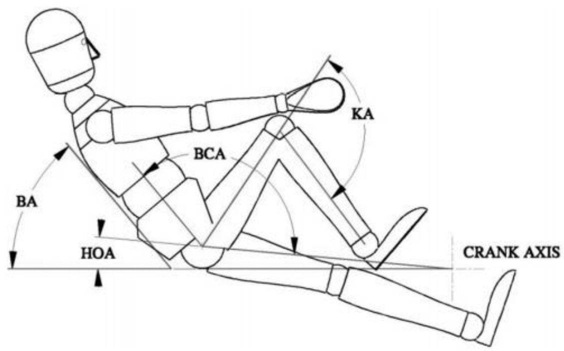


Figure 22: Ergonomic angles [18]

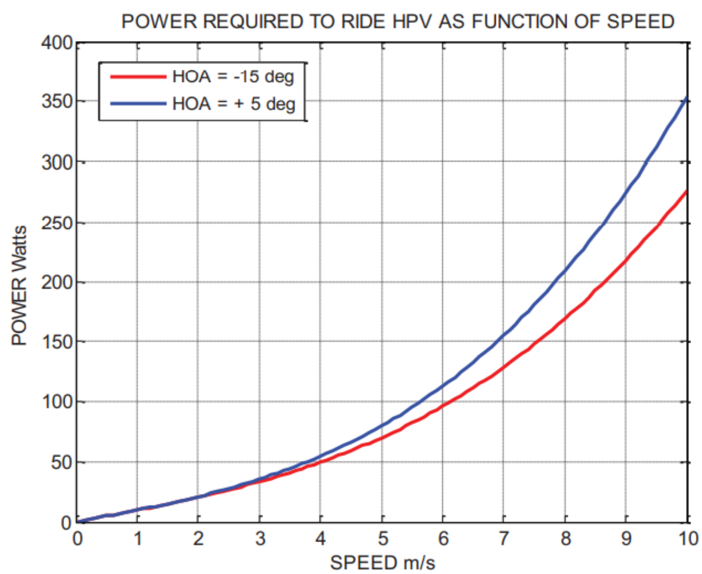


Figure 23: HOA performance [18]

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 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. The only way a fairing could be beneficial would be to use a partial clear fairing like seen in (Fig. 14), which would provide easier access into the HPV and would provide better visibility to the operator. Furthermore after discussing with our client it became clear there was no need for a fairing as it would add cost without benefit, and could cause additional risk to the children who will be operating this product due to visibility concerns, risk of fracture, and risk of trapping the rider in the case of a crash.

5 DESIGN SELECTED – First Semester

Rounding off this semester, the final design that the team chose to go with was a recumbent style tadpole trike. Utilizing a joystick and kingpin style steering system sometimes referred to as “Landstrider” steering. These systems along with other key components such as braking, adjustability, gearing, and roll cage will be further discussed and validated in the sections below.

5.1 Design Description

The vehicle went through multiple redesign phases. Many phases included small adjustments to the system that did not change the design intent. The team had kept a design for a 4-point roll cage for extra stability if the driver rolls the vehicle. The system follows a tadpole trike design with Ackerman steering to prevent tire skips. This design change was caused by using a recycled steering system from a past HPVC project and implemented onto our design. The team originally designed to have caliper braking on the vehicle but was changed during the manufacturing process to disc brakes due to parts available in the machine shop. The design has kept the indirect steering system, as initially intended. Compound chains were used to set up the guided derailer system to ensure proper flow of power to inflict propulsion. Small tensioners and welded tabs were needed to ensure all parts can be correctly mounted onto the vehicle. These changes came during the manufacturing process when parts did not fit as originally intended. The team was forced to make on-site decisions as small incorrect measurements threw off the locations of other parts. All sections below outline the key components of the vehicle.

5.1.1 Frame and Roll Cage

For the frame design and layout that the team chose to use a tadpole style recumbent bike design, which is a trike with two wheels in the front of the bike, with offers improved stability when compared the alternative 3-wheel delta layout which has two wheels in the back. As the tadpole is much less prone to rollover when cornering and as safety and stability is the main concern, the choice was clear. As seen in (Fig. 25) below, a four-point roll cage was selected due to the superior roll over protection and fitting the overall geometry. This roll cage connects to the rear arm which the rear tire is mounted to, providing additional structural integrity to the frame, and minimizing the moment forces at the joints compared to other roll cage designs. Our PVC prototype made it clear that our whole design was way too large and needed to be scaled down.

Figure 24: Prototype A

Since the roll cage and frame will be one welded piece, they will both be using 6061 T6 aluminum as the material. Aluminum was chosen over steel or carbon fiber as it offered the best overall value when balancing cost, weight, and strength, as aluminum is lighter than steal and similar in strength depending on the grade, and it is significantly cheaper than carbon fiber. However, it is important to note that aluminum is prone to fatigue and can fracture under stress without much warning. To validate our frame design bending moment calculations were made using the equations seen below, which produced an actual bending stress of 51.8 MPa which was acceptable compared to the allowable bending stress of 110 MPa.

$$\sigma_{max} = \frac{Mc}{I} \qquad (1)$$

$$I = \frac{bd^3 - hk^3}{12} \qquad (2)$$

5.1.2 Steering

The proposed steering system is a joystick and kingpin style steering system held in alignment by a tie rod as seen in (Fig. 26), this system is sometimes referred to as "Landstrider" steering. This design was chosen as it was worked with the two front wheels and is less mechanically complicated compared to comparable handlebar or steering wheel designs and is expected to be more enjoyable for the children who will be riding this bike. After doing some trigonometry it was confirmed that the wheels can rotate over 45 degrees before the joysticks will interfere with the seat, while its capable of more the wheels will be restricted to 45 degrees or less to prevent any risk of tip over due to over sensitive steering. With this information along with the dimension of the design Ackerman steering calculations (Fig. 27) can be performed to calculate the maximum and minimum turning radius, which came out to 2.64 and 1.6 meters respectively.

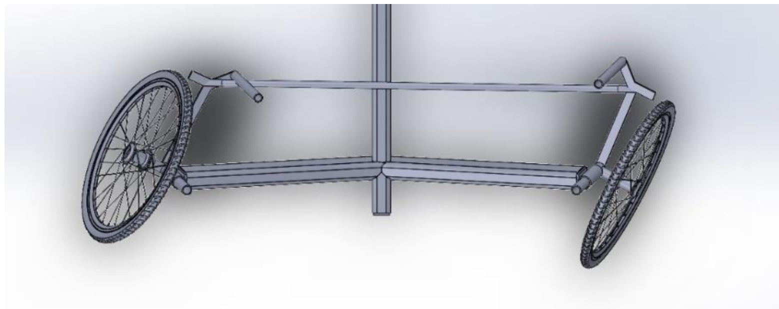
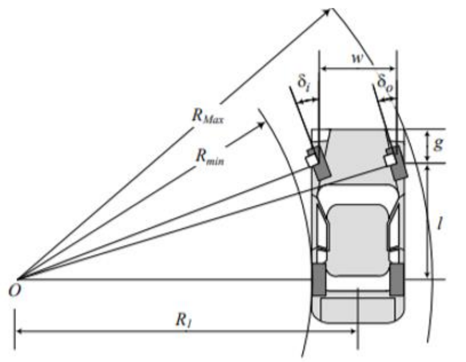


Figure 25: Steering Setup



$$R_{Max} = \sqrt{(R_{min} + w)^2 + (l + g)^2} \quad (6)$$

$$R_{min} = R_1 - (w/2) = (l/\tan\delta_i) = (l/\tan\delta_o) - w$$

Figure 26: Ackerman Steering Calculations [19]

Additional steering geometries high are highlighted in (Fig. 28) include a -10-degree caster angle which will help the wheels to naturally return to a straight position, which is due to the weight of the bike wanting to move to the lowest position, caster also helps the bike handle and frontal impact. The next geometry is camber angle which was chosen to be -10 degrees to accommodate any side forces acting on the wheels when turning, and further improving stability. Lastly and important detail is the team is planning on using 20" wheels for the front of the bike, and a 26" wheel in the rear.

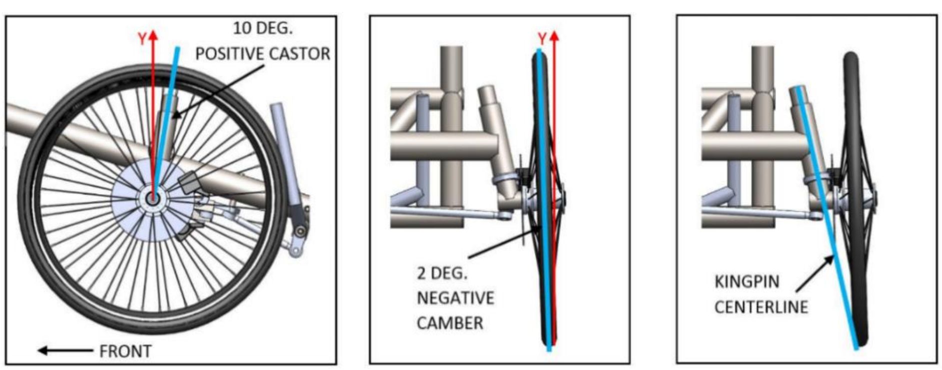


Figure 27: Castor, Camber, and Kingpin Angles

5.1.3 Remaining subsystems

For braking, the plan is to use a disk brake for the front of the bike, which can mount off the spindles and a similar disk brake in the rear. The disk style was chosen as it will be easy to mount and offers the best performance. The team also had the idea to provide an auxiliary brake mounted to the roll cage, so instructors could stop the vehicle if anyone gets out of control, or to prevent movement when riders are climbing in or out of the trike. The auxiliary brake was never installed as the team deemed it to be unnecessary due to the safety harness installed. Braking forces were calculated using the equations below to better understand the declaration, and forces which will need to be exerted by the brakes, which resulted in a net stopping force (F_{bi}) of 210 newtons and a brake force of (F_{br})of 828.2 newtons.

$$v_f^2 = v_i^2 + 2ad \quad [3]$$

$$a = \frac{-v_i^2}{2d} \quad [4]$$

$$F_{bi} = m_{total}a \quad [5]$$

$$F_{br} = F_{bi}\frac{r_{wheel}}{r_{rotor}} \quad [6]$$

For the drive chain, the team plans on buying a basic multispeed chain and sprocket crank system, as having a large top speed is not a priority in this design this choice will mainly be made off cost and ease of operation. With the lowest gears offering at least a 3:1 ratio to ensure even the smallest of riders will be able to easily propel the trike. The last main subsystem is the adjustability for the range of riders which is accomplished with a bracket which the seat can move along like seen in (Fig. 29) which consists of plate metal welded together to allow it so slide along the 2” main frame tubing, hanging just enough below to use two quick release clamps that will secure the seat from sliding.

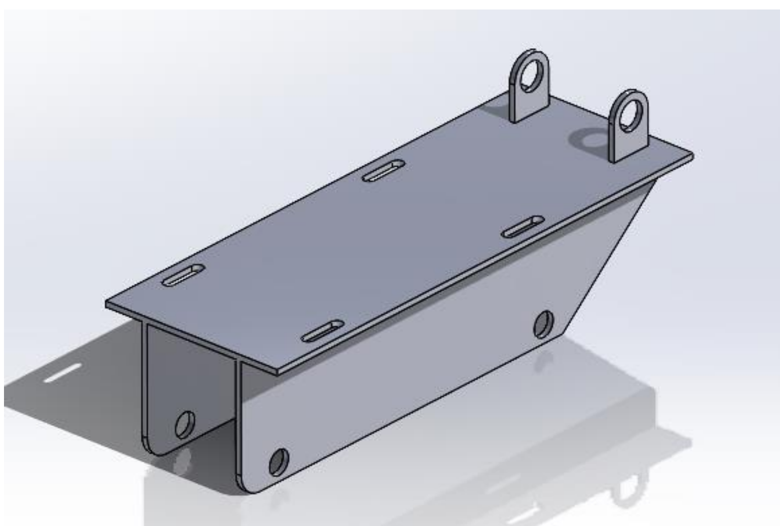


Figure 28: Seat Bracket

6 IMPLEMENTATION – Second Semester

The team has undergone several design changes to the roll cage design and body layout. These changes were to adjust dimensions and alter the fitting of parts. Design considerations were considered with safety of the driver and available manufacturing processes in mind, to properly utilize the equipment available in the machine shop to ensure that manufacturing and finishing the product was possible.

6.1 Design Changes in Second Semester

Several design changes were made in the second semester that overhauled a complete redesign. This was due to not being able to get into the machine shop until the second semester and gaining an understanding of the tooling available. Shifting the teams focus to design for manufacturing and utilizing recycled parts from previous teams to save on budget and manufacturing time. Every change in design had a ripple effect in terms of changing dimensions across the entire bike, for example the recycling the steering system changed steering dimensions including camber angle.

6.1.1 Design Iteration 1: Change in steering

A pre-existing steering system was salvaged off a donated bike to save time and money. This system didn't deviate from the original design much, utilizing the same indirect joystick style steering, with the main difference being a third headset in which the joystick steering actuators pivoted around. This saved a large portion of the budget as steering was the highest allocated cost of any subsystem, and with the manufacturing limitations, the team felt it would be difficult to fabricate precise spindles and brake rotors. A few modifications had to be made with the geometry of the steer such as turning down the tie rods to allow for a better mounting position and a tighter turn radius.

Figure 29: Reused steering

6.1.2 Design Iteration 2: Change in frame

The overall frame design has had several iterations as this project has progressed becoming more realistic with each iteration, from improving the roll cage design, to drastically scaling down the dimensions which were highlighted through the PVC protype seen in (Fig. 25) above. Further iterations were made once manufacturing began and a better understanding of fabrication and welding was developed. For one, having a flat frame on the bottom made it significantly easily to position for welding, since aluminum isn't magnetic and angle magnets typically used for steel fabrication were rendered useless. Along with the flat frame being ideal for the seat adjustability, steering setup and routing the chain.

Figure 30: Welding Frame

6.1.3 Design Iteration 3: Change in roll cage

The final large design change was with the roll cage as there were roughly four roll cage redesigns. Originally the team decreased the tubing diameter from 1.5” to 0.75” to reduce weight and bring down the center of gravity. The next iterations were due to the limits of the pipe bender in both the max degree of bend and the radius of bend. The only roller available had roughly a 3” bend radius compared to having a bend radius that matched up with the width of the roll cage like was previously planned.

Figure 31: Bending roll cage

7 RISK ANALYSIS AND MITIGATION

Each project has the risk of failure. To ensure the team designs a trike that does not fail guided the path to risk analysis and mitigation through means of FMEA sheets and physical testing. Below are discussions of how the team mitigated possible failures within the system based on decision making. Risk discussions are broken down into what potential failures were analyzed in ME 476C, any potential failures that came up through manufacturing/testing in ME 486C, and the team's plan for mitigating each failure.

7.1 Potential Failures Identified First Semester

A list of the top ten ranked critical potential failures is below. The top ten are ranked on severity, occurrence, and detection. All ranks are multiplied together to visibly show which parts or functions would most likely have the potential to fail under stated conditions. Each discuss how the failure could be caused, the effect of the failure, and how the failure can be mitigated. The full FMEA worksheet can be found in Appendix A.

7.1.1 Potential Critical Failure 1: Head Tube

Failure at the head tube of the frame would cause the HPV unsafe to operate in the case of an accident, compromising the safety customer requirement. Large loads at concentrated joints can potentially cause the failure, depending on the material chosen and quality of welds at each joint. Cracks, fracture, and/or bending can potentially happen, causing the HPV unsafe for operation until the members are repaired or replaced. Mitigation from this failure include selecting the correct material (6061 Aluminum), and quality of welds.

7.1.2 Potential Critical Failure 2: Brake Cable Failure

Brake cable failure would result in an unsafe HPV. The probability of an accident happening increases if a brake cable is compromised. High cycle life, plastic deformation, and tears are potential failure modes. The loss of brake force reduces the safety in operating the HPV because it will not allow the HPV to come to a safe and steady stop within the 8m, stated by the engineering requirements. Maintaining and replacing brake cables regularly will mitigate the failure.

7.1.3 Potential Critical Failure 3: Sprocket & Chain

Rust corrosion is common in any metal part if not properly maintained. Rust can corrode the sprocket and chain assembly, compromising the ability to efficiently operate. Overhydrating either sprocket or chain can potentially cause corrosion to occur. The corrosion can cause the HPV to lose its ability to function properly and can potentially cause the chain to snap. The failure can cause the HPV to become inoperable until the parts are replaced. Properly storing the HPV away from environmental effects, or keeping it inside, will mitigate rust or corrosion from happening.

7.1.4 Potential Critical Failure 4: Drive-train Gears

Corrosion or plastic deformation can cause the HPV to properly operate. If the gear teeth begin to sand down, the chain could potentially slip from position. Fracture from a side blow can cause the gear prone to plastic deformation and environmental effects can cause corrosion. Maintaining and replacing gears as necessary is critical in owning an HPV. Using a gear shield will also help mitigate deformation from a side blow.

7.1.5 Potential Critical Failure 5: Handlebar

Loading can cause cracks or failure along the handlebar. Loading failure has typically been seen on a traditional bicycle where the rider stands and leans forward so their weight is focused along the handlebar beam, causing cracks or a broken beam. A crash can result from a fracture in the handlebar while operating a bicycle. The team mitigated this failure by designing a recumbent tadpole HPV with a large hip angle to avoid handlebar loading.

7.1.6 Potential Critical Failure 6: Steering Fork Failure

Sharp corners in the design, especially at loaded points in the frame, can potentially cause part failure through crack propagation. Aluminum is prone to this and can cause an accident if not handled properly. The team designed each change of direction along the beams to be filleted or chamfered with no sharp corners. Load testing would visibly validate that the steering fork is structurally sound.

7.1.7 Potential Critical Failure 7: Steering Welds

Welds along the frame discussed in previous section are potentially compromised if they are not done properly. Ensuring a filleted weld along all edges is critical in mitigating crack propagation. Limiting excess parts and using correct fasteners is the key to mitigating this failure. The team is going to attend a manufacturing class to learn about welding prior to assembly will take place.

7.1.8 Potential Critical Failure 8: Spindle

A poor design for load and/or high cycle life can potentially cause the spindle to fail. Using the correct uprights will help prevent spindle failure. Spindle failure can also potentially cause the HPV out of alignment or plastically deform. The team will assemble the wheel mounts close to the axis of rotation to mitigate spindle failure.

7.1.9 Potential Critical Failure 9: Joint Members

The roll cage is critical in keeping the driver safe if the HPV rolls over. Large loads in the roll cage can compromise the integrity of the HPV if fractured. The HPV roll cage cannot break because safety is top priority for the scope of this project. Using effective geometry to design an ideal roll cage frame with reinforced joints has helped in mitigating failure. Fillet reinforcements will be placed on all joint members to reduce the likelihood cracking or fracture.

7.1.10 Potential Critical Failure 10: Tire Failure

Tires are prone to failing over time. High cycle life can cause the tread to decay, compromising the traction needed to safely brake. Nails in the road are a big problem causing tire failure. If unrepairable, one nail can take out a whole tire. Consistent maintenance and replacing as necessary will help prevent tire failures on the road. Tire failures compromises everyone’s safety if the tire completely pops.

7.2 Potential Failures Identified This Semester

Many of the potential failures found this semester were previously anticipated such as derailing chains, and tire decay which became a concern as the reused tires had some sun damage but after replacing the tubes and test riding the HPV and making minor modifications, they were determined to be safe and acceptable.

7.2.1 New Potential Failure 1: Weld Failure

Learning to TIG weld and all the unique properties of aluminum was a new learning experience for the team as there were so many variables is obtaining a solid weld, such as equipment setup, proper cleaning of aluminum, and gas post flow to properly cool the welds. Welds were thoroughly inspected for crack propagation and penetration, there was only one weld in which a crack was discovered likely stemming from not holding the torch long enough for the post flow gas. This was quickly fixed by laying a new a new bead and penetrating through the crack, after this weight was applied to the frame and welds rechecked.

7.2.2 New Potential Failure 2: Steering and Chain Collison

Once the steering and drive train had been implemented there was a risk of the steering hitting the chain at full turn. This could cause the chain to derail or bind the steering, this risk was mitigated by dropping the height of the steering system by roughly half an inch to allow for proper clearance.

7.3 Risk Mitigation

The list of potential failures needed solutions to mitigate and minimize their possibility of occurring. The discussion includes the mitigation of each potential failure to ensure a low likelihood of failure. Trade-offs were brought up throughout the redesign process as manufacturing took many turns throughout the semester. While some risks were more difficult to mitigate, the team is confident that the vehicle has a low likelihood of failure.

Table 4: Potential Failure Mitigation

Critical Potential Failures	Mitigation
Handlebar/stem failure when loaded by steering	Reinforcement along joints
Joint cracks	Joint reinforcement (fillets)
Snapped chain	Maintain oil, keep spare on HPV, keep derailleurs aligned
Wear on brake pads	Maintain brake pads and control cables regularly
Brake levers	Tadpole design = brake levers are behind wheels
Head tube	Fillet reinforcement
Pedals/crank arm	Recumbent design = not all weight loaded on pedals Hip angle implementation Material properties/finishes on material to expand cycle life
Seat/seat post	Recumbent design = no seat post
Fork leg	Material properties/finishes

While there is a possibility of failure in every aspect of the design, it is important to outline mitigations for each potential failure. Table 4 shows the mitigation plan for the respective potential failure. These will be included within the operation manual to ensure knowledge of potential failures are shared with the client. Major risks regarded the failure of the seat post but was later mitigated through the redesign of the seat mount.

8 ER Proofs

The following contains the completion of all testing procedures for this project. This section is divided by engineering requirements followed by its respective test. Each requirement includes any resources used, locations, and/or the schedule of the tests throughout the semester.

Table 5 - ER Proofs

ENGINEERING REQUIREMENT	Status of Test
BRAKING DISTANCE (TARGET: ≤ 8 METERS ± 1 METER)	Met (1.5 m)
MINIMUM OF 3 WHEELS	Met (Trike)
SEAT-TO-PEDAL DISTANCE (TARGET: 50 CM ADJUSTABILITY ± 10 CM)	Met (51 cm)
VOLUME (TARGET MUST FIT 6.5' X 5.5' TRUCK BED)	Met (6' x 3'
WEIGHT (TARGET: ≤ 45 KG ± 5 KG)	Met (~12kg)
Cost (TARGET: ≤ $1,200 ± $400)	Met (~$600)
Gear Ratio (3:1 or 4:1)	Met (3:1)
Turn Radius (TARGET ≤ 8 METERS ± 1 METER)	Met (1.7 m)
Tensile Strength (250-560 MPa)	Met (290 MPa)

A condensed table of what each ER is fulfilled with is shown above in Table 6. Each section below this paragraph breakdown each ER into their respective tests and what targets/tolerances were used, along with how well the vehicle performed within each test.

8.1 ER Proof #1 – Braking Distance (Target: ≤ 8 meters ± 1 meter)

The team tested for brake distance after every speed increment of 3 mph. (Figure 33) below shows how this test was completed; by actuating the brake system once passing the orange cone and measuring the distance. The team completed this for all increments and found that the trike stops at 1.5 meters traveling at 10 mph and 4 meters traveling at 20 mph.

Figure 32 - Brake Distance Test

This test was utilized to show that the brakes are sensitive enough for an emergency stop, without feeling aggressive during actuation. This was the last test the team completed because it came after the full system assembly.

8.2 ER Proof #2 – 3-wheel design

The tadpole trike design fulfills the requirement of 3 wheels. Instead, the team tested the durability of the vehicle by driving off-course, making sharp turns, and tipping it over. The team drove the trike uphill and downhill on dirt paths off-pavement to visually test the durability of the vehicle. As anticipated, the vehicle passed these tests and was shown to tip over well beyond what was anticipated. (Fig. 34-36) show the vehicle passing the off-course and tip over tests.

Figure 33 - Off-course Downhill Test

Figure 34 - Off-course uphill Test

Figure 35 - Tip Over

Through evasive maneuvers, the team is confident that the vehicle is capable of standing emergency situations. The derailer stands at a close height with the ground, however, this worry was alleviated through testing. These tests occurred at the end of ME 486C, after the system was fully assembled.

8.3 ER Proof #3 – Seat adjustability (Target: 50cm adjustability ± 10)

The ER states that there must be 50 cm of adjustability within the seat for differently sized children. The test conducted was shortening and extending all adjustable components. The seat bracket slides linearly along the frame and the back rest adjusts rotationally to give a total adjustability of 51 cm.

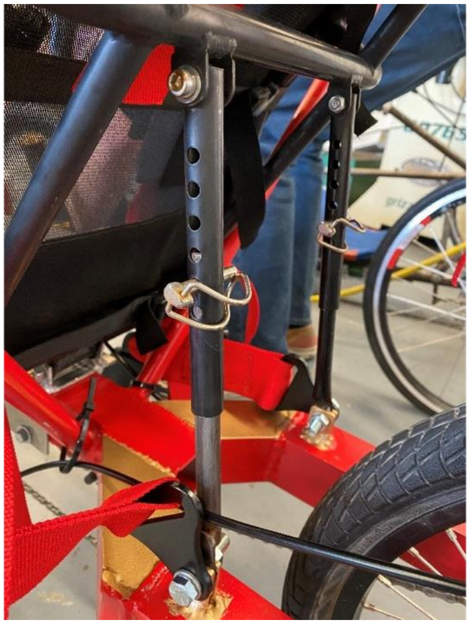


Figure 36 - Height Adjustments

Figure 37 - Axial Adjustment

Implementing an adjustable seating system is important to the project to fulfill the ER of children 5-13 years of different heights. Figures 37 and 38 show how the system can adjust vertically and horizontally , respectively both with quick releasing features so all adjustments can easily be made by hand. The vertical adjustment reaches a maximum 20 cm, and the horizontal adjustment reaches a maximum 31 cm, fully validating the ER.

8.4 ER Proof #4 – Volume (Target: Fit in 6.5' x 5.5' area)

The purpose of this ER is to make the transportability of the vehicle an easy task. The compact lightweight design makes loading the vehicle into a truck simple without the need to disassemble any components. Figure 3 shows how small the area that the vehicle takes up is. The final design fits in a 6' x 3' area, well within the ER parameters.

Figure 38 - Width Measurement (3')

Figure 39 - Length Measurement (6')

(Fig. 39 and 40) show the team members measuring the area the vehicle takes up to validate that it will fit in a standard sized truck bed. The purpose of fulfilling this ER is to make transportation to neighboring schools an easy task that can be done by anyone who owns a large vehicle. This test was completed after the steering system was implemented and again after the full assembly.

8.5 ER Proof #5 – Cost Effective (Target: $1,200 ± $400)

During ME 476C the budget for the project was fluctuating based on the change in project scope. The team designed to $1,200 before getting into the Machine Shop. It was not until ME 486C that the team obtained a concrete budget of $1,600. After the team was able to recycle old parts from other HPV's, the team landed at a total cost just under $600. Appendix B has the full breakdown of costs and materials used throughout the duration of the project. There was no physical test to fulfill this ER, so the team utilized as many recycled parts as possible to minimize total cost.

8.6 ER Proof #6 – Turn radius (Target: ≤ 8 meters ± 1 meter)

The turn radius test occurred in the middle of ME 486C, after the steering was implemented onto the frame. The calculations done in ME 476C theoretically proved the test would pass within a radius of 8 meters. (Fig. 41) below shows how this test was completed by using a measuring tape and positioning the trike in a full turn to measure the radius of a 180° turn, proved at 1.7 meters.

Figure 40 - Turn Radius Test

The purpose of this ER is to ensure comfortable operation during turns. Another benefit is the capability of evasive maneuvers if sharp turns must be made. Measuring tape was the only resource needed for this test after the implementation of the steering system.

8.7 ER Proof #7 – Material Properties (Target: 400 MPa ± 150 MPa)

The preliminary research helped the team select the material used for the project. Maintaining the idea of a robust lightweight design led the team to selecting 6061 aluminum alloy. The analysis performed showed no deformations in the central beam as loads were applied to the area where the seat bracket mounts. The alloy has a tensile strength of 290 MPa, which falls between the given boundaries and tolerance.

8.8 ER Proof #8 – Weight (Target: ≤ 45 kg ± 5 kg)

A transportable HPV cannot be heavy beyond its ability to be lifted into a truck bed. The team was able to find total weight of what was built in SolidWorks, but that excludes the steering, sensor, Arduino, and any other miscellaneous parts assembled onto the frame.

Figure 41 - Weight of Vehicle

The frame, without any other subsystems, weighed 6.5 kg. The team was surprised when after the other systems were implemented onto the frame, the total weight of the system came out to be 27.2 kg. (Fig. 41) shows the process of weighing the vehicle. It is important to note that under each wheel is an even weight distribution, each at 9 kg. The team was able to utilize scales in the machine shop and completed the last weigh in after the system was fully assembled.

8.9 ER Proof #9 – Gear ratios (Target: 3:1 or 4:1)

Gear ratios are important in limiting actuating systems in a design. Typically, gear ratios A and B of 3:1 or 4:1 are seen in bicycles, respectively. The team has designed to a 4:1 ratio to aid in the propulsion of the vehicle using the least amount of human power to preserve energy. A visible validation test was done after the completed assembly. The calculations have proven the gear ratio of 3:1 is suitable for the intended design. The physical rating of propulsion occurred after the final assembly had been built to ensure low power input from the driver. Unexpected issues implementing the drivetrain and lack of proper tooling did end up postponing testing by a day.

9 Looking Forward/Future Work

The completion and successful testing of the HPV has proven that this product is completely operational and ultimately doesn't need any future work. However possible modifications could be made by future teams or the ASME club to improve its performance including shorting the cranks from 170mm to 150-15mm to better fit the geometry of the bike and provide better ergonomics for the smaller riders. Along with fine tuning the shifting system to get better consistency with the gear shifting. Additional recommended for design iterations based of the results of testing are included in the opportunities for improved section below.

10 CONCLUSIONS

Overall, the team feels very confident in the design and are very happy with the resultant product. Furthermore, the team believes we have met the customer requirements, have tested thoroughly, and is ready to tour to other schools. This project allowed team member to develop critical new skill and improve on existing such as teamwork, communication, design, and project management. Working in the shop was a great opportunity to gain critical manufacturing skills with a variety of equipment including TIG welding and machining, we take pride knowing the HPV was manufactured completely by our team without any outside work orders. The team is very happy of being able to reuse previous HPV parts to reduce budget, while also including small aesthetic pieces to help with engaging the interest of kids. Ending up successfully designing and manufacturing a product that holds up to the client's standards and expectations. Hopefully this project can be appreciated by others inspire children at schools to gain an interest in engineering and promote STEM education.

10.1 Reflection

Initially, moving from a competition bike to a child size bike changed the major scope of the project and the entailments. Furthermore, the team tried to create something that would inspire and excite the kids to get involved in a STEM major. While also upholding the standards of safety and engineering principles. To continue, the team had an end goal of creating something "cool" for the kids but had an initial goal of designing and manufacturing a product that functioned and operated within a safe manner for kids to ride. Within the idea of inspiring, we wanted something that would bring children in from different cultures, economic classes, and ethnicities to enjoy. Furthermore, the team decided an Iron Man theme would help address this, along with other small pieces such as strip LEDs and a speedometer. The team took major steps into ensuring a safe design for the kids, starting with initial tadpole layout, following with the full 4-point roll cage and lastly, a 4.2-point harness. The HPV, being a human powered trike to tour to other schools, contributes very minimal to environment and can be used as a presentation piece into public health problems.

10.2 Post-Mortem Analysis of Capstone

The purpose of the post-mortem was to completely answer where the biggest contributors and project success came from, along with opportunities for improvement in the future. The team previously completed a post-mortem at the start of ME 486C to promote accountability towards the project's success. It reflects on how the ME 476C semester went for the team and which areas need more focus or implement changes. Below is a broken-down outline of contributors to the project success and future opportunities of improvement.

10.2.1 Contributors to Project Success

The project's success can be broken down into multiple aspects of the design process. At the initial phases of the capstone journey, the team agreed and signed a Team Charter, to outline member expectations and goals for the project. As stated, the team successfully completed the purpose and project goals from the Team Charter. The ruled stated in the charter were followed but, at times, the coping strategies were not as well as they could have been. There were issues with scheduling, forcing some team members to take on more work than evenly distributed. This led to team frustration surrounding some assignments. However, there were many positive aspects that guided the team to success. These aspects were manufacturing capabilities allowing additional weldments to the system as necessary, utilizing recycled parts to save cost, on-site creative solutions, and the commitment that most team members made to fully complete the project by the given deadlines. Some negative aspects of the design process slowed down the project down later than the anticipated completion date. Purchase order delays were a big contributor to slowing down the team. Without the necessary parts it is difficult to complete a subsystem; the team mainly saw this issue with the drivetrain. Incorrect measurements forced the team to make on-site creative solutions, as seen in the added tensioner in the front chain loop and the welded tabs added to the bottom rear of the fork/frame.

The tooling which contributing to the team's success include: TIG welder, pneumatic pipe bender, horizontal band saw, vertical mill, machine shop tools, and the ability to implement creative solutions to unforeseen problems all guided the team to success. Machine shop hours of operation slowed down project production because of the small window of hours the team was allowed to work in, causing many other problems along the process. These problems include chain adjustments to fit gearsets, height of steering system to avoid contact with any other subsystem, replacing brake cables, mounting the seat and back support, mounting the derailer, recreating the seat mount, and schedule of completion towards the end of the ME 486C semester. If there was an opportunity to improve performance, the height of the derailer and tension in the front chain loop would be the first to improve efficiency. Through practice of creative solutions, many technical skills were developed over the course of the project. Knowledge regarding welding, programming, web development, and bike tuning were all gained throughout the year. Every team member gained pieces of knowledge that had not been practiced before this project.

10.2.2 Opportunities/areas for improvement

Looking back over all the work this team did over the last year there are areas in design and manufacturing which could be improved. First and foremost, FEA analysis could've been better utilized to make a more efficient design, along with getting in the machine shop earlier would've been incredibly beneficial to the team. As manufacturing and equipment limitations caused several issues, leading to almost a complete design change based off what was proposed at the end of the first semester. Some of the components on the bike are not ideal for performance or quality as many parts were recycled from previous bikes to focus on keeping the budget low.

Specifically, a few areas that could be improved on the bike include the drive train could've been cleaner as a few things weren't considered such as the possible chain lengths having to be change in increments of two links leading to a last-minute makeshift chain tensioner on the front. Another thing that would be beneficial to change would be to use shorter cranks to better fit the geometry of the bike, and provide better ergonomics for the smaller riders, currently there is a standard 170mm crank which is a bit too big ideally a 150mm crank would be used but likely would require custom manufacturing or a change on the hub style. Since the steering was recycled some of the geometries are less than ideal and required modifications. For one a larger camber angle would've improved stability, as well as adding a caster angle, the caster angle wasn't added due to limited manufacturing capability at the time. Finally, the derailer system could use some fine tuning as occasionally it will fail to shift, this is likely due to the throw on the shifter.

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12 APPENDICES

12.1 Appendix A: FMEA

Product Name	HPV				Page No of
System Name			Count =	36	FMEA Number
Subsystem Name					Date
Component Name					

Subsection	Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S) [1-10]	Potential Causes and Mechanisms of Failure	Occurance (O) [1-10]	Current Design Controls Test	Detection (D) [1-10]	RPN	Recommended Action
Braking	Lever	Sheared lever due to impact	Impaired ability to actuate brake	7	Large impact force	2		1	14	Brake away lever
	Cable	Loss of tension in cable	Loss of brake force	5	Plastic Deformation	4		3	60	Cable Maintence
	Caliper Clamps	Brake pad wear	Loss of brake force	6	Large fricition	1		5	30	Maintain & replace pads as needed
	Brake Mount	Bending or fracture under load	Plastic deformation	4	Large load	1		5	20	
	Bolts	Loosens over time	Impaired ability to actuate brake	7	High cycle life	1		4	28	
	Wheel	Deformation of rim	Loss of effecive braking	3	Bent rim due to impact	3		4	36	Larger wheel treadwall
	Tires	Tread decay	Loss of traction to brake	5	High cycle life	5		2	50	Maintain tires & replace as necessary
	Brake disk	Bent disk	Impedes wheel from spinning, damag	5	Impact to disk causing it to bend	3		3	45	Protect with frame or gaurd
									0	
									0	
Drive-train	Chain Slipped teeth	Sprocket over- or under-slipped chain	Loss or inefficient Power	3	Inaduquate tensioning	2		5	30	Set Tensioner
	Chain slipped off sprocket	Chain skipped teeth and fell of spocket	Loss of Power	9	Inaduquate tensioning or maintence	3		1	27	Set Tensioner and Lubricate Chain
	Broken Chain	Chain broke at pin or link	Loss of Power	9	Lack of maintence	3		1	27	Lubricate Chain
	Loose Sprocket	Sprocket seperated from axis of rotation	Inefficent power output	3	Poor Manufacturing	2		7	42	Ensure adequate sprocket Seating
	Corroded Sprocket/Chain	Rust fatiguing sprocket and chain	Broken chain (Loss of Power)	6	Enviromental Effects	2		5	60	store HPV inside
	Tensioner Misalligned	Chain slip or broken chain	Slipped chain (Loss of Power)	8	Tensioner not parralel to drivetrain	1		5	40	Ensure tensioner is inline
	Tensioner not Calibrated	Chain slip teeth or sprocket	Slipped chain (Loss of Power)	6	Tensioner under or over tensioned	2		3	36	Set Tenioner
	Crank Arm	Deformation, bending, fracture	Loss of operational efficiency	3	Large loads, high cycle life, poor material selection	2		5	30	Reinforce Crank Arms
	Pedals	Fracture, plastic deformation	Loss of operational efficiency	1	Large loads, high cycle life, poor material selection	2		2	4	Reinforce Pedals
	Gears	Fracture, corrosion	Slipped chain (Loss of Power)	5	High cycle life, poor material selection	3		4	60	Maintain gears & replace as necessary
Steering	Design	Alingment	excess tire wear, decrease efficiency	2	Excess compression forces, impact	8		2	32	Plan alignment in CAD design
	Handlebar	Crack propagation	Broken handlebars	5	Sharp corners in design (especially with Aluminum)	2		6	60	Reinforce as needed (fillets)
	Handlebar clamp	Loss of grip	Unalligned handlebars	4	Incorrect clamp or dimensioning	5		2	40	Design correct diameters, make one piece with spindle
	Tie rod	Deformation underload	Loss of allignment	3	Impact to wheel or tie rod	5		2	30	Design to handle compression
	Fastners	Losen or fracture	Loss or allignment or function	5	Impact, incorrect harware/ installation, fatigue	4		2	40	Use correct grade and fastners, locktite
	Fork	Bending, fracture under load	Part failure	8	Excess braking force or impact	2		3	48	Design for impact, caliper rim brakes
	Fork	Crack propagation	Part failure	8	Sharp corners in design (especially with Aluminum)	2		6	96	Reinforce as needed (fillets, camfer)
	Spindle	Deformation under load	Part failure, out of allignment	6	Fatigue, poor design for load,	3		3	54	Design for correct load, mount wheel close to axis
	Welds	Weld failure	Part failure	6	Fatigue, poor weld, impact	3		4	72	Preform pratice welds, inspect welds
	Handlebar linkage	Deformation, or failed connection	Loss of steering	4	Impact, or excess force	5		4	80	Use correct fastners, limit excess parts
Frame/Rollcage	Base Frame	Bending due to loading	Frame can't support weight	8	Loading, inadequate supports/geometry	3		2	48	Testing and proper geometry
	Roll Cage	Fracture, bending, plastic deformation	Offers no protection, hazard	7	Large Impact force, weak material, cracks	2		2	28	Testing, geometry, material
	Cross Members	Fracture, bending, plastic deformation	Stability and supports weaken	6	Large loading, critical joint angles	1		2	12	Geometry, material
	Joint Members	Crack Propagation	Material strength decrease	8	Fatigue/ cyclical loading	5		7	280	Geometry, material, fillet reinforcement
	Seat/Seat Post	Plastic Deformation	Unable to properly sit	5	Large cyclical loading	1		4	20	Geometry, material
	Fork Leg	Plastic Deformation, fracture, bending	Compromised Stability	4	Weak material, loading cycles	1		4	16	Geometry, material
	Head Tube	Cracking, fracture, bending	Unsupported operator load	5	Large loads at concentrated joints	2		8	80	Geometry, material
	Weldments	Weld failure	Part Failure	9	Improper Weldments	6		5	270	Weldment Standards

12.2 Appendix B: Budget

Purchased	PO#	Vendor	Item	Quantity/Size	Total Costs	Totals
						$1,600.00
9/3/21	1	Mayorgas	2"x 2" Hollow Square	10ft	$73.72	$1,526.28
9/3/21	1	Mayorgas	1.75" Round Tube	20ft	$42.58	$1,483.70
9/29/21	2	OnlineMetals	1.5" Hollow Tube	2ft	$44.10	$1,439.60
9/29/21	2	Amazon	Hall Effect Sensor	1x6pc	$12.91	$1,426.69
10/15/21	3	Amazon	Wire Brush Stainless Steel Wire Scratch Brush for Cleaning Rust	1x1pc	$13.05	$1,413.64
10/15/21	3	Amazon	OVIMAG Super Strong Neodymium Disc Magnets	1x5pc	$9.23	$1,404.41
10/15/21	3	Amazon	24PCS Sand Paper Variety Pack Sandpaper	1x24pc	$5.43	$1,398.98
10/15/21	3	Amazon	Rust-Oleum 7582838A2 Professional Primer Spray	1x2pcs	$15.18	$1,383.80
10/15/21	3	Amazon	Rust-Oleum 249127 Painter's Touch 2X Ultra Cover	1x1pc	$7.90	$1,375.90
10/15/21	3	Amazon	K01706 Krylon Spray Paint, Gold	1x1pc	$15.62	$1,360.28
10/15/21	3	Amazon	Rust-Oleum 271920 Gloss Cherry Red	1x4pcs	$6.82	$1,353.46
10/15/21	3	Amazon	Amazon Basics 9 Volt Everyday Alkaline Battery	1x1pc	$7.58	$1,345.88
10/15/21	3	Amazon	Mybecca Upholstery Foam Cushion Sheet High Density	1x1pc	$32.61	$1,313.27
10/15/21	3	Amazon	emma kites Black Ripstop Nylon Fabric	1x1pc	$9.73	$1,303.54
10/15/21	3	Amazon	Gorilla Super Glue with Brush & Nozzle	1x1pc	$6.49	$1,297.05
10/15/21	3	Amazon	Battery Powered LED Strip Lights, 24-Keys Remote Controlled	1x1pc	$18.37	$1,278.68
10/25/21	4	HomeCo	CDX Plywood.75"x2'x4'	1x1pc	$19.40	$1,259.28
10/25/21	4	Amazon	0.75" Lerox Tool	1x1pc	$10.37	$1,248.91
11/3/21	5	Amazon	4 Pack 20 Inch Bike Tubes with 2 Tire Levers	1x4pcs	$16.19	$1,232.72
11/3/21	5	Amazon	hooee Universal Bicycle Brake Cable Housing Kit for Mountain Bi	1x1pc	$10.86	$1,221.86
11/3/21	5	Amazon	TOPCABIN Bicycle Grips,Double Lock on Locking Bicycle Handleb	1x2pcs	$11.80	$1,210.06
11/3/21	5	Amazon	Sunlite Alloy Double MTN Lever	1x1pc	$22.35	$1,187.71
11/3/21	5	Amazon	AHEYHOM Bike Pedals 9/16 MTB Mountain Bike Peda	1x2pcs	$13.04	$1,174.67
11/3/21	5	Amazon	GANOPPER 170mm Crankset 32T	1x1pc	$59.80	$1,114.87
11/12/21	6	Amazon	Vbest life BB386 24mm Mountain Road Bike Press Fit Bearing	2x1pc	$52.40	$1,062.47
11/12/21	6	Amazon	ELEGOO UNO Project Super Starter Kit with Tutorial	1x1pc	$42.40	$1,020.07
					579.93	$1,020.07

12.3 Appendix C: QFD

Roof Matrix

		Braking (25 km/hr stop within 6 m)	Weight	Price	Velocity	Turn radius (8m)	Saftey Factor	Strength	Stability	Vision clearance	Volume	Seat displacement	Drag	Deflection (rollcage)
Braking (25 km/hr stop within 6 m)														
Weight		++												
Price		-	--											
Velocity		--	-	-										
Turn radius (8m)		--	-	-	--									
Saftey Factor		++	+	--	--	++								
Strength		-	+	+	-	-	++							
Stability		-	-	-	-	-	++	-						
Vision clearance		--	-	-	-	-	++	-	-					
Volume		-	+	+	+	-	+	-	+	-				
Seat displacement		+	-	-	+	-	++	-	+	++	++			
Drag		++	+	-	++	+	++	+	++	-	+	-		
Deflection (rollcage)		-	+	+	+	+	++	++	+	-	++	+		

PHASE I QFD

		Preferred (up or down)	-	+	-	+	-	++	-	+	-	++	+		
			Engineering Requirements (How)												
	Customer Needs (What)	**Customer Weights (1-5)**	Braking (25 km/hr stop within 6 m)	Weight	Price	Velocity	Turn radius (8m)	Saftey Factor	Strength	Stability	Vision clearance	Volume	Seat displacement	Drag	Deflection (rollcage)
Performance	High speed	4	3	9		9	3	3				3		6	
	High maneuverability	4	9	6		3	9			6	3	3		1	
	Cargo weight	2	3	9		3	1		1		1	3			
	Safety	5	9	3		3	3	9	6	3	6		1		9
Production	Lightweight	3	6	9	3	6			3			6			3
	Cargo space	1						1		1	1	3	1		
	Large field of view	3						6			9				
	Aerodynamic	3			3	6				1		9		9	
	Manufacturability	3	3	3	9			6	6	1		6	3		9
	Seat adjustability	2						3					9		
	Rollover protection	4		3	3	3	6	9	6	6	1	3			9
		Absolute Technical Importance (ATI)	126	141	57	117	89	136	83	70	76	108	33	55	117
		Relative Technical Importance (RTI)	10%	12%	5%	10%	7%	11%	7%	6%	6%	9%	3%	5%	10%
		Unit of Measure	km/h^2	kg	$	kph	m		mpa	m	degree	m^3	cm	N	m/m
		Techical Target	-52.08	<50	<1600	> 25	< 8	>3	>1	> 1	> 170	>1			>1