Spring 2021 HPV Exhibition Capstone

Final Proposal

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Capstone 476C – 2021

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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: 2014 NAU HPVC

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. Our team will be designing 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.

Figure 2: Current CAD Design

This final report encompasses all the design decisions and calculations to validate the design process, as well as the Failure Mode and Effect Analysis. Finally, the team has created its first prototype and is currently finalizing all CAD designs to begin purchasing the materials necessary to begin machining and assembling critical subsystems. Next semester's 486 Capstone class will be focused on manufacturing and testing of the final design.

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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 the 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.

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.

1.3 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 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.

1.4 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.

1.5 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."

1.5.1 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. The basic Black Box also helped the team 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

1.5.2 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.

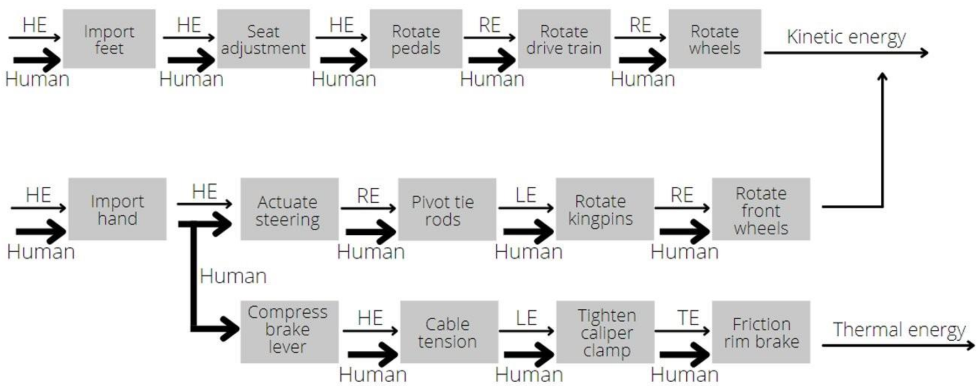


Figure 4: Functional Decomposition

1.6 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

1.7 Standards, Codes, and Regulations

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

Table 3: Table of Standards

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 A488/A488M-18 [4]	Standard Practice for Steel Castings, Welding, Qualifications of Procedures and Personnel	ASTM A488/A488M-18 outlines more safety and standard practices for welding. This will be another guide for the team for in-house fabrication and will ensure safety for the consumer and the team.

2 Testing Procedures (TPs)

This section serves to review the testing procedures developed by the team that will prove the satisfaction of each Engineering Requirement. Each testing procedure is numerically labeled according to the order tabulated in Table 2 for Engineering Requirements. Testing equipment, equipment sources, testing locations, and supervision will all be included with each TP.

2.1 Testing Procedure 1: Braking Distance

The team will test braking distance from various speeds to ensure a safe and steady stop occurs from the braking actuation. The ER states the initial speed will be 20kph and must come to a full stop within 8m. Calculations have been made to validate the stopping distance, forces, and acceleration within the parameters given.

2.1.1 Testing Procedure 1: Objective

Starting from rest, the testing driver will begin pedaling to reach speeds in increments of 5kph. The testing driver will reach 5kph, 10kph, 15kph, 20kph, and the speed yielded by the testers maximum human power. At each speed increment, the test driver will actuate the braking lever until a full stop is made. The team will measure the distance from when the brake lever is pulled to when the HPV comes to a full stop. Braking distance is important to test for because it incorporates the driver's safety in the case that a sudden stop is needed.

2.1.2 Testing Procedure 1: Resources Required

The team already has tools to measure long distances within 10m. The team has measuring tape and a laser distance measure to validate the HPV comes to a full stop within 8m. Helmet and body pads will be worn by the operator in the case of an accident. Our client, Perry Wood, will supervise to ensure the team is performing professional and efficient tests at various speeds. This test will be performed in the machine shop parking lot or the back of south commuter lot, both on NAU's campus.

2.1.3 Testing Procedure 1: Schedule

The tests will ideally take less than a few hours. These tests will occur in the second half of the fall semester, when the team has the final HPV built. All other deliverables for ME 486C must be completed before attempting the brake distance tests.

2.2 Testing Procedure 2: 3-wheel durability

There is no test for requiring the number of wheels to go on the HPV, therefore, the team will test the durability of the wheels through impact testing. The ER states that the HPV must have a minimum of 3 wheels; this requirement also fulfills the stability requirement to increase the difficulty to tip the HPV over.

2.2.1 Testing Procedure 2: Objective

To test the durability of the 3-wheel system, the team will perform impact tests on the wheels to ensure that no forces would deform or fracture the wheels under stress. While at rest, the team will lift one side of the HPV to full arm length and drop on the wheels to evaluate the load resistance within the wheels. With certain selection, the wheels must endure drop heights in the case that the driver accidentally drives off-course. This test is important to showcase that the HPV is meant for child-learning, not off-roading.

2.2.2 Testing Procedure 2: Resources Required

No other resources are needed other than the HPV and a tire pump. The tire pump will be used to adjust the pressure within the tires to validate the durability of each. This test will be performed in an open area; either the machine shop parking lot or the back of south commuter lot, both on NAU's campus, with client Perry Wood supervising all tests.

2.2.3 Testing Procedure 2: Schedule

This test will be split in two sections. One test will be run with dropping each wheel individually to validate the durability prior to the HPV assembly, likely to be the first test of ME 486C. The second test will be performed in the second half of the fall semester, after assembly, to validate the durability of each wheel while on the HPV.

2.3 Testing Procedure 3: Seat adjustability range

This test is to prove that children of different heights can comfortably operate the HPV. The team found a list of average heights for children ages 5-13, used to build a seat that can adjust over range of 50cm on the central frame.

2.3.1 Testing Procedure 3: Objective

To test the seat adjustability range, the team will ask friends of different heights to sit in the HPV and rate their comfort while sitting on a scale 1-10, where 10 represents a comfortable position to begin operating. The team will adjust the adjustability range as needed.

2.3.2 Testing Procedure 3: Resources Required

Friends of different heights are the only resources needed to perform validation that the adjustability range is wide enough to comfortably fit children to operate. Younger students at neighboring elementary or middle schools can also be used to validate the range with certainty.

2.3.3 Testing Procedure 3: Schedule

Testing the adjustability will happen when the central frame has been constructed. This will happen prior to the final HPV, likely at the beginning of ME 486C. The team will test again to validate heights once the final HPV has been built to ensure all children ages 5-13 years will be able to operate the HPV comfortably.

2.4 Testing Procedure 4: Cubic volume

The next ER states that the team cannot exceed a total volume of $5.2m^3$, any added volume will impede the ability to efficiently transport the HPV between schools. This volume requirement came from average sizes of truck beds, where the HPV will be placed to be transported.

2.4.1 Testing Procedure 4: Objective

The team has already begun testing this requirement. The dimensioning tools in Solidworks are useful for ensuring the design does not exceed the stated volume requirement. The team will not continue manufacturing without validating the total volume of the HPV is less than what the ER states.

2.4.2 Testing Procedure 4: Resources Required

Solidworks is the only resource needed to ensure the volume requirement has been satisfied. Once the final HPV has been constructed, the team will load it into one of the team member’s trucks to transport it to the machine shop or south commuter lot, on NAU’s campus, for other tests.

2.4.3 Testing Procedure 4: Schedule

This test has begun its first phase within Solidworks. Once the final HPV is completed on the second half of the fall semester, the team will test the volume by loading it into each team member’s trucks to validate the size to make transportation efficient.

2.5 Testing Procedure 5: Tip angle test

The team must provide extra stability to ensure a safe HPV is operational. The tip angle test is to ensure that the center of mass does not exceed 1m from the ground. From rest, the team will vertically lift one side of the HPV until gravity takes over in tipping the HPV. The test should follow the angle that was calculated to ensure that even sharp turns will not tip the HPV.

2.5.1 Testing Procedure 5: Objective

The team is testing to ensure the center of mass (COM) stays within 1m from the ground. This provides extra driving stability and adds safety to the CRs of the project.

2.5.2 Testing Procedure 5: Resources Required

The final HPV is needed to test the tip angle. The calculations show that the tip angle test fulfills the requirements, however, physical testing is needed to completely validate the HPV for the scope of the project.

2.5.3 Testing Procedure 5: Schedule

This test has begun within Solidworks to gain insight on where the COM would be located within the assembly. Once the final HPV has been built in the last half of the fall semester is when the team can fully complete the test and ensure the extra stability and safety has been fulfilled.

2.6 Testing Procedure 6: Turn radius

As a requirement, the team must construct an HPV that can turn within an 8m radius. As the team's calculations have shown, the turn is theoretically possible but still must be tested for. This test cannot come until the HPV has been built and can be maneuvered to ensure the turn radius requirement has been fulfilled.

2.6.1 Testing Procedure 6: Objective

The team will create a maneuverability course to ensure a turn radius within 8m can be made and validate the maneuverability of the HPV. The team will have a turning apparatus with an outside radius of 8m. The driver will maneuver through the course and if the HPV can complete turns within the boundary, the ER has been met.

2.6.2 Testing Procedure 6: Resources Required

The test will be supervised by client Perry Wood and performed in the back of south commuter lot, on NAU's campus, to ensure a course can be made. The maneuverability course will be made from orange cones. The team will create a half circle, with an 8m radius, to test the turning capabilities. The HPV passes the turn radius test if it stays within the orange cones without knocking any over.

2.6.3 Testing Procedure 6: Schedule

The first phase has been calculated for and the HPV will turn within 8m in theory. The second phase will take place in the last half of the fall semester after construction to ensure the ER is fulfilled through the maneuverability course.

2.7 Testing Procedure 7: Material Properties

The research done prior to this report led the team to selecting certain materials. Tensile & yield strengths, density, and modulus of elasticity of 6061 Aluminum were evaluated and ranked most ideal for use by the team. Once the frame has been constructed with the final material, the team will perform load testing on the frame to validate the structural integrity of the frame and material.

2.7.1 Testing Procedure 7: Objective

After constructing the frame from 6061 Aluminum, the team will conduct load tests to ensure the frame is structurally sound. While the frame and wheels are assembled, the team will load the frame of various forces at different points along the beam to validate no bending occurring. Halfway along the central beam is most likely to be compromised from loading. This test will visibly show the team if the statics calculations done are correct. The loads will be team members standing and sitting on different points throughout the frame.

2.7.2 Testing Procedure 7: Resources Required

The assembly of the wheels to the frame is needed prior to conducting this test. The test will be supervised by client Perry Wood and performed in the back of south commuter lot, on NAU's campus, before any other physical test can be performed.

2.7.3 Testing Procedure 7: Schedule

The calculations have been completed with the physical bending test remaining. This test can only be performed at the beginning of ME 486C, during the first stage of assembly when the team has the wheels and frame completed.

2.8 Testing Procedure 8: Weight

A transportable HPV cannot be heavy beyond its ability to be lifted into a truck bed. An analysis can be conducted for determining the weight of an assembly within Solidworks. Once a detailed CAD model is complete for assembly, the team will use the materials feature in the application to determine if the design fits within the ER of not exceeding 45kg.

2.8.1 Testing Procedure 8: Objective

The ER states that the full HPV cannot exceed 45kg. The team can analyze the weight within Solidworks after the CAD assembly is complete. After completing the weight analysis, the team will have to determine whether any parts can be reduced to save weight to fit the ER.

2.8.2 Testing Procedure 8: Resources Required

Solidworks is the only resource needed. The newest version may provide accurate results; the team will review their current versions to ensure all parts of assembly can be shared and gather accurate results. The team will quickly know if the weight requirement is not satisfied when attempting to lift the HPV into a truck bed.

2.8.3 Testing Procedure 8: Schedule

The team is currently working on the final CAD model at the time of this report submission. This is the closest test to be completed first, as Solidworks can efficiently analyze an assumed weight if all the materials within the design are correct. The last part to the test is when the team first loads the HPV into a truck bed to transport to conduct the other tests at the end of the fall semester.

2.9 Testing Procedure 9: Gear ratios

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. Dynamic calculations have been completed to ensure either ratios A or B will satisfy the ratio requirement.

2.9.1 Testing Procedure 9: Objective

The gear calculations completed show the team that the ideal ratios will be met when the assembly is completed. A visible validation test will be done when the assembly is complete. If the gear ratios are incomplete, the HPV would not operate in the manner intended, and the team will review the state of the design as needed.

2.9.2 Testing Procedure 9: Resources Required

The full assembly will be used at the end of ME 486C to ensure the gears work properly as they fit either ratios A or B. The calculations will be referenced throughout the assembly process to ensure a correctly built design.

2.9.3 Testing Procedure 9: Schedule

The calculation phase is currently being conducted for the gear ratios at the time of this report submission. The last phase will occur during the end testing phase in the last half of ME 486C. The calculations will be completed first to ensure our design fits the design criteria.

3 Risk Analysis and Mitigation

A complete FMEA analysis was completed using the template provided in the Capstone lecture. Due to the size of the file, it will be included within the appendix at the end of the report. The FMEA includes four critical subsystems: braking, steering, drivetrain, and the frame/roll cage. Each subsystem has ten parts/functions that have been noted for potential failures. The severity, occurrence, and detection rates were all used to determine which subsystems and parts were at most risk of critical failure. A refined FMEA sheet is provided below for quick reference.

Table 4: FMEA analysis

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

3.1 Critical Failures

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.

3.1.1 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.

3.1.2 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.

3.1.3 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.

3.1.4 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.

3.1.5 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.

3.1.6 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.

3.1.7 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.

3.1.8 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.

3.1.9 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.

3.1.10 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.

3.2 Risks and Trade-offs Analysis

There are some tradeoffs when trying to mitigate some of these risks the most obvious being weight, as any reinforcements will add weight, and the large range of rider weights creates the need for having an overbuilt design rather than an optimal design. The risks discussed above that would require reinforcement to mitigate failure include the headtube, spindle/fork, joint members, and handlebar failures, while tire failure would be mitigated by using a larger tread wall tire which would also add weight along with the chain and sprocket cover to prevent risk of chain blow out, or pitch points. Currently there isn't a negative correlation between a failure mitigation which would impede on the ability to mitigate a different critical failure. Asides from possibly the extra weight changing the FEA analysis of the frame, but even still this is minimal and likely won't have much effect as the trike is already built to accommodate a large range and weights and heights of the riders, making it overbuilt in a sense.

4 DESIGN SELECTED – First Semester

Rounding off this semester the final design that the team chose to go with, was a recumbent style bike tadpole trike. Utilizing 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.

4.1 Design Description

4.1.1 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 figure (6) 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 6: 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, further analysis will be needed before manufacturing can begin.

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

$$I = \frac{bd^3 - hk^3}{12} \quad [5](2)$$

4.1.2 Steering

The proposed steering system is a joystick and kingpin style steering system held in alignment by a tie rod as seen in figure (7), 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 are able to 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. 8) can be performed to calculate the maximum and minimum turning radius, which came out to 2.64 and 1.6 meters respectively.

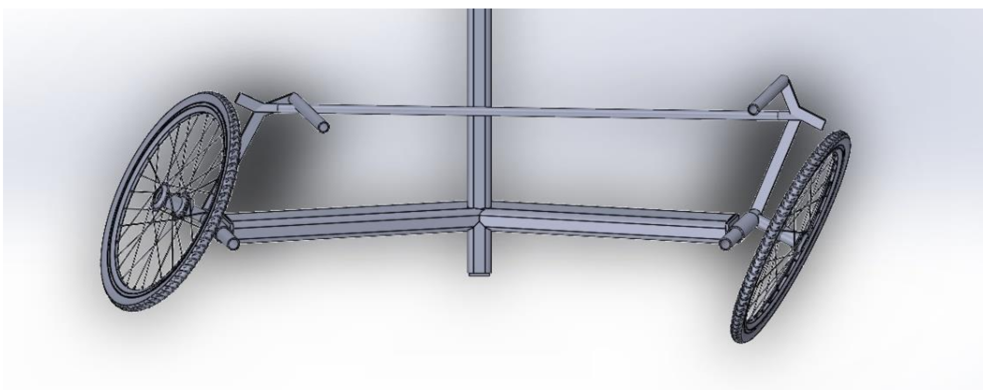
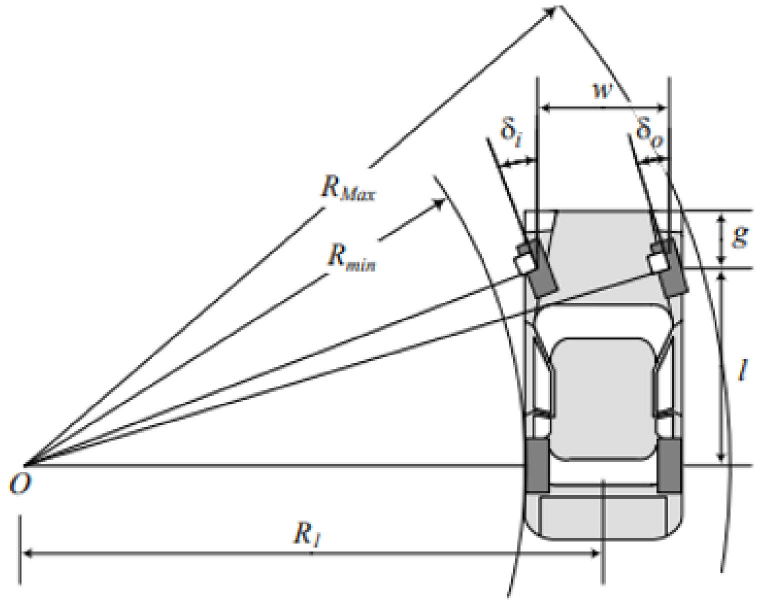


Figure 7: Steering setup



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

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

Figure 8: Ackerman steering calculations [6]

Additional steering geometries high are highlighted in figure (9) 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. Further geometries that will need to be evaluated include kingpin angle and axel offset, which the team would like to further test before making any decisions as a larger kingpin angle paired with the existing caster angle could require too much force to turn for some of the smaller kids who will be riding this bike. Lastly and important detail is the team is planning on using 20” wheels for the front of the bike, and a 24-26” wheel in the rear.

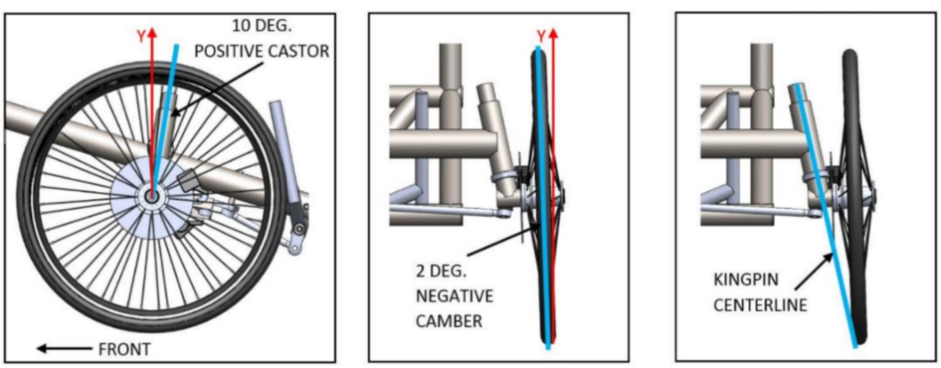


Figure 9: Castor, Camber, and Kingpin Angles [7]

4.1.3 Remaining subsystems

For braking is planned to use rim style caliper for the front of the bike, which can mount off the spindles and a disk brake in the rear. This is due to the risk of forward tipping under heavy braking, so the less effective and cheaper rim caliper brakes will be used on the front to minimize this risk, rim brakes also exert less forces on the spindle. While the rear brake can be either style, 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. 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 (F_{br}) of 828.8 newtons.

$$v_f^2 = v_i^2 + 2ad \tag{3}$$

$$a = \frac{-v_i^2}{2d} \tag{4}$$

$$F_{bi} = m_{total}a \tag{5}$$

$$F_{br} = F_{bi}\frac{r_{wheel}}{r_{rotor}} \tag{6}$$

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 figure (10) which consists of two plates being welded to the frame which a slot and pin system allowing for the seat to have a large range of adjustability for the riders, while also adding some structural integrity to the frame.

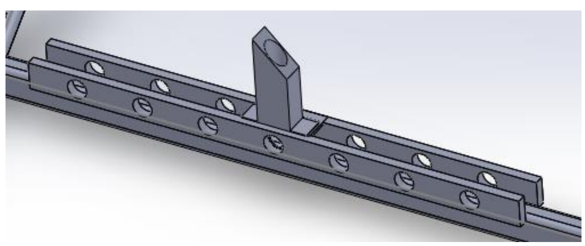


Figure 10: Seat bracket

4.2 Implementation Plan

The team plans on implementing the design by first redoing the current CAD model and finalizing all the parts, which will then be put through finite element analysis (FEA) software in order to evaluate the forces in critical structural parts including, the roll cage to ensure sufficient rollover protection, the entirety of the frame to ensure the design wont fail do deflection or torsion, the outrigger section which are the front arms which the wheels are connected to, and the spindles. Once these analyses are done providing a proof of concept the bill of materials will be finalized, a rough BOM and estimated costs can be seen in Appendix B, further client communication is needed to finalize the budget. The team hopes to be able to begin fabrication at the very beginning of next semester and needs to get at least two of the team members trained for TIG welding over summer and if this is not reasonable the material might have to be changed to steel in order to use MIG welding. A rough schedule for the remainder of this semester and the following semester has been created to help keep the team on track and prepare for critical deadlines seen below as figure (11), along with an exploded view of the current CAD model seen as figure (12) to give a better understanding of the parts that will need to be fabricated.

TASK	START	END
Capstone 1		
Final Presentation	19-Mar-21	2-April-21
Final Proposal	25-Mar-21	2-Apr-21
Individual Analytical Assignment	2-Apr-21	16-Apr-21
Final Bill of Materials/CAD	2-Apr-21	9-Apr-21
Final Prototype	2-Apr-21	26-Apr-21
Team Goals		
Frame Finalized	6-Sep-21	15-Sep-21
Functional Braking System	15-Sep-21	20-Sep-21
Functional Drive Train	15-Sep-21	27-Sep-21
Functional Steering	15-Sep-21	3-Oct-21
Capstone 2		
Post Mortem	16-Aug-21	22-Aug-21
Machine Shop Training	23-Aug-21	29-Aug-21
Finalize CAD and Begin Manufacturing	30-Aug-21	5-Sep-21
Finalize Manufacturing	6-Sep-21	3-Oct-21
Midpoint Presentation	4-Oct-21	10-Oct-21
Testing Procedures Outline	11-Oct-21	17-Oct-21
Device Summaries and Reports	18-Oct-21	24-Oct-21
Testing Device	24-Oct-21	7-Nov-21
Manual Report	8-Nov-21	14-Nov-21
Final Presentation, Report, and CAD	15-Nov-21	28-Nov-21

Figure 11: Implementation schedule

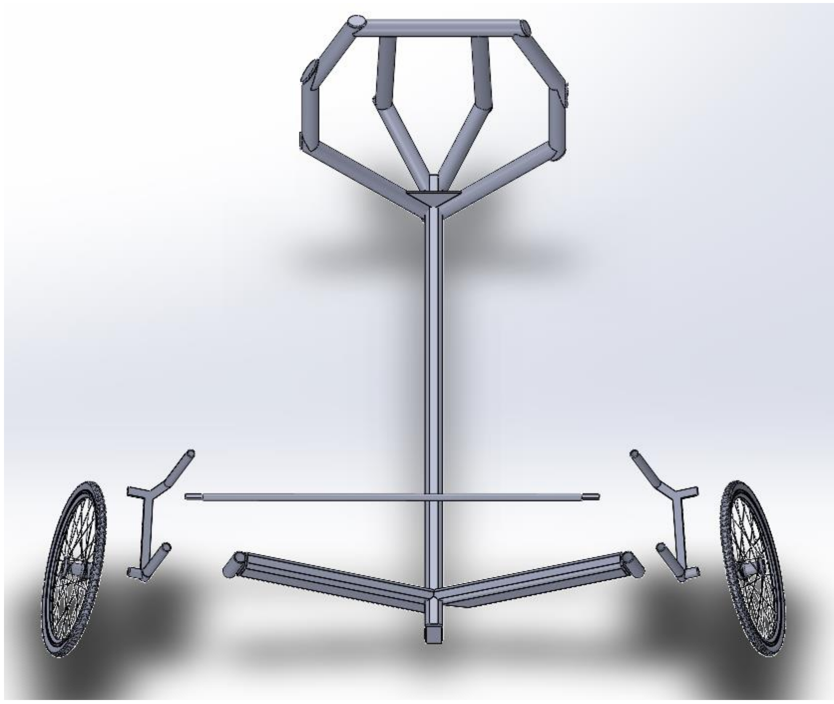


Figure 12: Exploded CAD

5 CONCLUSIONS

Our NAU 2021 Human Powered Vehicle capstone team has been tasked with designing a recumbent tricycle that can be taken to neighboring schools and ridden by students from 5-13 years old. The project and our client, Perry Wood, require that the vehicle be designed on the bases of safety, transportability, stability, ease of operation, and adjustability. To satisfy the requirements our team decided upon the design of a tadpole recumbent trike, with a four-point roll cage, chain driven front wheel drive system, indirect steering, and three caliper braking systems. Critical subsystems were analyzed for potential failure modes, and designs were iterated to mitigate risks. The result of this report is the validation of our design decisions and the team can now move forward in the manufacturing and testing portion of the project. For the remaining weeks of the semester the team will be finalizing all CAD packages and finishing the team's website. Following approval of funds from our client, we will began ordering the necessary parts and materials to begin fabrication and assembly of critical systems. Next semester's 486 Capstone course will be focused on the final testing and construction of the proposed child sized human powered vehicle.

6 References

[1] American Society for Testing and Materials, ASTM Standard: F2843-19 (Condition 0), West Conshohocken: ASTM International, 2019. .

[2] American Society for Testing and Materials, ASTM Standard F2043-13 (Classification), West Conshohocken: ASTM International, 2018. .

[3] American Welding Society, "Safety inWelding, Cutting and Allied Processes," ANSI, Miami, 2012..

[4] D. R. B. R. C. A. B. Aakash, Design and Analysis of Roll Cage Chassis, India: ScienceDirect.com, 2020..

[5] J. N. R. Budynas, "Shigley's Mechanical Engineering Design," in Shigley's Mechanical Engineering Design, New York, McGraw-Hill Education, 2015, pp. 401-500, 665-712, 871-917..

[6] Reza N. Jazar Vehicle Dynamics: Theory and Applications Springer 2008.

[7] J. G. M. Mckenzie, "Ohio University HPV Report," Ohio University, Athens, 2016. .

APPENDICES

Appendix A: FMEA Sheet

Count = 36

Page No of
FMEA Number
Date

ns	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
	Sheared lever due to impact	Impaired ability to actuate brake	7	Large impact force	2		1	14	Brake away lever
	Loss of tension in cable	Loss of brake force	5	Plastic Deformation	4		3	60	Cable Maintence
	Brake pad wear	Loss of brake force	6	Large fricition	1		5	30	Maintain & replace pads as needed
	Bending or fracture under load	Plastic deformation	4	Large load	1		5	20	
	Loosens over time	Impaired ability to actuate brake	7	High cycle life	1		4	28	
	Deformation of rim	Loss of effecive braking	3	Bent rim due to impact	3		4	36	Larger wheel treadwall
	Tread decay	Loss of traction to brake	5	High cycle life	5		2	50	Maintain tires & replace as necessary
	Bent disk	Impedes wheel from spinning, dam	5	Impact to disk causing it to bend	3		3	45	Protect with frame or gaurd
								0	
								0	
	Sprocket over- or under-slipped chain	Loss or inefficient Power	3	Inaduquate tensioning	2		5	30	Set Tensioner
cket	Chain skipped teeth and fell of spocket	Loss of Power	9	Inaduquate tensioning or maintence	3		1	27	Set Tensioner and Lubricate Chain
	Chain broke at pin or link	Loss of Power	9	Lack of maintence	3		1	27	Lubricate Chain
	Sprocket seperated from axis of rotation	Inefficent power output	3	Poor Manufacturing	2		7	42	Ensure adequate sprocket Seating
ain	Rust fatiguing sprocket and chain	Broken chain (Loss of Power)	6	Enviromental Effects	2		5	60	store HPV inside
	Chain slip or broken chain	Slipped chain (Loss of Power)	8	Tensioner not parralel to drivetrain	1		5	40	Ensure tensioner is inline
ed	Chain slip teeth or sprocket	Slipped chain (Loss of Power)	6	Tensioner under or over tensioned	2		3	36	Set Tenioner
	Deformation, bending, fracture	Loss of operational efficiency	3	Large loads, high cycle life, poor material selection	2		5	30	Reinforce Crank Arms
	Fracture, plastic deformation	Loss of operational efficiency	1	Large loads, high cycle life, poor material selection	2		2	4	Reinforce Pedals
	Fracture, corrosion	Slipped chain (Loss of Power)	5	High cycle life, poor material selection	3		4	60	Maintain gears & replace as necessary
	Alingment	excess tire wear, decrease efficien	2	Excess compression forces, impact	8		2	32	Plan alignment in CAD design
	Crack propagation	Broken handlebars	5	Sharp corners in design (especially with Aluminum)	2		6	60	Reinforce as needed (fillets)
	Loss of grip	Unalligned handlebars	4	Incorrect clamp or dimensioning	5		2	40	Design correct diameters, make one piece with spindle
	Deformation underload	Loss of allignment	3	Impact to wheel or tie rod	5		2	30	Design to handle compression
	Losen or fracture	Loss or allignment or function	5	Impact, incorrect harware/ installation, fatigue	4		2	40	Use correct grade and fastners, locktite
	Bending, fracture under load	Part failure	8	Excess braking force or impact	2		3	48	Design for impact, caliper rim brakes
	Crack propagation	Part failure	8	Sharp corners in design (especially with Aluminum)	2		6	96	Reinforce as needed (fillets, camfer)
	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
	Weld failure	Part failure	6	Fatigue, poor weld, impact	3		4	72	Preform pratice welds, inspect welds
	Deformation, or failed connection	Loss of steering	4	Impact, or excess force	5		4	80	Use correct fastners, limit excess parts
	Bending due to loading	Frame can't support weight	8	Loading, inadequate supports/geometry	3		2	48	Testing and proper geometry
	Fracture, bending, plastic deformation	Offers no protection, hazard	7	Large Impact force, weak material, cracks	2		2	28	Testing, geometry, material
	Fracture, bending, plastic deformation	Stability and supports weaken	6	Large loading, critical joint angles	1		2	12	Geometry, material
	Crack Propagation	Material strength decrease	8	Fatigue/ cyclical loading	5		7	280	Geometry, material, fillet reinforcement
	Plastic Deformation	Unable to properly sit	5	Large cyclical loading	1		4	20	Geometry, material
	Plastic Deformation, fracture, bending	Compromised Stability	4	Weak material, loading cycles	1		4	16	Geometry, material
	Cracking, fracture, bending	Unsupported operator load	5	Large loads at concentrated joints	2		8	80	Geometry, material
	Weld failure	Part Failure	9	Improper Weldments	6		5	270	Weldment Standards
								0	
								0	
								0	
								0	
								0	
								0	

Appendix B: Rough BOM

Part List						
			sum =	$2,760.27		
Part / Expense	**comments**	**Cost Per unit**	**qauntity**	**Projected To**	**source**	
0.75" OD Aluminum Round Tube 6061-T6-	8ft sticks (.29lb/ ft)	11.28	3	$33.84	https://ww	
1" x 1.5" x 0.125" Aluminum Rectangle	8ft sticks (.67lb/ ft)	31.93	1	$31.93	https://ww	
Wheels + Tires		$100	3	$300.00		
6 Pieces Bike Brakes Calipers	2 front brakes (incluc	$22.99	1	$22.99	https://ww	
Bike Disc Brake Kit, Aluminum Front and Re	2 rear brake	$36.99	1	$36.99	https://ww	
1' x 2' 0.1' 6061 T6 plate	2.84 lb		1	$34.52	https://ww	
Steering system + spindles				$500.00		
Seat		$125.00	1	$125.00	https://ww	
Derailleur		100	1	$100.00		
Groupset (Rear Der, Trigger Shifter W Clam	needs additional part	375	1	$375.00	https://ww	
Misc drive train		200	1	$200.00		
Misc harware/ parts/ 3d printing		500	1	$500.00		
Misc labor/ shipping/ prototyping/ testing		500	1	$500.00		

Appendix C: 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 i	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