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Human Powered Vehicle Capstone

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Human Powered Vehicle

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MECH 402: Design Capstone Project

Faculty Advisor: Dr. Wilson

Abstract

Held by ASME, the Human Powered Vehicle Challenge (HPVC) gives university students the opportunity to design, develop, construct, and test different designs of human-powered vehicles. LMU built upon the objectives set forth by ASME and formed design specifications with which a preliminary design was developed. This current design utilizes two wheels, the rear of which is responsible for power transmission from a pedal crank and braking through a disc and caliper. The design also utilizes the front wheel fork wheel for steering. Steering and braking are controlled by two levers on the handlebars. To determine whether the design was sufficient, it was compared to the standards set by ASME. These standards include maximum weight, minimum speed, minimum turning radius, minimum ride distance, load testing, harness verification, and a complete rollover protection system. Assembling the design consisted of welding the unique frame and attaching all parts which includes wheels, gears, chains, a seat, and a harness. Testing the design was done by applying the specified loads after assembly, which was not able to be completed at the time of the report. Speed testing was done by using a GPS spedometer while riding the bike, and the vehicle met speed standards. Testing of the brakes was done similarly and braking distance was measured once the bicycle met the desired speed, which the vehicle passed. Sustained travel testing was done by attempting to ride the bike without assistance, but this failed. All other testing was done by inspection of the vehicle, including turning radius, harness, and proper functioning of the rollover protection system. Overall, the vehicle would have failed to compete in the HPVC due to its inability to travel without assistance.

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1. DESIGN

a. Objective

The Human Powered Vehicle Challenge (HPVC) is an annual competition hosted by the American Society of Mechanical Engineers. The main objective of the challenge was to design, manufacture, and test a vehicle that complies with the published HPVC requirements and developed standards based on analysis. The HPVC requirements include a minimum speed of 6.2 mph, a turning radius of 26.2 ft, a Rollover Protection System (RPS), and the ability to brake from 15.5 mph to a complete stop within 19.7 feet. These requirements have been adjusted for the purposes of the capstone project.

b. Background

i. History

Human-powered vehicles (HPV) have been in existence for over 600 years, with the first human powered vehicle design (created by Giovanni Fontana) consisting of four wheels and rope connecting the gears [1]. The more commonly known predecessor to the modern-day bicycle was only created in the late 1800s, with the onset of pedal-driven two-wheeled vehicles, such as the Pennyfarthing. By the beginning of the 20th century, the bicycle industry had begun to grow at a blistering rate.

ii. Human Physiology

An important component of an HPV is to maximize the amount of power that can be transmitted to the drivetrain to propel the vehicle forward. The largest muscle in the human body is the gluteus maximus (also known as the buttock muscles), and the strongest muscles in the human body are considered to be the soleus and gastrocnemius (calf) muscles [2]. Legs are commonly used as the primary source of power because their movement incorporates the use of the gluteus maximus, the soleus, the gastrocnemius, and the quadricep muscle group. This allows for power to be generated from multiple sources at once. The primary muscles that contribute to the power phase of each pedal downstroke are the glutes and quadriceps, with the hamstrings, gastrocnemius, and soleus acting as stabilizers to efficiently transmit force into the pedals [3].

iii. Wheels and Tires

While the wheel's general shape has remained constant from its inception, there have been significant developments which have improved modern-day wheels. The present state of materials science and modern manufacturing techniques has allowed for current aluminum or carbon-fiber-reinforced-polymer wheels to be significantly lighter and stronger than their predecessors. Other than ensuring that the wheels are able to withstand the load of the frame and occupant(s) with a set factor of safety, the selection of a wheel to be used in an HPV is dependent upon several factors, including grip, rolling resistance, and weight. Minimizing the weight of the spinning mass reduces the mass moment of inertia, making the wheel less difficult to accelerate and decelerate. Grip is often correlated to the tire contact patch thickness, because an increase in contact patch thickness corresponds to a larger area for friction to act on. Rolling resistance is defined as the amount of energy required to maintain movement at a constant speed [4]. An increase in contact patch thickness also corresponds to greater rolling resistance, so designers should determine what tire size is capable of transmitting the optimal amount of power while minimizing rolling resistance.

iv. Drivetrain

For land HPVs in particular, there are countless methods by which the power of the occupant is transferred to the wheels. The most common method of power delivery is through a chain-and-sprocket drivetrain. In this drivetrain, power is transmitted from the crank pedal, through a chain, and into a separate set of gears which are connected to the drive wheel. Other methods of power transmission involve replacing the chain for a rubber belt, which is advantageous for longer life and smoother, quieter function [5]. In contrast, a chain has many metal-to-metal interfaces that rub against each other, creating friction and resulting in more drivetrain losses. The current disadvantage of belt-driven bicycles is the inability to change gears. It is important to consider the distance between the crank pedal and the driven wheel, as a longer chain or belt results in more friction and reduced power transmission.

The vast majority of HPV drivetrains will involve some form of gears. The difference in size of two gears with teeth that mesh will result in a difference in angular velocity. When designing the drivetrain, it is important to carefully consider the drive ratio between the crank pedal and the gear(s) connected to the drive wheel(s) to ensure that the optimal pedal cadence correlates to the intended speed of the vehicle.

v. Structure/Frame

The geometry of the frame and chosen design can have a significant effect on the speed, control, and safety of the HPV. Other than the common bicycle design, popular designs for the HPVC are recumbent bicycle or tricycle variations. The delta tricycle configuration incorporates two rear wheels and a singular front wheel, while the tadpole tricycle configuration uses two front wheels and one rear wheel [6]. Different recumbent tricycle designs can utilize either the rear or front wheel(s) for steering and for power transmission, but it is common for one end of the vehicle to be used for power transmission while the other is used for steering. The wheelbase of the HPV must also be considered, as a longer wheelbase will result in better high-speed stability, while a shorter wheelbase will result in a smaller turning radius.

c. Standards

Finding proper guidelines to develop a vehicle that is safe, economical, and well-functioning is imperative to the success of this project. In order to ensure the practicality of the student team's proposed method of transportation, the vehicle must travel a certain speed so as to have advantages over walking or running in terms of both speed and endurance. The guidelines for both of these requirements are given by the HPVC [7]. To ensure safety, the team has also set standards of operational capacity relating to braking, turning, and weight. In order to function without putting the driver in danger, the vehicle needs to be able to stop completely, turn at the radius determined in the following Design Specifications section, and sustain the weight of the average person with a margin of error. The team has also decided to include a rollover protection system to make sure the driver is safe in case of an accident. The guidelines and regulations set forth by the ASME were minimal, so some regulations have been determined by the team according to the safest and most functional approach deemed necessary.

d. Prior Work

This was the first phase of the Human Powered Vehicle capstone. There was no work prior to the beginning of the fall semester of 2020. However, many evolutions of the design were created prior to the design that the team eventually settled upon. These iterations of the frame are shown below.

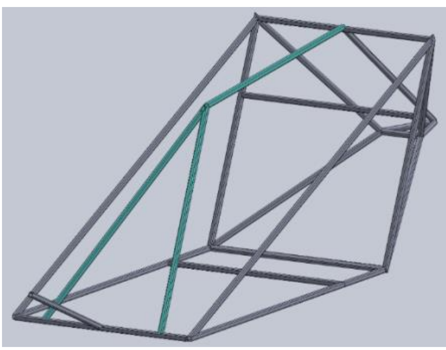


Figure 1: First iteration of frame design.

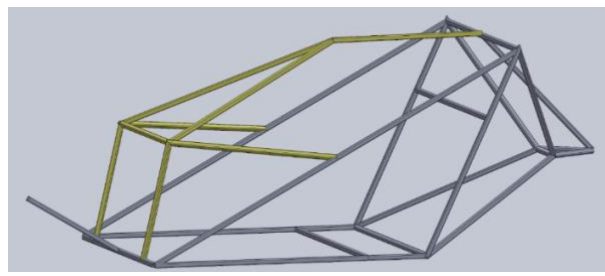


Figure 2: Second iteration of frame design.

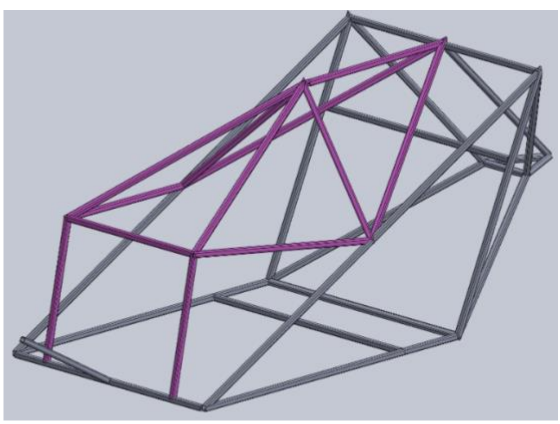


Figure 3: Third iteration of frame design.

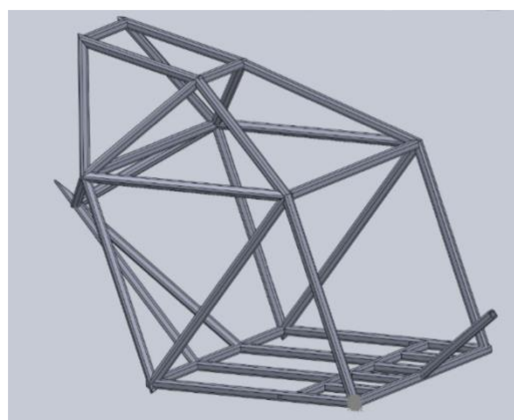


Figure 4: Fourth iteration of frame design.

As shown by the coloration of the first three designs, the primary alterations were focused on the cage set at the front top of the vehicle. The fourth iteration was a completely unique design from the previous three. Most engineers would argue that all of these designs are heavily overengineered, which was why the final design was chosen and will be explained later. All four iterations were designed with the idea of developing a three wheeled vehicle in a tadpole configuration, with two wheels in the front rotating on a shared axis.

e. Design Specifications

Table 1: Specifications and justifications

D.S. ID	Design Specification	Justification
1	The HPV (without occupant) shall not exceed 100 lbs.	Recumbent touring bikes weigh approximately 40 lbs [8].
2	The HPV with occupant shall not exceed 350 lbs.	Allows for maximum occupant weight of 250 lbs.
3	The minimum vehicle speed shall not be below 10 km/hr (6.2 mph).	ASME HPV Challenge Rules
4	The turning radius of the HPV shall not exceed 8.0 m (26.2 ft)	ASME HPV Challenge Rules
5	The HPV shall stop from 25 km/hr (15.5 mph) in 6.0 m (19.7 ft) or less.	ASME HPV Challenge Rules
6	The HPV shall travel for 30 m (19.7 ft) in a straight line between 5 and 8 km/hr (3.1 – 5 mph)	ASME HPV Challenge Rules
7	The Rollover Protection System (RPS) shall be made of a continuous hoop.	ASME HPV Challenge Rules
8	The RPS must include a safety harness with lap and shoulder belts.	ASME HPV Challenge Rules
9	The HPV must withstand a load of 2670 N on the top of the roll bars towards the rear of the vehicle (for a single occupant) with a max deflection of 5.1 cm (2.0 in) from applied load.	ASME HPV Challenge Rules
10	The HPV must withstand a load of 1330 N being horizontally applied to the side of the roll bar (for a single occupant) with a max deflection of 3.8 cm (1.5 in) from the applied load.	ASME HPV Challenge Rules
11	The seat belt must withstand reactant forces within the simulation of crash.	ASME HPV Challenge Rules

The design specifications were informed by the HPVC guidelines and the following engineering standards:

Table 2: ASTM Standards pertaining to the design.

Organization	ID	Description
ASTM	F2043-13	Standard classification for bicycle usage [8]
ASTM	F2215-15	Standard specification for balls, bearings, ferrous and nonferrous for use in bearings, valves, and bearing applications [9]
ASTM	F2273-11	Standard test methods for bicycle forks [10]
ASTM	F2680-17	Specifications for manually operated front wheel retention systems [11]
ASTM	F2711-19	Standard test methods for bicycle frames [12]

Unfortunately, ASTM standards specifically for non-stationary recumbent bicycles do not exist. However, the most applicable standards were referenced during the design process of the vehicle. ASTM F2043-13 classifies bicycles according to their usage under certain conditions. According to this standard, this recumbent bicycle for the HPVC is classified as a Condition 1, meaning that it is designed for use on paved roads and that the wheels remain on the ground for the duration of usage [8]. The bicycle frame must be labeled with the appropriate Condition 1 icon and it must be a square of at least 1.2 inches. This icon in Figure 5 would need to be added to the frame in order to use the vehicle in public spaces.

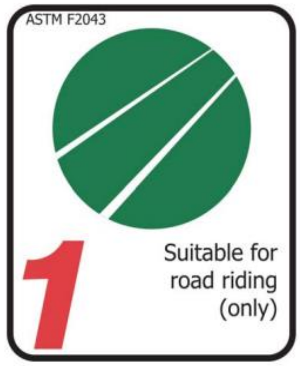


Figure 5: Condition 1 graphical indicator [8].

F2273-11 outlines bicycle fork mechanical tests for the compression and bending loads, impact resistance, and bending fatigue life [10]. F2680-17 applies to quick releases and other manually operated retention systems [11]. For this model, the specifications in F2680-17 are most applicable to the singular rear wheel. A manually operated primary retention system must also have a secondary retention, which is intended to prevent wheel removal or partial separation during testing. F2711-19 describes vertical and horizontal loading tests for frame fatigue, falling mass, and falling frame [12]. The details of the tests in standards F2273-11, F2680-17, and F2711-19 are outlined in the testing section of this report. F2215-15 is the general specification for ball bearings and includes information for purchases [9]. When purchasing ball bearings from a supplier, the following information must be provided: ASTM specification number, diameter, composition number, grade, tests and test conditions, and material identification records [9]. There are sixteen composition numbers, with the third representing carbon steel. This standard does not outline any tests. Because the tests in the standards here apply to traditional bicycle frames, they could not be directly applied to this recumbent bicycle. However, they provided significant insight for the design process.

f. Concept Development and Selection Methods

Table 3: Pugh's Concept Selection chart for the vehicle's important components.

Alternatives	Baseline	Reclined Seat	Stability	RPS Complexity	Four Point Harness	Gear System Complexity	Braking System	Manufacturability	Front Wheel Steering	Totals	Rank
Elliptical Bike	0	-1	-1	-1	-1	-1	-1	1	1	-4	5
Recumbent Tri V1	0	1	1	0	1	0	1	-1	1	4	2
Recumbent Tri V2	0	1	1	-1	1	-1	1	1	-1	2	3
Rowing Machine	0	1	1	0	1	-1	0	-1	0	1	4
Recumbent Bike	0	1	-1	1	1	1	1	1	1	6	1

Passenger safety and comfort were prioritized in the design selection process. This process utilized the Pugh Matrix to compare how various design choices met the specified criteria. One reason why the elliptical bicycle option was not selected was that it is not as driver-friendly as other designs. After an extended period of time, standing and keeping one's arms elevated could become tiring. Because of the height of an elliptical bicycle, adding an RPS would mean extra material and therefore excess vehicle weight. The two recumbent tricycle designs were the tadpole (two front wheels) and delta (two rear wheels) configurations. The tadpole configuration was preferred to the delta because the driver's legs could rest comfortably between the two front wheels in a more natural and relaxed position. The recumbent bicycle was ultimately chosen because the RPS and steering system are less complex than the previously selected tadpole design while still being highly effective. The RPS for the new bicycle design uses significantly less material than the previous RPS and also reduces welding costs.

The gear and braking systems were evaluated for their complexity level, and for this reason, the rowing machine design was rejected. Various designs were considered for their performance in relation to a four-point harness. This harness style fits the best with the design of the reclined seat. Considering all of these factors, a recumbent bicycle design was selected.

g. Innovation

Compared to most two-wheeled recumbent bicycles and other HPVC entrants in the past, the updated design here is unique in its geometric RPS for protecting the driver. While other vehicles use a more minimalist approach in both frame and RPS, this HPV design process focused on creating a robust design that would ensure driver safety and prevent large roll angles. This was achieved with two side bars to keep a large margin of distance between the driver and ground, as well as a simple triangular pyramid-like configuration above the driver's head to both protect the driver and influence the position in which the vehicle would be more likely to crash.

For the two side bars, they are welded between the front end of the vehicle frame and to a top horizontal bar behind the driver's shoulders and above a harness attachment bar. These bars would be spaced apart such that in a horizontal rollover position, they would ensure a large amount of space between the driver's torso and the ground, as well as raise the legs further away from the ground due to the angle caused by the distance between both bars compared to the vehicle frame sloping inwards towards the back wheel. Furthermore, the length and orientation of these bars would distribute the weight of the vehicle and driver over a large surface area, thus reducing vehicle deformation and the chance of driver injury from such deformation.

As for the pyramid configuration part of the RPS (which was connected to the same top horizontal bar as the aforementioned side bars), its design would cause the vehicle to be more likely to roll onto its side rather than remaining upside down in such a rollover situation. Additionally, the triangular geometry would strengthen the RPS and cover the front of the driver's head, increasing the level of protection.

h. Description

The goal for the HPV design is safety and practicality. Emulating other human-powered vehicles is useful to make sure design aspects reflect these vehicles' successful components. A picture of the CAD model of the vehicle's frame layout can be seen below. Elements of the design take inspiration from different types of recumbent bicycles, but the design itself is completely unique.

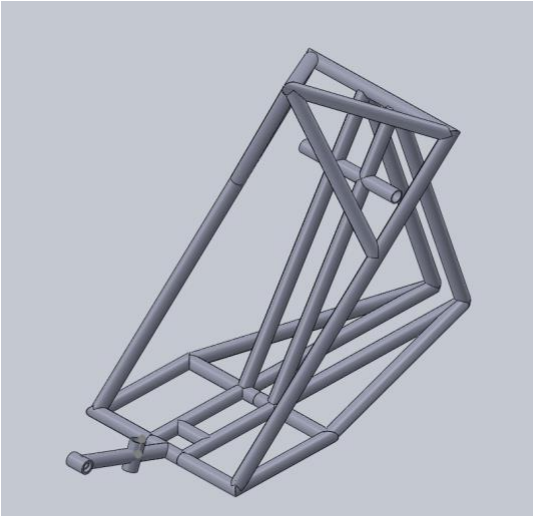


Figure 6: CAD of the custom designed frame looking from front to rear.

The frame design in Figure 6 combines many different objectives and requirements to make the unique design perfect for its purpose of safe and comfortable travel. The round poles of the frame form a complex arrangement of cage intended to hold and protect the driver. Looking at the rear end, the frame extends in triangular shapes to hold the rear wheel in a secure fashion, while also managing to distribute the weight and crash forces in an efficient manner.

Figure 7: Complete assembly of the vehicle.

Each of the poles in the center of the frame are strategically placed for a different purpose. The two main poles reclined in the center of the frame are the support for the driver's back so they can comfortably sit in a reclined position. A cushion was intended to be attached (not shown in Figure 7) to these poles extending up until the first cross-section bar for the driver's comfort, but the vehicle was comfortable without the cushion so it was not included. This first cross-section bar, combined with the parallel bars on the outside of the bottom part of the frame, has the four-point harness attached so that the driver can sit securely and safely within the vehicle. At the bottom of the frame, the seat is held by two parallel beams leading from the center of the front of the frame all the way to the rear wheel attachment.

The frame was designed so that a driver under roughly six feet and two inches tall could fit under the RPS at the top. Weight and center of gravity are important for the vehicle, which was why additional poles were used sparingly apart from the most necessary. Most of the frame's weight is carried near the center, which makes it harder to balance and turn. This design flaw was not realized until after assembly. Similarly, the width of the frame was kept as slim as possible to maintain the driver comfort and minimize any excess weight, but excess weight was found nonetheless.

Figure 8: Entire assembly CAD design.

The basic layout of the assembly can be categorized as a two-wheel recumbent bicycle. Various design iterations with two wheels in the front and one in the back were considered and analyzed, but the cost-effective and simple nature of the bicycle design eventually took precedence. Steering functions via a handlebar, connected to the steering fork and installed onto the frame through two headset bearings, as can be seen in Figure 9.

Figure 9: Steering and power generation shown with handlebars, fork, wheel, and pedals.

To power the vehicle, a basic pedal-gear system was used and attached with a custom extended chain to the rear wheel. The chain was placed under the frame to eliminate any interaction with the driver during the pedaling process when the chain is moving. It is guided by a custom-designed chain guide using right angle metal brackets and two roller guides designed for sliding doors.

For the braking system, a single brake rotor was installed on the rear wheel, with a brake caliper and pads bolted to the rear dropouts of the frame with extensions. Given the security of the recumbent bicycle design, as well as the lack of a front brake caliper, it is extremely unlikely that a front rollover will take place, whether accelerating, coasting, or braking heavily. A brake lever was attached to the handlebars and connected with a braking line running along the underside of the vehicle on the frame, tied in with zip ties in key places to ensure that the brake line does not interfere with any of the power, braking, or steering systems as well as the occupant's ability to control any of these systems.

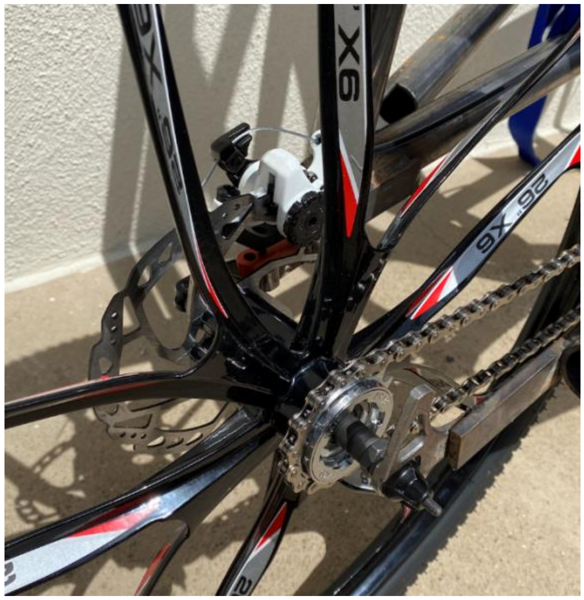


Figure 10: Disc brake on rear wheel.

The most complicated aspect of this vehicle’s design is the RPS, which was designed to keep the driver safe in case the vehicle is flipped or collides with an object. As described in the Innovation section, a series of metal bars was arranged around the driver for protection while also not impeding pedaling movement. The rollover protection system itself was redesigned several times with the goal of making the simplest effective system. Previous versions were much larger and more intrusive on the driver’s space. A comparison of the RPS design iterations was given in the Prior Work section. This final adaptation operates as desired while making it easy for the driver to mount the vehicle and it does not inhibit the driver’s vision. More information about the RPS is given in the Safety and Ethics section.

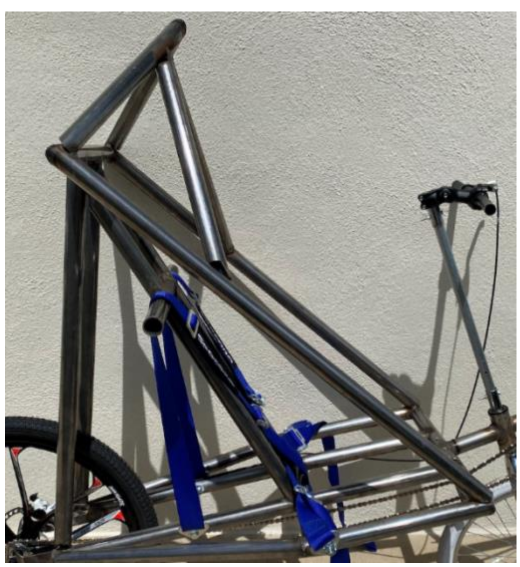


Figure 11: RPS system.

2. ANALYSIS

a. Minimum Desired Speed Analysis

The vehicle's desired speed was set at a minimum of 10 kilometers per hour according to the competition guidelines, but the design aimed to exceed this minimum. The pedal length, gearing system, and wheel diameter all play a part in determining the vehicle's speed, with power being delivered from the pedals to the front axis and through the wheels. In order to reach 10 kilometers per hour with the power coming from the 26-inch diameter rear wheel, the wheels have to rotate just under 81 times per minute. The proposed gear set has a gear-tooth ratio of 146 teeth to 32 teeth. Considering the wheels rotate 32 times for every 16 rotations of the pedals, the pedals only need to be rotated just over 40 times per minute to achieve a speed of 10 kilometers per hour, per the speed at cadence calculator [15]. According to Paul Norman of BikeRadar, the average recreational rider pedals with a cadence around 60 rpm [16]. Therefore, if the driver of the vehicle maintains a typical cadence using this vehicle's design, they will be able to exceed the speed requirement.

Determining the driver's ability to rotate the pedals 40 times per minute was difficult considering the wide range of fitness and strength levels a driver could have. The force with which the driver has to push the pedal should be within reason for a person with an average fitness level. To reach the desired speed at a reasonable rate, an acceleration of 2 km/hr/s would be needed for five seconds to get up to 10 km/hr. This acceleration times the mass - which if recorded at a maximum weight of 158.8 kg - would be 88.23 N of force. To put this into perspective, a 50 lb leg press (22.68 kg) takes just under 225 N, which is achievable for any person capable of a brisk walk. Given the heaviest passenger, the vehicle would be capable of reaching the desired speed with ease.

b. Turning Radius Analysis

The redesigned steering system, which uses handlebars to turn the front wheel fork, makes it possible to meet nearly any steering requirement. Since the handlebars can turn 360 degrees, meeting the 10 m turning circle requirement will be easy for the bicycle. With a wheelbase of 36 inches, the schematic in Figure 12 was used to determine the minimum angle to reach a maximum turning circle of 26.2 feet. Based on the equation $R = W/\sin(\Theta)$, the minimum angle required to reach a maximum turning circle of 26.2 feet would be just 6.57 degrees.

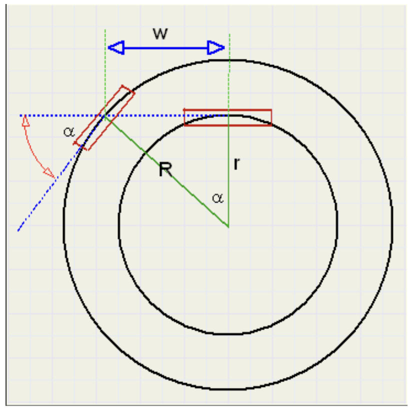


Figure 12: Turning analysis visual breakdown.

Achieving an angle of 6.57 degrees on the turn was achievable with this frame, and the wheel could be turned at a much sharper angle. Given the decision to make the front wheel fork capable of rotating a full 360 degrees, the turning circle could realistically be much smaller. As shown in results, the steering ended up being capable of turning at any desired angle, and testing was done at a 45 degree angle.

c. Braking System Analysis

Estimating the braking distance of a vehicle prior to testing can be difficult. Many factors play a part in calculating the conceptual braking capability of the vehicle. Given the brake set being used for this vehicle, calculations are impossible due to the lack of information about properties and mechanics of the brakes. Testing will be done on the brakes to ensure they meet the requirements established by the contest. Prior to testing, inexact estimates that do not account for the weight of the driver or vehicle, which are important factors, provide an idea of how the vehicle might perform. According to Korkort Online, with minimal information under the assumption of good conditions, tires, and brakes, the braking distance is calculated by squaring a tenth of the travelling speed and multiplying this value by a constant of 0.4 [17]. In this case, it would be $1.55 \times 1.55 \times 0.4 = 0.961$ meters. This is a generous estimate which does not account for the weight the vehicle might carry if the driver is up to 250 lbs. Realistically, the braking distance, at full force, will most likely be longer. Accounting for weight, material, thickness of the braking disc, size of the wheel, size of the braking disc, force of the brake, road conditions, and tire quality would allow for a more realistic estimate, but many of these properties and values cannot be found or assumed.

d. Frame Finite Element Analysis

Several finite element analyses (FEA) were conducted on the main frame and RPS of the human-powered vehicle. The SolidWorks structural member feature works very well with the FEA simulations, but any non-structural member solids on the part would result in countless errors. Therefore, a simplified frame made of structural members was used instead of the complete frame design. This simplified frame includes all of the crucial supporting structural components, and also accounts for the holes in the floor of the frame which are used to mount the front axle brackets as well as the occupant's seat. The SolidWorks structural member feature effectively treats the whole frame as one continuous part of the same material. While this could potentially be a problem with a different welding material, a similar if not higher strength filler metal was used. Furthermore, the desired factor of safety chosen accounts for suboptimal weld quality and joinery. This was to ensure that the structural members, rather than the welds, are the cause of failure, although the analysis shows that this will not happen. Due to the simplified nature of the simulation methodology, the joints where the front fork meets the frame and where the rear wheel attaches are set as fixed geometry (3 joints total). Therefore, a higher factor of safety was preferred in the results. While such analysis is not an exact science, it offers a reliable approximation of the amount of stress applied on the frame from occupant load, side loads, and a top load, as per the design specifications.

When considering the material used for the construction of the frame, cost, yield strength, and weldability were of high importance. Therefore, carbon steel was chosen, specifically carbon steel that adheres to the ASTM A500 standard for cold-formed welded and seamless carbon steel structural tubing in rounds and shapes [18]. The manufacturer did not provide any more specific descriptions for the supplied metal other than the A500 standard, therefore the yield strength values within the standard were used. The ASTM A500 standard is split into different grades. Because the metal supplier did not offer a specific grade for their material, the grade with the lowest yield strength was assumed for simulation purposes. Grade A has the lowest yield strength of the different grades, therefore the Grade A carbon steel yield strength value of 220.59 MPa was utilized for the calculations.

Table 4: Plain Carbon Steel Material Properties for Finite Element Analysis.

Elastic Modulus (N/m^2)	2.1E+11	Mass Density (kg/m^3)	7800
Poisson's Ratio	0.28	Tensile Strength (N/m^2)	399826000
Shear Modulus (N/m^2)	7.9E+10	Yield Strength (N/m^2)	220594000

When the welding company was contacted, it was determined that utilizing plain carbon steel would be a cheaper alternative, so the analysis was conducted once more with updated values for max stress, max displacement, and stress factor of safety. The SolidWorks program which students used to conduct FEA on the frame contained a library of accepted values for numerous materials, including the plain carbon steel used for construction of the frame, therefore students utilized those values to streamline the process of analysis. The material properties of the plain carbon steel are depicted in Table 4.

Table 5: FEA Simulation Results and Calculations.

FEA Simulation	Max Stress (N/m^2)	Max Displacement (mm)	Stress Factor of Safety
Occupant Load	12.20	0.1535	18.08
Side Load 1	45.16	1.405	4.88

Side Load 2	45.07	1.411	4.89
Top Load	42.07	1.252	5.24

Occupant Load

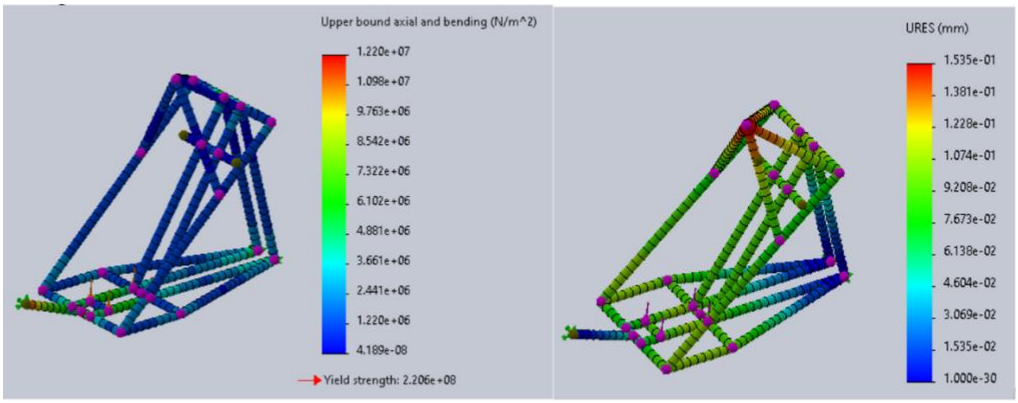


Figure 13: Occupant Load FEA Results

For the occupant load simulation, four point forces were applied at the four joints where the seat bottom will be secured. The four point forces have a combined load of 250 lbf/1112 N.

Side Load

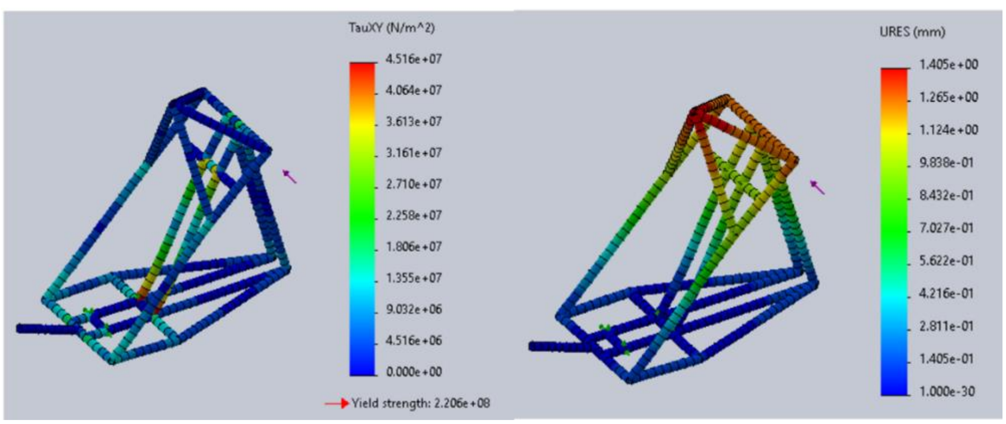


Figure 14: Side Load Round 1 FEA Results

For the first round of side load simulation, one point force was applied to the joint at shoulder height on the left side of the frame, as per the ASME HPV Challenge specifications. The point force had a force of 1330 N.

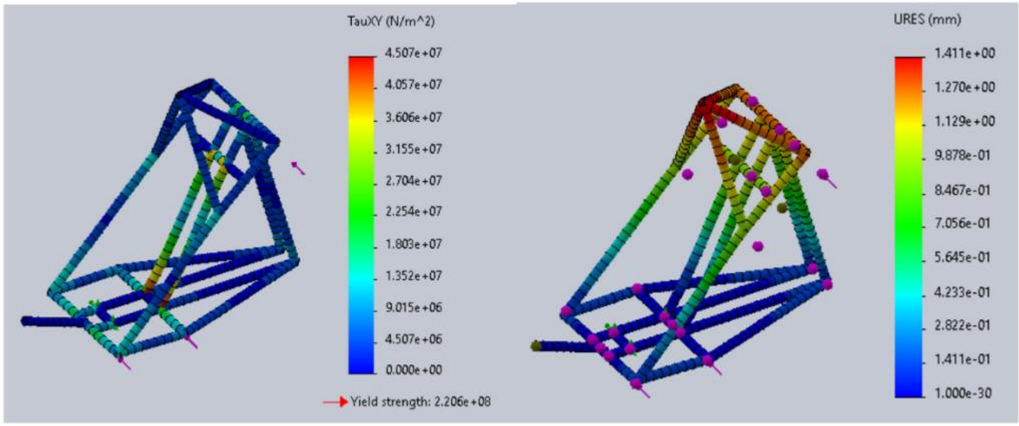


Figure 15: Side Load round 2 FEA results.

For the second round of side load simulation, the same forces were applied at the same joint as round 1. However, two point forces with individual loads of 1330 N were also applied at the joints at the bottom left of the frame (when looking at the frame from the rear of the vehicle).

Top Load

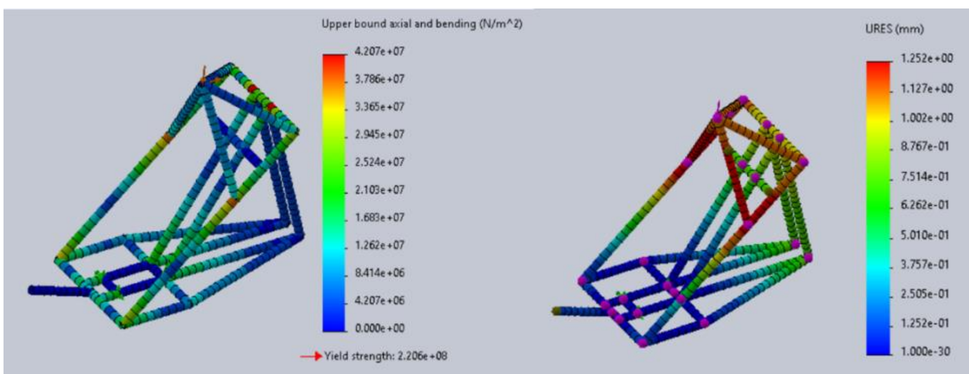


Figure 16: Top Load FEA results.

For the top load simulation, one point force was applied with a force of 2670 N and 12 degrees toward the rear of the vehicle and downward. This force was applied at the top joint of the frame.

General Results

In all simulated cases, the frame was able to withstand the applied forces and remain under the specified maximum displacement from the challenge requirements. With the smallest factor of safety being 4.88, it is reasonable to assume that the frame, given the materials meet the standards and the welds are of good quality, will not fail during use. The desired factor of safety value for yielding was 3, accounting for imperfections and complications in construction and welding, so it was expected that the frame would be well within the challenge requirements.

e. Failure Modes and Effects Analysis (FMEA)

Table 6: FMEA analysis and breakdown with recommended action.

Failure Mode	Cause	Effect/Impact	Likelihood	Recommended Action
Lower Frame Collapse under weight of driver	Inadequate strength of Lower frame	Potentially injure driver and potential operational failure of vehicle	Extremely Unlikely	Increase cross-sectional thickness of the Lower Frame beams or change design to redistribute weight
Upper Frame/RPS Collapse under force of collision	Inadequate strength of Upper Frame/RPS	Potentially injure driver and potential damage to steering system and seat	Extremely Unlikely	Reconfigure the RPS to target locations that can withstand force of collision or increase the cross-sectional thickness of the beams
Instability when riding	Two-wheel design and potentially high center of gravity	Poor control over vehicle and increased potential for a crash	Unlikely	Perform low speed dynamic testing or add extra non-drive or break wheels to left and right of rear wheel for stability

The top three failure modes threatening the success of the vehicle are frame collapse on the lower part of the frame holding the seat, the RPS or upper part of the frame collapse, and dynamic instability. The first failure mode, lower frame collapse, would be caused by inadequate strength of the lower frame, and this could be caused by many factors. First, the frame cross-section design itself could be adapted if failure occurs. Should the failure occur apart from a joint, the frame strength itself would be to blame. In this case, the beam could be thickened or enlarged, which would increase yield strength. If this is not cost-effective, a change in the material could be more cost-effective and prevent the failure of the design. Both options would be explored if this failure occurs, but it is not likely. If the design fails at a welded joint, it could be the fault of the weld. In this case, a different welding procedure or a redesign of the joint would be in order. Changing the material could also help with this. None of these failures are likely given that the design itself is made of 1.5-inch ASTM A500 standard round steel tubing, and because the FEA results in a more-than-adequate factor of safety.

Next, the most likely failure mode is the collapse of the rollover protection system. This part of the vehicle is made of the same tubing, but is much more skeletal in its design. The load requirements of this system are much greater than those required of the lower frame, and the spread-out design that leaves room for the driver could lead to weakness that the test loads could exploit. Should the RPS fail to hold up against the forces on the sides and/or top of the system, changes can be made similar to the lower frame's proposed fixes. Thickness and size of the beams could be increased, which would greatly increase yield strength. A redesign of the cage that is less aerodynamic but better translates the loads to the entire frame could be done. Ultimately, the design of the RPS was the biggest factor for its success, so redesigning the system is the most logical step to take should failure occur. Similar to the lower frame, failure is unlikely given the robust and cautious design of the upper frame.

Dynamic instability due to the two-wheel design was deemed to be unlikely, although this assumption was based on little data other than comparing performance of other recumbent bicycles. With the design specifications allowing for a vehicle weight of up to 100 pounds, a solution of utilizing extra non-drive wheels could be a reasonable option, although the heavy weight of the vehicle would require significant reinforcement of those wheels to withstand the forces applied without yielding. More on the resultant vehicle's dynamic stability will be discussed in the testing section.

f. Cost Analysis

Item #	Qt	Item	Description	Compatibility Check	Price/Unit	Price	Source
1	1	Disc Brake Kit	all inclusive	160mm rotor	36.99	36.99	Amazon
2	1	Freewheel Hub	16T ACS main drive	threaded hub	11.69	11.69	Amazon
3	1	Rear Dropouts	axle mount for rear	10mm axle and caliper mount	46.45	46.45	Paragon Machine Works
4	1	Wheelset	magnesium	disc and free hub	169.99	169.99	Amazon
5	1	20" fork	solid, no disc	1-1/8" threadless	59.99	59.99	eBay
6	1	Head Tube (HT)	105mm length	44mm headset compatible	21.55	21.55	Paragon Machine Works
7	1	HT Bearings	28.6mm to 44mm adapted	compatible	16.59	16.59	eBay
8	1	Handlebars	25.4mm OD	yes	12.59	12.59	eBay
9	1	Riser Stem	110mm, adjustable	25.4mm	16.99	16.99	Amazon
10	1	26" Tire	26"	yes	24.99	24.99	Amazon
11	1	26" tube	26"	yes	3.96	3.96	Amazon
12	1	Harness	4 point	yes	38.99	38.99	PowerSports
13	1	Bottom Bracket	steel	yes	5.95	5.95	BikeFab
14	1	Crank Set	bearing, crank, chainring	yes	59.99	59.99	Amazon
15	1	Seat Bottom	securable seat pad	yes	24.99	24.99	Sam's Fitness
16	1	20" wheel	no disc	yes	37.99	37.99	Amazon
17	1	20" tire and tube	combo	yes	19.54	19.54	Amazon
18	3	20' 1.5" tubing	Carbon steel	yes	73.99	221.97	Welder
19	1	Seat Back	top seat	yes	24.99	24.99	eBay
20	1	Pedals	universal	yes	9.83	9.83	Amazon
21	4	M10 Bolts	Half threaded	yes	1.09	4.36	Home Depot
22	4	M10 Nuts	For the bolts	yes	0.79	3.16	Home Depot
23	1	Chain Guide	Guides the chain	yes	7.49	7.49	Home Depot
24	1	Steel Pole	Extends steering fork	yes	3.99	3.99	Home Depot
25	4	M6 Bolts	Mount bottom seat	yes	0.89	3.56	Home Depot
26	4	M6 Nuts	For the bolts	yes	0.79	3.16	Home Depot
27	2	Break Caliper Ext.	Attach caliper to frame	yes	11.49	22.98	Amazon
		Welding Cost	ARC MachineWorks	yes	600.00	600.00	
				Total before taxes and shipping			$1,514.72

Figure 17: Total cost breakdown.

Most of the parts for the recumbent bicycle are standard bicycle parts. Because the bicycle frame and detachable RPS combine into one custom part, this part has the additional costs of material and welding. Many of the parts comprising this vehicle are tried, tested and manufactured parts that are best purchased from an outside source rather than designed from scratch. By a large margin, the most expensive part of the vehicle was the frame. A custom frame with such an extensive safety cage for the RPS requires a lot of round steel tubing, and this tubing came out to over $220.00. Cost was cut down by eliminating several unnecessary parts of the RPS that were deemed excessive in design. Even more expensive than the frame material was the welding expense. Fortunately, ARC Machineworks Welding gave the lowest quote and delivered quality welds for the vehicle, so welding expenses were spared.

With different requirements, costs could be reduced by using a less expensive harness, but this harness was a requirement of the competition. Compared to the original three-wheel tadpole design, the two-wheel redesign had a calculated cost before taxes and shipping that was approximately $250.00 cheaper, at $914.72, assuming similar welding costs. The two-wheel design also resulted in less steel tubing and fewer joints, which should further decrease the cost of production.

3. TESTING

a. Developmental Testing

Some of the iterative testing of the vehicle's design was completed through analysis with online modeling and CAD development. A few of the aspects of the design could not be tested online or conceptually and required developmental testing to ensure that the vehicle can fulfill all of the contest's requirements. All operational requirements have been tested and the assembly was completed, but a few specific operations had to be tested several times as adjustments were made to solve issues that arose during assembly.

The proposed design had a single chain that looped from the crank gear to the gear located on the pedal going under the frame. Unfortunately, the students could not find a chain that fit the exact dimensional needs of the frame, so three separate chains were cut to correct size and then fit together in order to ensure that the chain could hook on both gear sprockets without too much slack. With each change to the length, the students tested the function of the power system to make sure that the length would properly power the rear wheel.

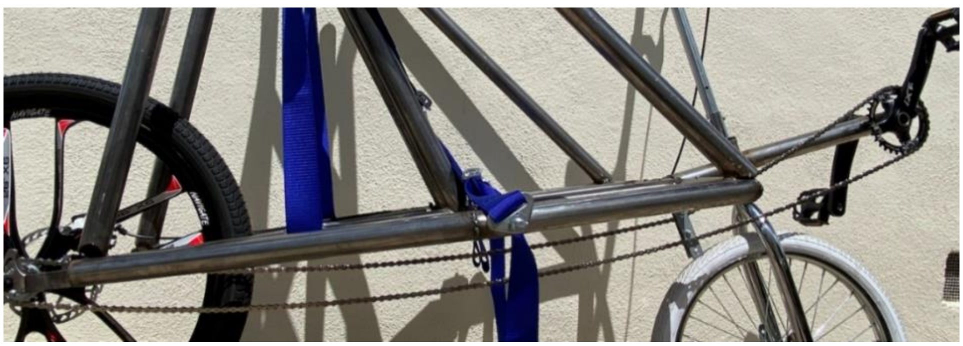


Figure 18: Chain stretching under between sprockets under the main frame.

The system had its setbacks when assembly began. The planned caliper brake set was supposed to be perfectly distanced to fit the frame and wheel setup so that it would sit right on the disc attached to the wheel and screw into the mount on the frame. When the students noticed a sizeable gap between the caliper and the frame, adjustments had to be made. A couple of caliper mount extensions were purchased and applied to the frame. Given the introduction of two new parts, the brakes did not function as intended at first and the students had to continually adjust the positioning of these new parts to make sure the caliper would not apply friction unless triggered.

Figure 19: Caliper gap adjustments and final positioning.

The third significant unplanned adjustment made to the vehicle was a makeshift chain guide. Due to the fact that the top of the chain undergoes tension during vehicle acceleration, a guide was required to make sure that premature wear is not experienced by the frame due to chain-frame interference. Time constraints limited the student's ability to procure a proper chain guide utilizing a compatible sprocket at any bicycle shops, so a unique guide was fashioned out of items purchased at Home Depot. The guide functioned as intended and consists of two right angle brackets bolted to the frame with two small steel wheels rolling on bolts placed in between the brackets. Positional adjustments were made and the brackets were bent as students tested the functionality. These adjustments were made to ensure that the chain did not interfere with the two right angle brackets which hold the sliding door rollers in place.

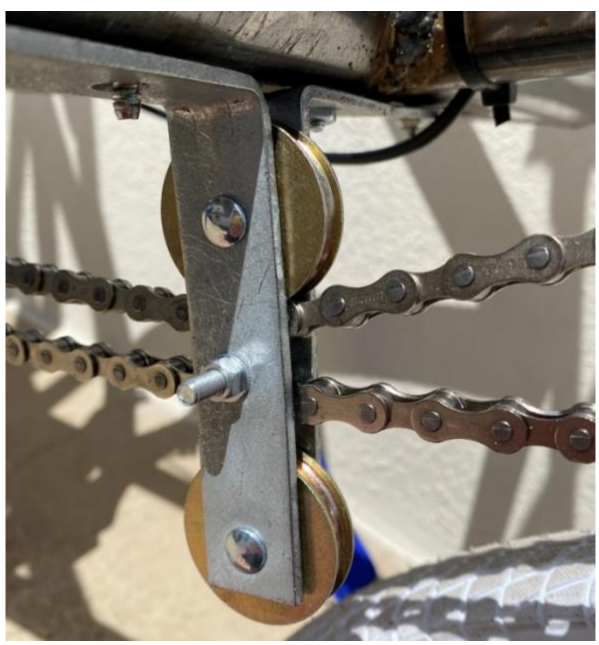


Figure 20: Custom built chain guide.

Once preliminary testing was conducted, it was determined that the original placement of the handlebar was too low on the frame and interfered with the occupant's ability to steer and accelerate. Therefore, one steel tube was cut to the needed size and bolts were added to properly increase the height of the handlebar and clearance the movement of the legs during the act of pedaling the vehicle. This handlebar extension effectively resolved the interference problem.

Preliminary testing also revealed that the occupant was unable to effectively balance the vehicle due to its excessive weight. Therefore, one time-constrained solution was to purchase and install two 26" metal training wheels. While this did allow for easier ingress and egress due to assistance in balancing, the forces experienced by the training wheels when the vehicle was in motion resulted in the metal training wheel brackets yielding, rendering them ineffective for dynamic stability.

b. Performance Testing

Table 7: Verification cross-reference matrix.

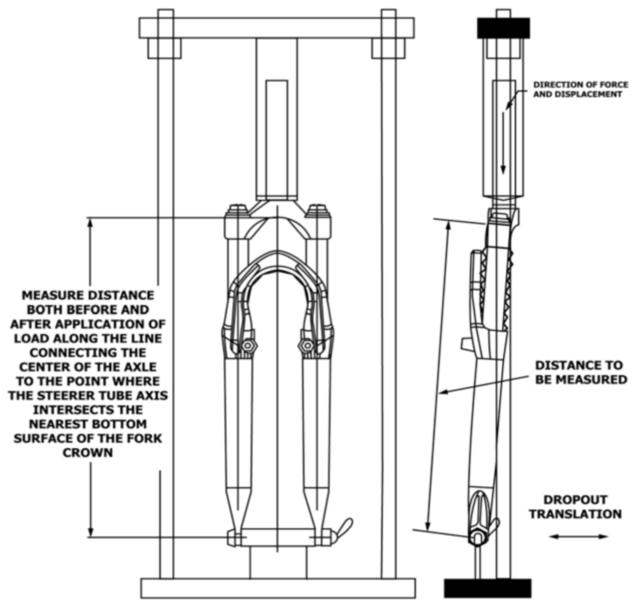
Design Specification	D.S. Cross Reference Number	Verification Method(s)	Test Conductor	Compliance
100 lb max HPV weight (w/o occupant)	1	I	Jack	
350 lb max HPV weight (w/ occupant)	2	I	Jack	
6.2 mph minimum HPV speed	3	T	Marc	
26.25 ft turning radius	4	T	Marc	
19.685 ft stop (adjusted)	5	T	Marc	
98.5 ft straight travel	6	T	Marc	
RPS hoop continuity	7	I	Marc	
RPS harness	8	I	Jack	
600.24 lbf (2670 N) Top Load	9	S	Marc	
299 lbf (1330 N) Side Load	10	S	Marc	
Seat belt mount	11	S	Jack	

<u>Legend</u>
S - Simulation
T - In-person Experimental Testing
I - In-person Inspection

The performance tests were conducted the weekend of April 23, 2021. Videos and written evidence for the tests exist but were not included in this report due to the large export size and clarity of test result summary. Final values for the vehicle's performance on empirical standard tests are included in the Conclusions section under Comparison.

c. Standards Testing

Three of the five ASTM standards in the standards section (F2273-11, F2680-17, and F2711-19) also outline testing methods. Unfortunately, these tests are specific to traditional bicycle frames and were not considered to be applicable due to the unique design of the recumbent bicycle with the RPS. However, standards testing research was an important part of the design process. In the compression load test described in F2273-11 and as shown in Figure 21, the bicycle fork is compressed parallel to the steerer tube, while the distance is measured between the center of the axle and the crown (the part that connects the steerer tube and the fork upper tubes) [10].



NOTE 1—For some fork designs, a dropout support that allows translation may be required.

Figure 21: Compression load test setup [10].

The bending load test (Figure 22) is intended to measure the bearing separation when a load is applied to the horizontal bicycle fork and specifies that the separation should be 150 mm. The impact resistance test is similar in that the steerer tube axis is horizontal and that the bearing separation is 150 mm. In this test, the impact was applied perpendicular to the steerer tube axis. The following diagram shows the setup for both the bending load and impact tests [10]. The fatigue test setup is also presented in Figure 23 [10].

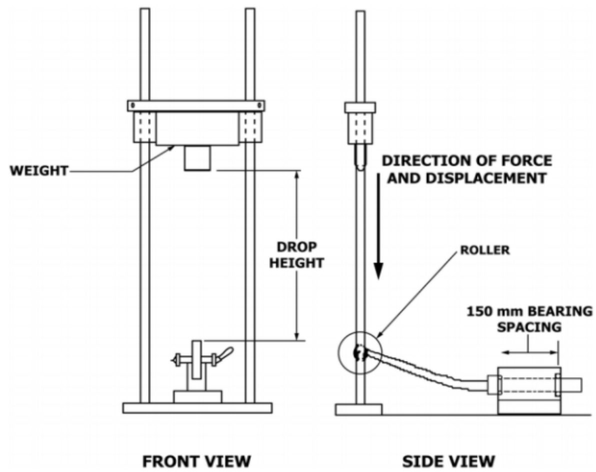


Figure 22: Bending load and impact test setup [10].

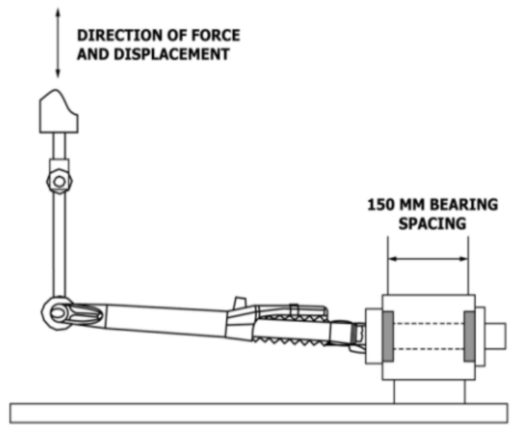


Figure 23: Fatigue test setup [10].

F2680-17 has test methods for both the primary and secondary retention systems. The primary tension system in Figure 24 shall have a force of 2300 N evenly applied on the axle for one minute [11]. The secondary retention system in Figure 25 shall have a force of 200 N evenly applied. Both of these forces are applied in the opposite direction of the fork. For the secondary retention test, a separate force of 100 N is applied on the wheel rim [11]. F2711-19 includes horizontal and vertical fatigue tests (Figures 26 and 27, respectively) to verify the strength of the frame, which would have needed to be adapted due to the uniqueness of the recumbent tricycle frame and RPS. This standard also includes a deflection ratio calculation. According to both the horizontal and vertical tests, the deflection ratio cannot exceed 1.0:

$$Deflection\ ratio = (K \times 10000 \times \delta) \div L^3$$

In this equation, K is a constant equal to 1417 and all values are in millimeters [12].

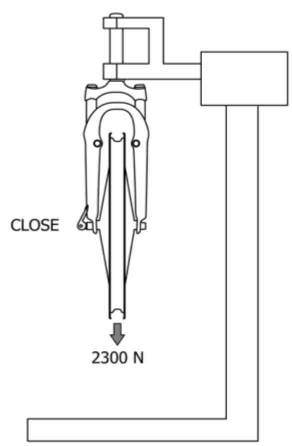


Figure 24: Primary retention test setup [11].

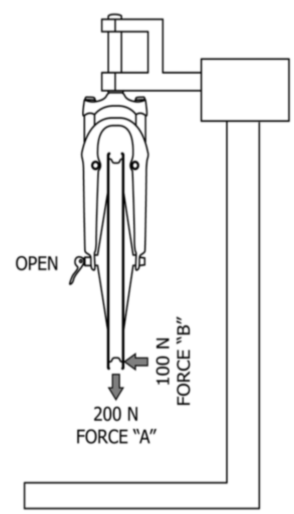


Figure 25: Secondary retention test setup [11].

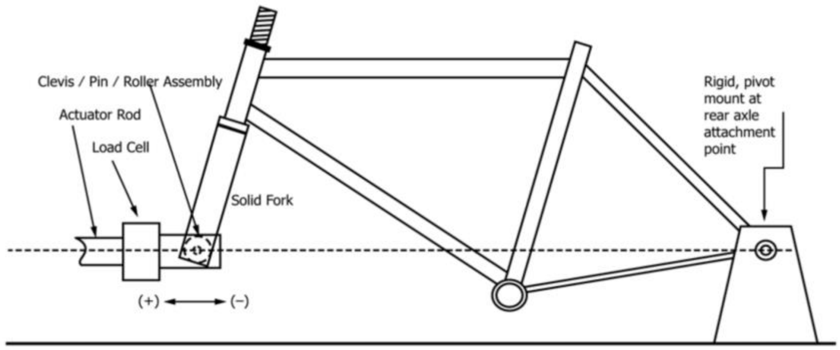


Figure 26: Horizontal fatigue test setup [12].

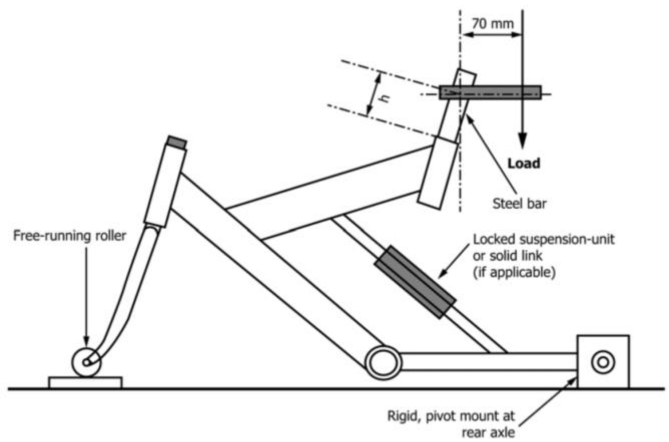


Figure 27: Vertical fatigue test setup [12].

The tests explained above are specifically designed for a two-wheeled bicycle with a typical triangular frame. While these tests were not conducted due to the specialized equipment required and due to time constraints, they did offer insight into how the team's frame ought to be designed.

d. Testing Design

Testing was intended to be conducted by the entirety of the team based on the availability of testing equipment. Due to the COVD-19 pandemic, only two members were able to conduct the tests. Load testing for the occupant, top, and side loads within the design specifications was intended to be conducted in the Engineering Design Center (EDC). However, time constraints due to the longer-than-expected time frame for acquiring and contacting a welding company, in addition to the process of cutting, notching, and welding the frame of the vehicle, limited the students to conducting tests without the equipment that LMU or the EDC could provide. The initial testing design involved testing the vehicle by applying forces at specific points on the frame where the forces would act upon using free weights. Due to the aforementioned time constraints, approximate load testing was done in a different fashion, which will be explained in the Conclusion section of this report. Tests for braking, acceleration, and turning radius were also intended to be conducted on campus, but time constraints limited the student's testing location to the site of construction, which was an empty street a few blocks from LMU's main campus.

4. SAFETY AND ETHICS

The safety and ethics of any engineering design, especially those which directly involve human interaction, are of high importance. The purpose of this engineering project is to meet or exceed the objectives and design specifications set forth by the HPVC. Many of the design specifications set by the HPVC take into account the safety of the vehicle, including, most notably, the RPS, which was tasked to withstand a significant amount of stress in the event of a rollover accident. While the HPVC guidelines have a variety of set standards, it is important as aspiring engineers to look beyond the design specifications. This is to ensure that the resulting design and completed build will not only function as intended, but also keep occupant safety as the priority. It is the ethical responsibility of the human-powered vehicle designers to ensure that the vehicle meets or exceeds the safety standards set by the ASTM and ASME standards. The HPVC design specifications set by the HPVC guidelines and modified by the project's designers with respect to safety must be met or exceeded analytically before any physical prototypes can be human-tested. Failure to do so would significantly increase the risk of injury or worse.

Table 8: RPS elastic deformation matrix.

Applied Loads	Maximum Allowable Deformation (cm)	FEA Deformation Analysis (cm)
Top Load	5.1	0.03990
Side Load 1	3.8	0.1817
Side Load 2	3.8	0.1972

As shown in Table 7, the RPS would experience a negligible amount of elastic deformation under the loads used in the FEA analysis to simulate an inverted crash scenario as well as crashing onto the vehicle's side. Additionally, as seen in Figures 14 to 16, there was no indication of permanent deformation, delamination, or fracture throughout the vehicle frame and the RPS. This was accomplished by liberal use of triangular trusses to ensure that the design would be stable and capable of absorbing large amounts of pressure in a general rollover scenario, protecting the driver while keeping the ground a reasonable distance away from their body, head, and helmet. Furthermore, these trusses helped distribute the forces of the crash scenarios across a greater surface area and thus reduced their effect on the overall design. The RPS was designed to be structurally attached to the vehicle frame such that no part of the driver would touch the ground in a rollover condition and that it would not touch the helmeted head of the driver. The sloped shape of the upper half of the RPS was made so that the vehicle would be more likely to come to rest on its side rather than remain inverted.

The goal of creating a robust human-powered vehicle would be more than achieved with the current design and its simple RPS and frame, although improvements could be applied in a transition to mass manufacturing for reducing costs. Additionally, different materials and pipe sizes could be tested with this design to determine the best combination of a low price and vehicle weight, the latter of which would increase ease of transportation and make the vehicle easier to turn right side up in a crash scenario. With that said, the robustness of the design could potentially cause issues in a crash scenario other than those related to deformation. The minimal crumple zone in the RPS could lead to passenger whiplash from crashes at higher speeds, so padding could be added to alleviate this. Also, while the legs and feet are more exposed to potential injury compared to the rest of the body due to the open front, additional materials could be added in front of the pedal crank section of the vehicle for more effective full-body protection. Overall, the RPS is capable of protecting the most vulnerable part of the driver and keeps the vehicle within safety standards.

5. CONCLUSION

a. Comparison

Each of the tests for the vehicle determine whether it would qualify for the competition for a typical, unaltered competition (years prior to the COVID-19 pandemic). The performance of this vehicle was underwhelming in some senses and encouraging in others. First, the vehicle met all of the safety standards that were tested. A four-point harness, continuous RPS hoop, and mount for a seat belt were all effectively implemented into the design. In terms of the vehicle's capability to withstand weight and forces, its performance was inconsistent. The weight of the vehicle was far greater than designed or expected, which means it did not meet the 100-lb maximum weight specification. On the other hand, the vehicle was able to adequately support over 350 lb on its frame. Both assemblers, Marc Sunga and Jack Rettenmier, whose combined weight totals 375 pounds, were able to sit on the frame in unison without any difficulty.

Unfortunately, the load testing designed to ensure the RPS can withstand heavy forces was not able to be completed by the time of this report. FEA shows that the frame would be able to support the forces with its design, but this is largely dependent on the quality of the welds. In terms of ride performance, the vehicle met a few of its requirements but failed to operate as intended. Its turning radius, stopping distance, and speed were all tested and confirmed successful by riding the vehicle with stability assistance provided by another individual not driving the vehicle. The main failure of the vehicle is its inability to maintain an upright position while riding without assistance. At high enough speeds, which could most likely be achieved, the vehicle would stay upright without assistance. Reaching these speeds would have been dangerous, so it was decided to not push the vehicle to reduce the risk of danger to the driver and to others.

Table 9: Modified verification cross-reference matrix.

Design Specification	D.S. Cross Reference Number	Verification Method(s)	Test Conductor	Compliance
100 lb max HPV weight (w/o occupant)	1	I	Jack	N
350 lb max HPV weight (w/ occupant)	2	I	Jack	Y
6.2 mph minimum HPV speed	3	T	Marc	Y
26.25 ft turning radius	4	T	Marc	Y
19.685 ft stop (adjusted)	5	T	Marc	Y
98.5 ft straight travel	6	T	Marc	N
RPS hoop continuity	7	I	Marc	Y
RPS harness	8	I	Jack	Y
600.24 lbf (2670 N) Top Load	9	S	Marc	NT
299 lbf (1330 N) Side Load	10	S	Marc	NT
Seat belt mount	11	S	Jack	Y

<u>Table</u>
Y – Yes
N – No
NT – Not Tested

Table 10: Results Table.

Overall Assisted Speed	9 mph
Braking Distance	~ 9 feet
Turning Radius	75 inches
Weight of Vehicle	106.2 lbs

Figure 28: Recorded stopping distance of the vehicle when traveling 10 mph.

The braking requirement was not exactly the same as the requirement outlined by the HPVC. Due to the size of the vehicle and despite its ability to travel at this speed, it was decided wise not to push it to 15.5 mph to test the braking at that speed. For this reason, the braking was tested at 10 mph where the vehicle could be guided with another individual holding onto the frame for safety reasons. Braking in 9 feet from 10 mph shows a successful trajectory for braking in 19.685 ft at 15.5 mph.

b. Evaluation

The performance of the vehicle was inconsistent. There were major successes, including a very comfortable ride for the occupant, but a few important design improvements would need to be made for the vehicle to fully function. Notably, the root of most of the issues with the vehicle's instability and weight was a frame design that focused too specifically on structural rigidity at the expense of balancing capability. When making the transition from a three-wheeled design to a two-wheeled design, the students did not adequately prioritize the center of mass' effect on balance. With a three-wheeled vehicle, stability can almost be assumed because of the three points of contact with the ground. For a typical bicycle, the weight of the vehicle has to remain low in order to maintain balance. Due to the focus on the RPS, the students designed the vehicle with some excess weight on the upper half of the vehicle to ensure that the RPS would withstand the required load testing. This excess weight was what caused multiple issues with the performance. Near the rear of the vehicle, there is a pair of poles that connects the rear steering to the back of the rider somewhat unnecessarily.

There are a couple of main reasons the vehicle underperformed. The first was that the team failed to follow the self-determined schedule that was created towards the end of the first semester and adapted throughout the second semester. Assembly was intended to begin around the middle of March, but setbacks and redesigns delayed the dates. Redesigns from the three-wheeled approach to the two-wheeled approach also resulted in expedited analysis and preparation. The design was not finalized until February, and this delay forced the rest of the schedule into a smaller window.

A proper understanding of the welding process would have greatly assisted in preparing the vehicle. The time it takes to cut and notch the pieces was underestimated, which led the students to assist the welder with aspects of the welding process. This was beneficial for the students as they received hands-on experience and gained a deeper understanding of the practical side of the design. Without the students' assistance, there would not have been any results or assembly prepared in time for this report. The translation from conceptual to practical was a steep learning curve for the students. It was not what ultimately led to the vehicle's insufficiencies, but it did cause several assembly processes to take longer to complete and further congested the already shortened timeline.

c. Recommendations

To match the final design with the desired specifications, potential future modifications would involve welding two extra supporting beams at the back and bottom of the frame. These beams would be used for mounting training wheels that are further from the rear wheel, which would help provide greater stability while traveling in a straight line and avoid the yielding of the training wheel bracket. Additionally, the front of the vehicle could also be reconfigured for the use of two connected and adequately spaced steering forks to return to a three-wheeled design for further stability. The two side bars of the RPS could also be removed while the triangular pyramid at the top could be redesigned to be similar to a hoop for protection. This would still maintain the requirements for the RPS while reducing the overall weight of the vehicle and lowering the center of gravity. Finally, the arrangement of bars holding the back wheel could be redesigned to be closer to the center of the frame. This would further reduce the weight of the entire vehicle by shortening the lengths of the bars involved.

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APPENDIX A: Project Timeline

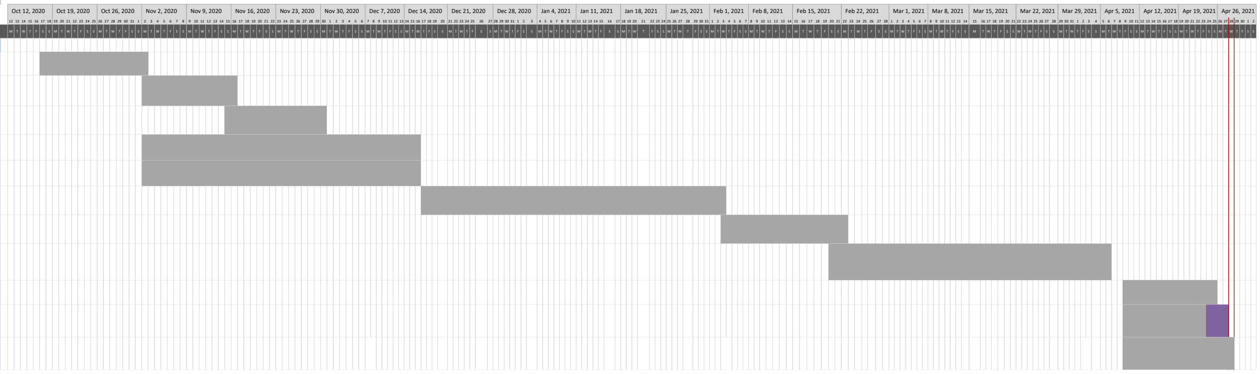
HUMAN POWERED VEHICLE COMPETITION

Ryan Apolonio, Maya Washington, Jack Rettenmier, Marc Sunga

Project Start: Sat, 10/17/2020

Display Week: 1

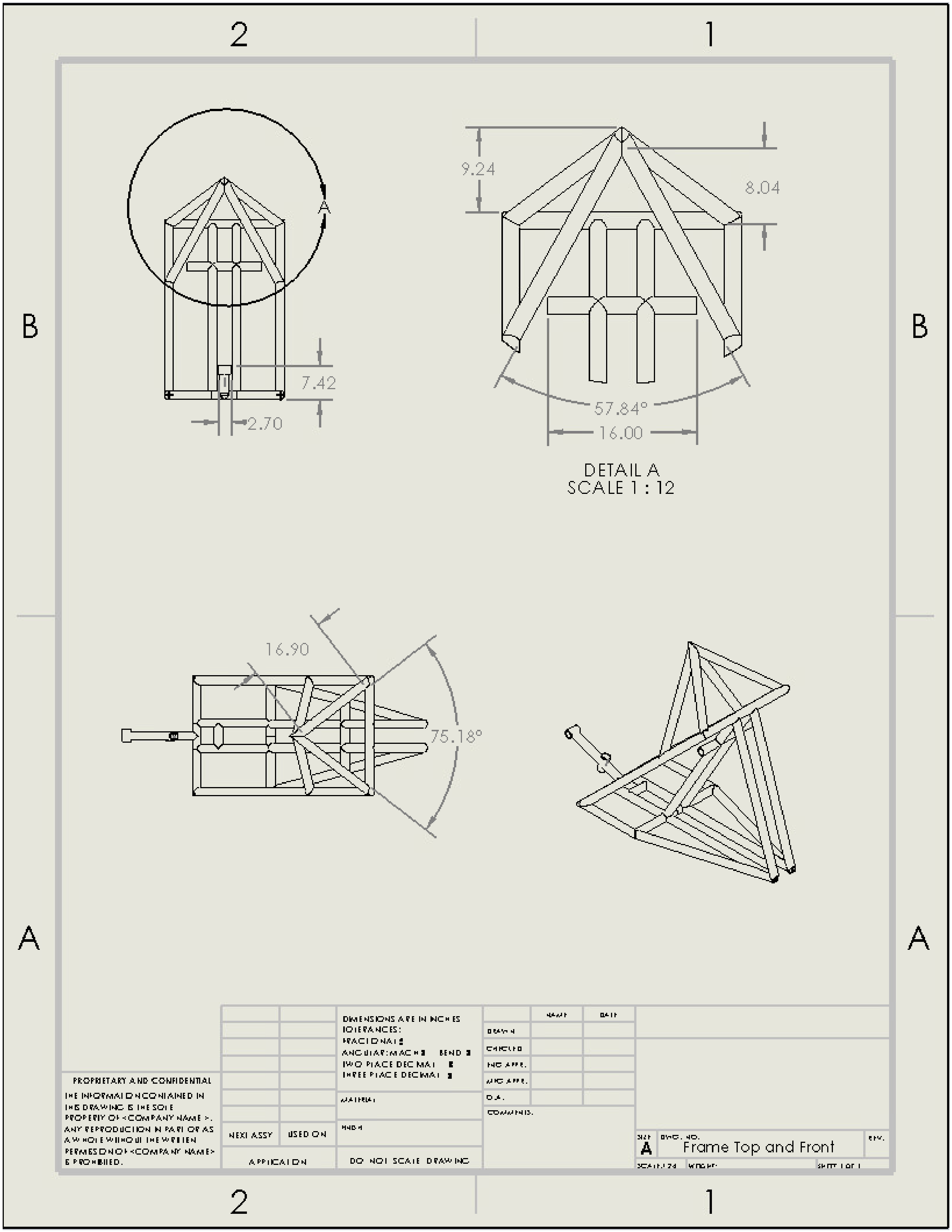
TASK	ASSIGNED TO	PROGRESS	START	END
Phase 1 Title				
Turn In Complete PDR		100%	10/17/20	11/2/20
Complete CAD of main frame		100%	11/2/20	11/16/20
Get cost estimates of non-custom parts		100%	11/15/20	11/30/20
Complete CAD of RPS		100%	11/2/20	12/16/20
Turn in complete CDR		100%	11/2/20	12/16/20
Complete CAD for remaining parts		100%	12/17/20	2/3/21
Complete CAD redesign (two-wheel)		100%	2/3/21	2/22/21
Make arrangements for full vehicle assembly		100%	2/20/21	4/6/21
Assemble full vehicle		100%	4/9/21	4/25/21
Complete all required tests and analysis		80%	4/9/21	4/27/21
Turn in complete FDR		100%	4/9/21	4/28/21

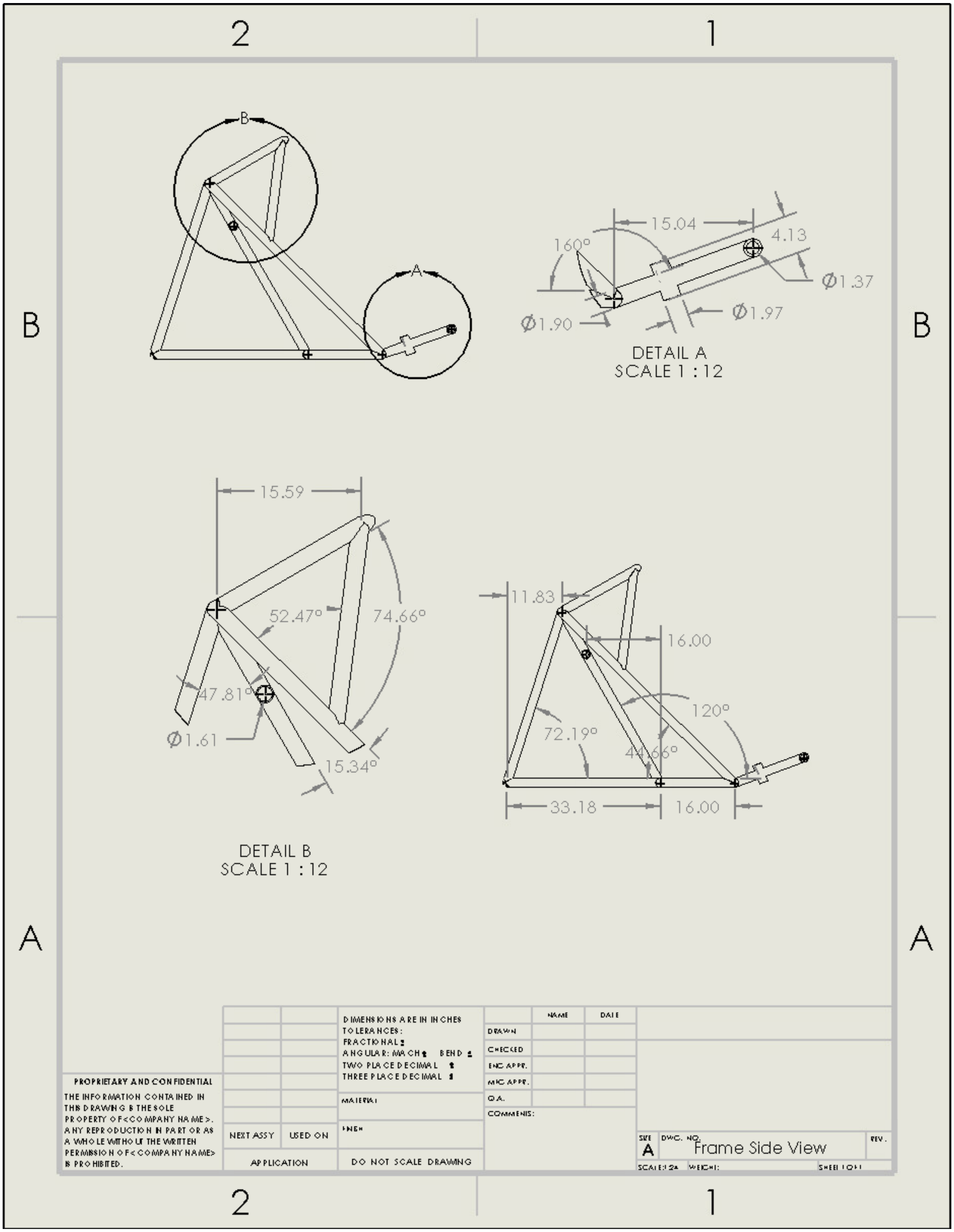


APPENDIX B: Bill of Materials

Item #	Quantity	Item	Description
1	1	Disc Brake Kit	all inclusive
2	1	Freewheel Hub	16T ACS main drive
3	1	Rear Dropouts	axle mount for rear
4	1	Wheelset	magnesium
5	1	20" fork	solid, no disc
6	1	Head Tube (HT)	105mm length
7	1	HT Bearings	28.6mm to 44mm adapted
8	1	Handlebars	25.4mm OD
9	1	Riser Stem	110mm, adjustable
10	1	26" Tire	26"
11	1	26" tube	26"
12	1	Harness	4 point
13	1	Bottom Bracket	steel
14	1	Crank Set	bearing, crank, chainring
15	1	Seat Bottom	securable seat pad
16	1	20" wheel	no disc
17	1	20" tire and tube	combo
18	3	20' 1.5" tubing	Carbon steel
19	1	Seat Back	top seat
20	1	Pedals	universal
21	4	M10 Bolts	Half threaded
22	4	M10 Nuts	For the bolts
23	1	Chain Guide	Guides the chain
24	1	Steel Pole	Extends steering fork
25	4	M6 Bolts	Mount bottom seat
26	4	M6 Nuts	For the bolts
27	2	Break Caliper Ext.	Attach caliper to frame

APPENDIX C: 2D CAD Drawings





B
A
15.04
4.13
160°
Ø1.37
Ø1.90
Ø1.97
DETAIL A
SCALE 1 : 12
15.59
52.47°
74.66°
47.81°
Ø1.61
15.34°
DETAIL B
SCALE 1 : 12
11.83
16.00
120°
72.19°
44.66°
33.18
16.00
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
FINISH
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <COMPANY NAME>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <COMPANY NAME> IS PROHIBITED.
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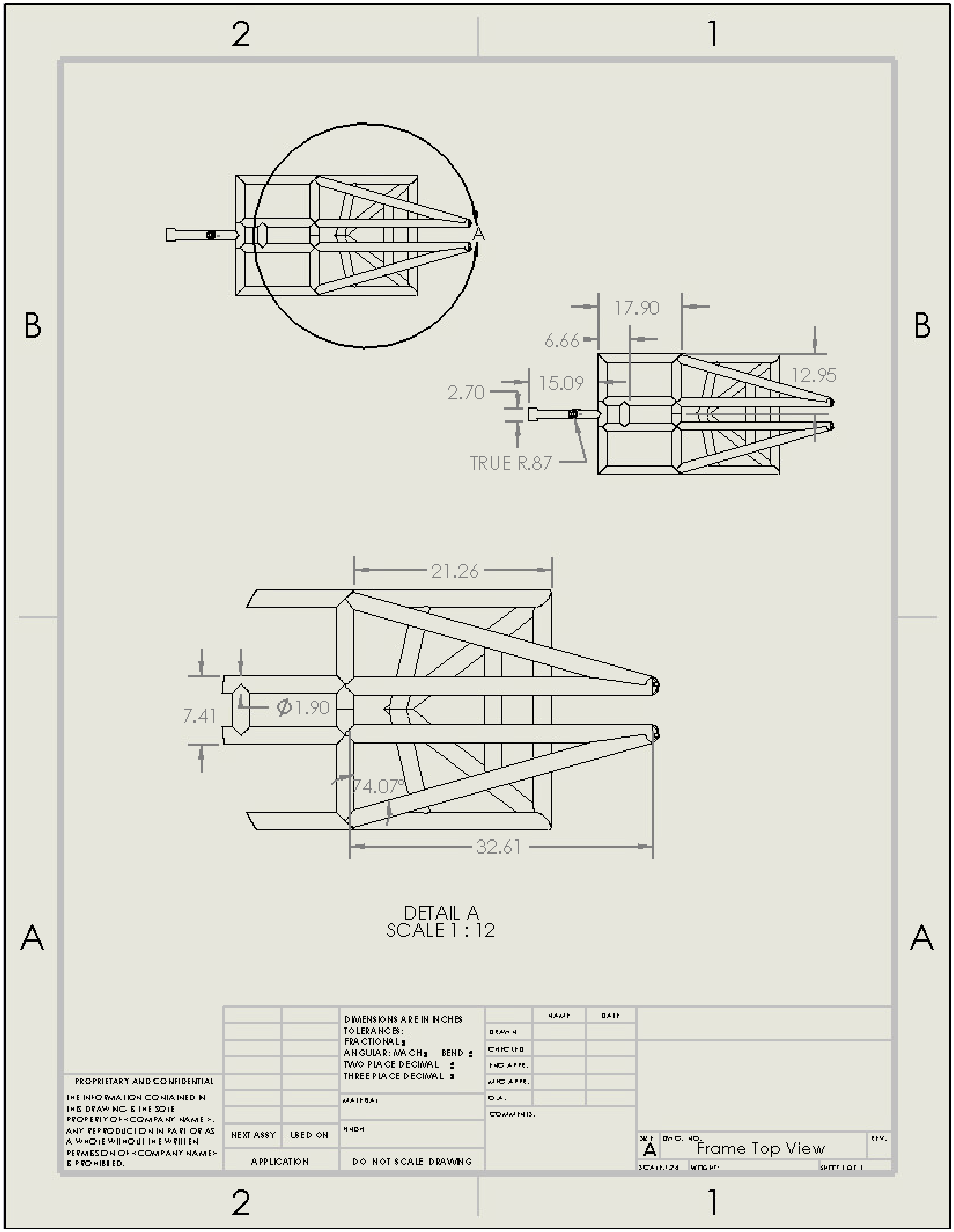
2
1
B
A
A
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6.66
15.09
2.70
12.95
TRUE R.87
21.26
7.41
Ø1.90
74.07°
32.61
DETAIL A
SCALE 1 : 12
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL
ANGULAR: MACH BEND
TWO PLACE DECIMAL
THREE PLACE DECIMAL
PROPRIETARY AND CONFIDENTIAL
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DO NOT SCALE DRAWING
NAME
DATE
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