Human Powered Vehicle Competition

Preliminary Proposal

Samantha Robbins

Ryan Podell

Sebastian Ruvalcaba

Anuththara Allujage

Paolo Quattrociocchi

Allison Bedrin

2020

Project Sponsor: American Society of Mechanical Engineers

Faculty Advisor: Perry Wood

Instructor: Dr. David Alexander Trevas

DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

TABLE OF CONTENTS

Contents

1 BACKGROUND

1.1 Introduction

The HPVC project is an intercollegiate competition that requires all teams to design a completely human-powered vehicle. The purpose of the vehicle is to provide alternative transportation options for people in third world or developing countries. To be a viable option for these conditions, the vehicle must be inexpensive, easily manufacturable, and easy to use. When an effective design is completed, it could solve transportation issues in rural areas as well as reduce the use and reliance on fossil fuels. An effective design could be an important step in the future of humankind to reduce environmental impacts and improve access to important resources such as water, groceries, and medicine that are necessary to promote the development and growth of communities worldwide.

1.2 Project Description

The following is the original project description provided by American Society of Mechanical Engineers (ASME).

“Human powered transport is often the only type available in underdeveloped or inaccessible parts of the world, and if well designed, can be an increasingly viable form of sustainable transportation.

ASME’s international Human Powered Vehicle Challenge (HPVC) provides an opportunity for students to demonstrate the application of sound engineering design principles in the development of sustainable and practical transportation alternatives. In the HPVC, students work in teams to design and build efficient, highly engineered vehicles for everyday use – from commuting to work, to carrying goods to market.”

1.3 Original System

NAU mechanical engineering has students who have a long history of designing, manufacturing, and competing in the ASME HPVC competitions. Detailed in this section are the previous design iterations carried out by those teams.

1.3.1 Original System Structure

The original system created by the 2014 HPVC team will be the comparison for this team's future endeavors. The 2014 vehicle was a three-wheeled recumbent design with several unique innovations that made it a highly functional and practical vehicle. The frame, constructed of aluminum, was rigid and robust enough to handle the rigors of competition. It featured a fairing to reduce air resistance to improve results in the endurance and sprint races during competition. Steering was handled by a twin-stick design with controls to shift and brake all located on each stick. Also included, was a camber adjustment for the two front wheels which allowed the team to alter the turning responsiveness and straight-line stability of the vehicle. Built into the fairing were temperature sensors that would automatically open vents in the fairing should cause the internal temperature rise or lower to a certain level.

1.3.2 Original System Performance

The overall performance made by the team and the vehicle were exemplary. The 2014 HPV team placed 2^{nd} overall in the competition. They took 1^{st} place in the women’s sprint race, 2^{nd} place for innovation, and 3^{rd} in the endurance race.

1.3.3 Original System Deficiencies

This team had trouble with the chain derailing off the sprockets during high load situations typically in the sprint race. Additionally, due to the dark color of the carbon fiber fairing, the internal temperatures were uncomfortable for the rider. During the endurance race, part of the fairing was not used to prevent the temperatures from causing discomfort to the operator. It is for these reasons, that the 2014 design could be described as not user-friendly.

2 REQUIREMENTS

Detailed below are the criteria that will determine what features are most important in the design of an HPV. These include the customer requirements, engineering requirements, and a functional decomposition of the necessary features that must be included.

2.1 Customer Requirements (CRs)

The following is a list of customer requirements for the HPVC:

1. Cost within budget
2. Durable and Robust design
3. Reliable design
4. Safe to operate/rider protected in case of collision
5. Vehicle can reach high speeds
6. Vehicle must be light weight
7. Highly maneuverable
8. Contains cargo space
9. Unobstructed field of view
10. Aerodynamic
11. Fits different riders of varying heights and weights

The overarching customer need is for a human-powered vehicle that is capable of scoring the top 10 of any of the events specified at the E-Fest competition. The secondary goal is that the vehicle is useable and accessible to any rider so that it may be used for community outreach and demonstrations. The eleven requirements that precede this are the means by which these goals shall be met.

2.2 Engineering Requirements (ERs)

The following is a list of engineering requirements along with the targeted value for each.

Table 2.1: Engineering requirement list and target values.

Engineering Requirement	Target Value
Weight	< 50 pounds
Frame Strength	Yield FOS > 1.5
Turning Radius	≤ 15 feet
Top Speed	45 MPH
Drag Coefficient	CD < 1
Innovation	Points
Cost	< $5000
Mount/Dismount Time	< 30 sec
Frontal Area	≤ 5 square feet
Ergonomic	Comfort for 2 hours

1. Weight (<50 pounds)

The weight of the vehicle will affect the handling, top speeds, and operator fatigue significantly. For the vehicle to be competitive it is imperative that weight be kept down to a minimum.

2. Frame Strength (Yield FOS > 1.5)

Structural integrity is crucial. If at any point there is a structural failure, the vehicle will no longer be viable for competition or for general use. For this purpose, a structurally sound design is required. Given the operating conditions and the lack of severe terrain and harsh environments, there is no need for overly conservative safety factors.

3. Turning radius (<=15 feet)

The slalom event requires the vehicle to make an 8-meter (32 foot) U-turn. By aiming for a tighter turn radius, this increases the maneuverability of the vehicle during high speed maneuvers where sliding could occur.

4. Top speed (45 miles per hour)

An important part of the competition is speed. In order to place top 10 in sprint or endurance, the vehicle must be faster than most of the competing teams.

5. Drag Coefficient (CD < 1)

Another crucial part of preventing operator fatigue and ensuring highest possible efficiency and speeds is to have the lowest coefficient of drag possible.

6. Innovation (Points)

Innovation is a key factor in the design report as well as a high priority customer requirement. In order to develop and push existing technology further, the team will need to create unique solutions to problems that will score high marks for innovation/.

7. Cost (< $5000)

The purpose of the project is to create a relatively inexpensive vehicle for use in developing countries. As such, cost is an important factor. While the prototype is always more expensive than full production, it is wise to stay well within the allotted budget to account for travel, room and board, as well as competition fees.

8. Time to mount/dismount (<30 seconds)

Some events in the race demand that the operator get into and exit the vehicle to complete certain tasks. Therefore, to maintain a competitive edge, it must be easy to mount and dismount.

9. Frontal area (<= 5 square feet)

A lower frontal area will reduce aerodynamic drag forces and reduce the amount of material necessary to construct an effective fairing.

10. Ergonomic (minimum time in vehicle > 2 hours)

The endurance race requires long time periods of vehicle operation. Performance must not come at the expense of the operator's comfort, especially in the case that the discomfort becomes chronic and reduces the desire to use the vehicle.

2.3 QFD (HoQ)

In order to relate customer needs to engineering requirements, a QFD was created. By assigning weights to the features most desired by the customer, the team can focus on the engineering requirements that need to be developed to directly satisfy those needs. This will aid the team in the design process by creating a hierarchical list of solutions in order from most important to least important.

Weak Correlation	1	
Moderate Correlation	3	NAU HPVC Summer 2020
Strong Correlation	9	

Customer Requirements / Engineering Requirements		Frame strength (Yield FOS)	Weight (lbs)	Turning radius (feet)	Top speed (mph)	Drag Coefficient (CD)	Innovation (Points)	Cost (dollars)	Time to mount/dismount (	Frontal area (sq. feet)	Ergenomics (hrs)
Low cost	2						3	9			
Durable and robust	5	9					1	3			
Reliable	5			3			9	3	3		
Safe to operate	5	9	3	9							3
High speed	4		9	1	9	9	3			9	
Maneuverability	4		3	9	3		3		3		
weight	4	3	9		9			3			3
Cargo space	3		3							1	
Field of View	4										9
Aerodynamic	4				9	9	3			9	
Fits multiple riders	5										9
High design report score	5	3	3	3	3	3	9	1	1	3	3
Absolute Importance		117	123	115	135	87	137	65	32	90	123
Relative Importance		11	12	11	13	8	13	6	3	9	12

Figure 2.1: Customer needs and engineering requirement comparison (QFD)

2.4 Functional Decomposition

The main function of the HPV is to effectively use human energy to power a recumbent bicycle through several different competition obstacles and events. The functional decomposition process is the defined functional parts of a product and how they can be differentiated into their functional composition. The following two sections will explain the black-box model and the hierarchical task analysis that the team created. The black box model will show the inputs and outputs from the user of the product. The hierarchical task analysis provides the team's objective tasks to complete the final goal of the project.

2.4.1 Black Box Model

Black-box modeling introduces the functionality of the product through materials (thick black line), energies (thin black line) and signals (dotted line). The left side of the model shows the input functions while the right side enhances the output of the product. This model creates an analysis of the general design and has no technical work of the design involved.

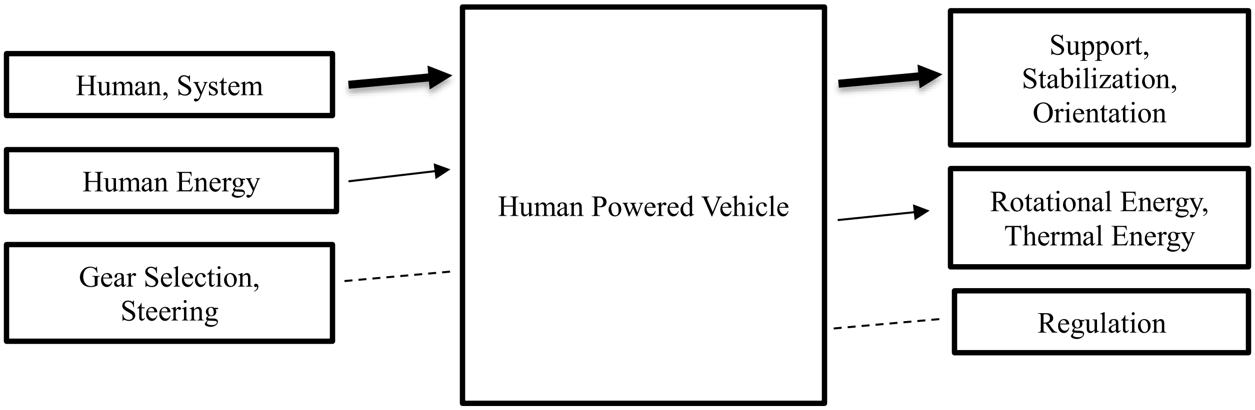

Figure 2.2: Human Powered Vehicle Black Box Model

Modeling the inputs and outputs of the human-powered vehicle has allowed the team to understand the general concept of the bicycle. Human interaction provides the vehicle with all functions resulting in braking, determined speed and rotation of wheels, and the final orientation of the vehicle. The team analyzed separate parts of the vehicle based on the model to create rough technical designs for the decision matrices and to explore the functional model as seen in the following section.

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

The Hierarchical model was used to build a structured and objective approach to determine the order that should be followed to achieve the goal of producing a final design.

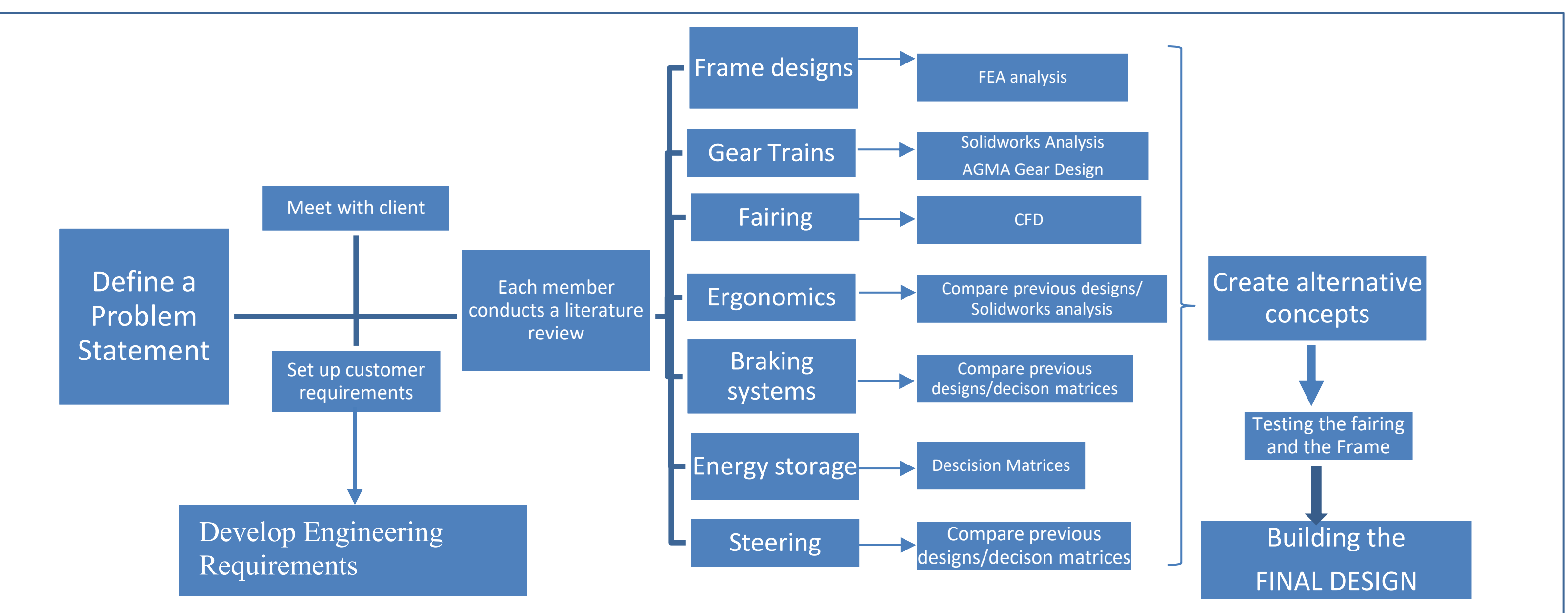

Figure 2.3: Hierarchical Task Analysis

The Hierarchical chart was used by the team to determine the order in which tasks should be completed. After meeting with the client and setting up customer and engineering requirements, the team was able to divide the overall function of the HPV into sub-functions. Then each member was assigned a sub function to research and carry out respective analysis. The results obtained from the analysis were used to build alternate concept designs. The alternative designs were further analyzed using decision matrices and a Pugh chart to conclude the final design.

3 DESIGN SPACE RESEARCH

Extensive research has been done by the team in order to fully understand the complete system and subsystems involved designing a human-powered vehicle for competition. Outlined in section 3.1 is each team members individual subsystem research which combined to give the team a full understanding of what is currently available and what has been done in the past for similar problems and systems. Section 3.2 highlights the benchmarking done for both complete HPV's and subsystems of them. These benchmarks were used in decision and design choices of our team's HPV.

3.1 Literature Review

3.1.1 Allison Bedrin

Allison Bedrin is in charge of researching store energy systems, their applications, and their compliance in the ASME HPVC 2021 Rules. The main idea behind stored energy is to decrease braking since it creates heat energy. This energy loss cannot be put back into the system. Therefore, the vehicle could store energy while slowing down into a turn or riding down a decline. The two main types of stored energy systems are regenerative braking and flywheels. The first two articles discuss regenerative braking while the last three articles discuss flywheel applications.

The ASME HPVC 2021 Rules state that any energy storage device used must be safe during use and in case of a high-speed incident. The rules also state that combustion engines are not allowed and that any stored energy that is used in moving the vehicle must be at zero prior to each race (Commitee, 2020).

The article written by Micah Toll discusses the effectiveness and efficiency of regenerative braking in small vehicles. The efficiency of regenerative brakes on a vehicle depends on how much of the time the vehicle uses its brakes. For example, driving a vehicle in a city would utilize their brakes more than a vehicle driving on an empty freeway. Next, the article explains that the effectiveness of regenerative braking comes from the driving conditions as well as the vehicle specifications. From the effectiveness point, vehicle size is the largest impacting factor. The article states that a larger vehicle benefits more than a lighter vehicle (Toll, 2018).

The technical article written by Panda EBikes talks about electric bikes and the possibilities of charging while braking and pedaling. Similar to the article written by Micah Toll, Panda EBikes says that most electric bicycles do not incorporate regenerative braking because the return rate of energy is low. In other words, the weight and cost to add regenerative braking to a bicycle is not comparable to the energy put back into the system (EBikes, 2017).

The article written by Larry Greenemeier talks an upright bicycle with an integrated flywheel. This design was able to utilize the flywheel's energy by using a continuous variable transmission and accelerate the vehicle. The article did not go into detail about the gyroscopic effect when turning but did discuss the efficiency of the design to retain energy (Greenemeier, 2011).

Lastly, the technical article by Dave Matthews discusses how to choose the correct flywheel for your application. The article goes into material choice and weight ranges and define their characteristics. The article also notes the difference between standard and lightweight flywheels. The standard flywheel is able to hold more energy than the lightweight flywheels (Matthews, 2020).

3.1.2 Anuththara Allujage

Anuththara Alujjage was responsible for researching about the aerodynamic shell called a fairing for the HPV. It is important to decide whether a fairing will be needed, if it is required, what type of design will give the lowest drag and the highest speed. The fairing selected should have the ability to accommodate all members of the team, a payload, the frame and should ensure the safety of the rider.

The "Human Powered Vehicle frame design" (Alan & Aumann, 2015) article discusses designing a fairing that allows comfort, safety and is spacious. The article compared different fairing designs used in previous competitions and what type of modifications were done to increase the speed of the vehicle.

The website "Recumbent" (Warren,2003) mainly discusses the steps taken to build a fairing and the importance of knowing the expectations of the vehicle. The website also explores the steps taken when selecting a streamliner. It also compares different designs used in the past and what factors were taken into considerations when deciding on a specific fairing design. The website also helped to get a basic idea about scaling, sizing and the cost of the fairing.

The website "Aerodynamic fairing for a human powered vehicle" (Nelson, 2010) gives information of the step by step process followed to build the fairing. The author also discusses the aerodynamic SolidWorks flow simulations carried out to obtain velocity contour plots and pressure streamliners. This information will be helpful to the team when manufacturing the vehicle.

"2010 Human powered vehicle" (Smith et al. 2010), article focuses on partial fairings and analyze the conflicts such as a narrow fairing could interfere with the handlebars, fairing should be designed around the roller bar and give enough room for the rider to pedal without hitting the sides. This information is useful when determining the size of the fairing.

The final article "Automotive Composites and Polymer Material Selection for Fairing of a Human Powered Vehicle Using Multi-Attribute Decision Making Methodology" (Gewaily et al., 2017) explore material options the fairing could have, and the importance of the material chosen as it contributes to the overall weight of the HPV.

3.1.3 Paolo Quattrociocchi

Paolo Quattrociocchi will complete the design and analysis of the vehicle frame and structural components. Using SolidWorks Simulation tools and existing knowledge of engineering principles from coursework, a thorough analysis will be made to ensure a cost-effective, strong, and simple design is developed. Frame design is critical because any structural failure of the vehicle will render it useless and disqualify the vehicle from competition.

The first literature source considered was "Plastic-deformation analysis in tube bending" [6]. (Tang, 2000).. This article shows the effects of strain hardening, localized stresses and strains, as well as dimensional changes that occur when round tubes are bent to form elbows or any other shape. These are all critical factors that are considered when constructing structural members of the frame that are bent into the proper shapes.

Second a patent article titled "Bicycle frame with improved weld joint" (U.S. Patent No. US 8,042,822 B2 , 2011) was considered. This patent article details a unique way of joining bicycle tubes such that the weld area is reformed to accept higher amounts of filler metal from the welding source to increase strength and rigidity of weldments. This technique allows the welder to do so without having material rise above the outside diameter of the frame tubing. The main benefit of this process is eliminating the need for post-weld finishing procedures to prevent the weld material from interfering with other components.

"Bicycle Design: A different approach to improving on the world human-powered speed records" (H. K. Epemaa, 2012) is an article that might not apply directly to requirements of this project but contains good information regarding computational fluid dynamics, CFD, design and two different philosophies of design to achieve high speeds. The current speed record limiting factor has been determined to be air resistance. Thus, creating the most aerodynamic vehicle with the smallest possible rider should yield the highest speed attainable. This article shows the research to the optimize aerodynamic profiles using CFD for the average1.9-meter-tall male that can exert more power than the theoretical “smallest possible rider”.

In order to see another collegiate team’s attempt at a front-wheel drive system, the California Polytechnic University of San Luis Obispo HPVC team created a technical report, “ASME Human Powered Vehicle” (Supat, 2010). While the design of this team did not meet their performance expectations overall, the front- wheel drive system worked well and eliminated the issues encountered by other teams that attempt to use rear-wheel drive vehicles. Due to high chain lengths and the need to cross the chain there becomes issues with tensioning and preventing chain derailment.

Finally, “Design and fabrication of a composite human-powered land vehicle” (Raymond Kozak, 1996) discusses the processes and challenges of developing a completely composite framed HPV. This article details the physical analysis process as well as the strength of bonded composite joints which are inherently present in a composite frame. Some composites have a very high strength to weight ratios which make them a competitive option for frame materials.

3.1.4 Samantha Robbins

Research assigned to Samantha Robbins focused on the steering composition of the vehicle. The balance of the steering relies on the angles of the wheels, frame, structure and the rider height and length. The steering shall encompass where the head tube, handlebars, connections to the frame and other components such as gear selector and braking will be in a location to the rider. This research helps the team understand what type of steering design would be beneficial, easy to manufacture, and able to provide the eight-meter turning radius as given by the ASME rulebook (HPVC, 2020).

The student first read the article “The Geometry of Bike Handling: It’s All About the Steering” (Wikstrom, 2018)to fully understand the effect of steering components on the bicycle and how to place them to provide maximum usage for the rider. The article describes all parts relating to the steering and the equations used when building a bicycle. The section regarding the head tube angle describes the steering behavior for high and low speeds which helps the team view the difficulty of stability during a turn at several speeds.

The research performed and reported by Brad Lignoski in “Bicycle Stability, Is the Steering Angle Proportional to the Lean?” (Lignoski, 2002) goes into detail about the logistics of how the bicycle will be leaning in order to steer enough to turn the bicycle at the desired radius. An experiment was created in which a camera was oriented on the seat of the bicycle aligned with the center of the bike. The bicycle was then ridden in several circles at low speeds to examine the angles achieved. Data was collected through the images that were captured and equations were used to figure out the correlation between the steering angle and the lean.

The second article read by the student was “The Ultimate Guide to Bike Geometry and Handling” (Stott, 2018). The author, Seb Stott, writes about the effective lengths of each tube on the bicycle. The head angle will determine where the handles will sit amongst the rider and affect the amount of trail which correlates to the steering response at different speeds and different terrain.

“Bicycle Frame & Component Failures” (Bicycle Frame & Component Failures - Expert Article, 2015) is an article showing the failure points on a bicycle and where the failure should be located at. The handlebar/stem failure section reports on the weight from the rider when inputting steering to the bicycle. The integrity of the stem and outside of the handlebars is seen as the most compromised throughout the steering column and should be reinforced where needed.

The last source “Headset Standards” (Headset Standards, 2015) is an article discussing the different headset systems and installation of each for different types of bicycles. Each part necessary to the assemblage of the headset is listed and shown in relation to the type of headset being used. From that article there are several links for articles that go into deeper installation requirements and instructions on the same website. There are conventional headsets, oversized, integrated angular and low-profile styles to consider and this article explains the interchangeability of each one.

3.1.5 Sebastian Ruvalcaba

The focus of Sebastian’s research is ergonomics. The HPVC team along with client Perry Wood and Professor David Trevas decided ergonomics was a critical aspect to research into because of the nature of the physical intensity of the competition. The competition where the human-powered vehicle requires the rider to exert force for a considerable amount of time, especially for the endurance event. This endurance aspect makes ensuring the ergonomics of the design a top priority to maximize rider comfort and performance.

The first source read was the book, *Bicycle Design* (Hadland & Lessing, 2014). The book is an excellent overview of the entire bicycle and its subsystems. The areas of interest in ergonomic design from the book are the chapters on comfort, and saddles, pedals, and handlebars. The comfort chapter goes into detail on the history of the tire, how it was developed into the tire we use today, as well as the history of suspension systems and the many iterations of designs they went through to be the optimized versions there are now that provide maximum comfort to the rider. The chapter on saddles, pedals, and handlebars similarly goes into the history of each and explains how they were each developed into the modern saddles, pedals, and handlebars used today.

The second source reviewed is a conference proceeding article on the “Ergonomic study on human-powered vehicles” (Azman, et al., 2016). This conference proceeding goes into detail on the complete ergonomics of a recumbent style bicycle. The authors provide ideal angles for all parts of the human body that will provide the most comfortable riding experience especially when riding for a longer time.

The third source for ergonomics is an article on a “Muscle fatigue-based evaluation of bicycle design” (Balasubramanian, Mohan, & Kanagasabai, 2014). This article was a beneficial read because it covers a study that determined the muscles of the body that experience the most fatigue on a bicycle. The study also compared the fatigue of those muscles to the designs of the bicycles which were a hard bicycle with no suspension, a bicycle with full suspension, and a race bicycle.

The fourth source is another journal article that is titled, “Applying riding-posture optimization on bicycle frame design” (Hsiao, Chen, & Leng, 2015). The authors of this article stress the fact that injuries caused in bicycle sports are mostly related to incorrect adjustment of the saddle height, handlebar and /or pedals (Hsiao, Chen, & Leng, 2015). From this article, the HPVC team can learn that ensuring the human-powered vehicle is properly adjusted to the rider can lead to a safer and more enjoyable ride. Also, with correct adjustment of the vehicle, the rider can perform more efficiently during competition.

The last source researched specifically for ergonomics is an article titled, “Characteristics of maximum performance of pedaling exercise in recumbent and supine positions” (Kato, Tsutsumi, Yamaguchi, Kurakane, & Chang, 2011). This article describes the optimum seating position that will allow the rider to output the most amount of power efficiently. It compares being laid down in the supine position to the more upright sitting position and how each of those positions effects the power delivered from the rider’s legs and the oxygen intake to the rider’s lungs. This article will be beneficial to the HPVC team when determining the design of the vehicle.

3.1.6 Ryan Podell

Ryan Podell is to design and analyze the power train and gear system that will transfer human energy into mechanical energy for the HPV. This system must be efficient at transferring the power to deliver and be able to generate various output speeds for the various obstacles and challenges the team will face in competition.

The first source for researching this topic came from searching the types of conventional bicycle drivetrains currently used on the majority of bicycles. The result was a blog titled “Gears Galore: A Look At Current Drivetrain Options” (Hart, 2019). This blog highlighted many standardized gearing and drivetrain options that are found on most modern bicycles. This provided an initial understanding of what gear ratios and gear combinations are commonly found on a majority of bikes.

The second source of research for this topic highlights one of the more innovative and efficient drivetrain options currently in development. The article from New Atlas titled “World’s most efficient bicycle drivetrain” (CeramicSpeed, 2018), showcases a shaft-driven bicycle drivetrain being developed by the company Ceramic Speed. Utilizing highly efficient bearings and a one of a kind sprocket and driveshaft, this style of drivetrain boasts maximum efficiency by eliminating many points of contact which induce friction found on the common chain and sprocket setup.

The third source of research into drivetrain systems provided yet another innovative style of bicycle drivetrain. This drivetrain was highlighted on the manufacturer’s website, Fallbrook Tech (Technology, n.d.). This company is creating innovative continuously variable transmissions, CVT’s, and applying them to various types of vehicles and machinery. These systems provide an infinite amount of seamless gearing possibilities.

The fourth source of research focused on the rider’s cadence and input speed for the HPV. The article “What Should Your Ideal Cadence Really Be?” (Yeager, 2019) gave some generic standards for both average and professional riders for what sort of cadence they can both achieve and sustain for extended periods of riding.

The fifth and final source of research is the ME 465 textbook “Shigley’s Mechanical Engineering Design” (R. G. Budynas, 2015). This book highlighted key topics for AGMA gear design and analysis. These topics were used in designing the transmission to allow the HPV to achieve desired outputs.

3.2 State of the Art - Benchmarking

The state of the art and benchmarking come from previous HPVC designs. Section 3.2.1 covers the existing full system designs while Section 3.2.2 covers the existing subsystem designs.

3.2.1 System Level State of the Art - Benchmarking

In this section, previously executed designs will be discussed in limited detail. The purpose of this section is to show what existing technology there is to improve upon and to give starting values for this team.

3.2.1.1 Existing Design #1: Rose-Hulman 2015

The first vehicle for comparison is the Rose-Hulman 2015 vehicle “Shanon-igans” (2015 ASME East Coast HPV Challenge). This is a two-wheel, semi-recumbent, and fully faired design. This vehicle boasted a front and rear wheel steering system, landing gear, and road safety systems such as turn signals and a horn. The team’s goal was to create a very practical vehicle for use by the average person as well as having some high-performance features. This vehicle will be a good gauge for balancing practical features and performance design.

Figure 3.1: 2015 Rose-Hulman HPVC

3.2.1.2 Existing Design #2: MAGIC Race Recumbent ()

This vehicle two-wheeled, recumbent, unfaired design. Specifically designed for racing, this vehicle features a highly aerodynamic carbon fiber frame and rider position. It is also front-wheel drive which greatly reduces the effective length of chain. While less practical for the average user, this provides a top end estimation for what is possible with respect to performance.

Figure 3.2: MAGIC Race Recumbent HPV

3.2.2 Subsystem Level State of the Art Benchmarking

3.2.2.1 Subsystem #1: Fairing

Fairing is an aerodynamic shell which can be used to reduce the drag force action on the vehicle. It is important to decide on whether a fairing is needed, if need, what is the best design that could be used as it helps to increase the speed of the vehicle. The fairing selected must fit all team members, should not restrict any movements inside the vehicle, must be able to carry a payload and most importantly it should ensure the safety of the rider.

3.2.2.1.1 Existing Design #1: Fully enclosed fairing

One of the most used type of fairing in previous competition is the fully enclosed fairing. *Figure 3.3* represents a design of a fully enclosed fairing. The advantage of having a full fairing is that it the streamlined structure will help to reduce the drag force and increase the speed of the vehicle. Having a higher speed will ensure that the vehicle is able to complete and has the ability to protect the driver in an event of a crash.

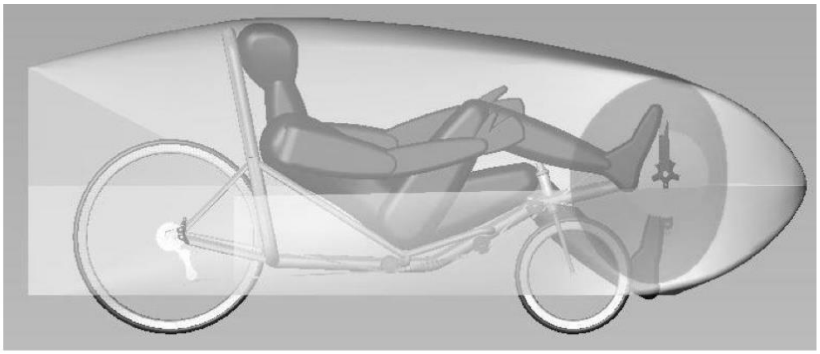

Figure 3.3: Fully enclosed fairing with the rider

3.2.2.1.2 Existing Design #2: Partial Fairing

The partial fairing can be of two types designs. The fairing can be attached to the front of the vehicle as shown *Figure 3.5* or the fairing could be attached to the back of the vehicle, represented in *Figure 3.4*. Partial fairing can eliminate any conflict that could arise when pedaling or steering as it gives more space to the rider. Some other advantages of having a partial fairing is that it will help reduce the manufacturing cost, reduce the weight of the design, allow good visibility, ventilation for the driver and reduce drag acting on the vehicle. These factors are important for the team as it fulfils customer requirements.

Figure 3.4: Partial Fairing attached to the back

Figure 3.5: Partial fairing attached to the front

3.2.2. 1.3 Existing Design #3: No Fairing

The last existing design type is having no fairing for the vehicle. This type of recumbent, two-wheel, single rider design is representing in *Figure 3.6*. Requirements this type of faring would fulfil are keeping the project underbudget, giving enough room for the rider to pedal, steer, low weight and gives visibility in all directions.

Figure 3.6: No fairing design

3.2.2.2 Subsystem #2: Gear Train

The gear train is the subsystem that converts human energy into the motion of the vehicle. This subsystem is a core component in the completion of the overall design as it is the acting component that moves the vehicle forward at various rates of speed. There has been very little innovation of this subsystem for similar style vehicles over the years and the team wanted to research as to why.

3.2.2.2.1 Existing Design #1: Chain and Sprockets

Found on most modern bicycles and bicycle-style vehicles is in one form or another a chain and sprocket drive system. This system works by the user pedaling a crank which is attached to a front sprocket. The front sprocket is then connected via a chain to the rear sprocket which is attached to the drive wheel providing motion to the vehicle. Variations of this design range from single speed, meaning a fixed gear ratio, to upwards of 30 available gear ratios. These ratios are obtained by utilizing a multi-gear front crank set and multi-gear rear cassette. Shifting mechanisms and chain tensioners allow for the user to select whichever combination of front and rear sprocket sizes they desire. These systems are relatively simple, easy to maintain and offer a wide range of gear ratios to drive the vehicle at various speeds given the conditions or requirements of the user. And if setup correctly and well maintained and lubricated, this design is relatively efficient as well. Downsides to this system are the limited output speed achievable with the gearing availability within most bicycles and the team's HPV.

3.2.2.2.2 Existing Design #2: Ceramic Speed Shaft Drive

This new iteration of an older design is still being developed by the company Ceramic Speed. It utilizes highly efficient ceramic bearings and a drive shaft system that eliminate many frictional contacts found in a traditional chain and sprocket setup and boasts of being the most efficient drive train available for a bicycle. The user pedals the cranks which are connected to a ring gear style of gear mated to the pinion gear attached to the drive shaft. The drive shaft then transfers power to another pinion gear consisting of ceramic bearings which is mated to the drive sprocket/ gear. Shifting between gears is done by an electronically controlled actuator which slides the bearing assembly at the driven end of the drive shaft into the next gear ratio position. This is done as a two-step process, moving the bearings not engaged with the drive sprocket first and as the shaft rotates, the second half of the bearings are slid into the new ratio position. This complex process is timed using electronic sensors located on the drive train. While this design does offer exceptionally high efficiency, the shifting mechanism and electronics are relatively complex, and the single point of gear adjustability limits the available output speeds of the design.

3.2.2.2.3 Existing Design #3: NuVinci CVT

Over the last few years, Fallbrook Technologies has introduced a continuously variable transmission, CVT, design to the cycling market. Their design utilizes a patented CVT providing an infinitely variable set of gear ratios within the minimum and maximum ratios allowed per the design. This setup is mounted to the cranks and has a belt-driven output gear that connects to the drive wheel. While seamless shifting is a major upside to this design, it is highly limited by the currently available overdrive ratios which is currently limited to 1:1.9. While these ratios may be practical for most cycling uses, it is not suitable for achieving the desired maximum speed of the HPV.

3.2.2.3 Subsystem #3: Steering

The steering subsystem comprised of the head tube, fork and handlebars, uses human signals to provide orientation and stability to the HPV. These functional components are important to the final product as it is a part of the frame and works around the engineering and customer requirements. Innovation for recumbent bicycle steering mechanisms focus on the wheelbase and location of the bar.

3.2.2.3.1 Existing Design #1: Short Wheelbase

Shorter wheelbase designs allow the rider to take a smaller turning radius at lower speeds due to the higher head angle at which the steering column connects to the frame. Within this design, the pedals have to be placed above the front wheel to accommodate for the length of the riders' legs. This design tends to hold the weight of the rider at a more central point in comparison to a longer wheelbase, this results in a more stable ride. Problems seen with this design include the drive chain since it has to run at several angles and lengths for versatility. While creating designs, the team decided that doing the short wheelbase with the smaller front wheel size will result in greater maneuverability and innovation points within competition.

3.2.2.3.2 Existing Design #2: High Bar Steering

High bar steering designs place the steering column and handlebars above the rider. The head tube length is long in comparison with regular bicycle columns and can cause less stability when turning corners by having the human input be higher than the center of gravity. This design will have to extend and shorten with the pedal length. Because of the connection to the front wheel, tight corners cannot be taken with high bar steering. The team has discussed this extensively due to the eight-meter turn radius the HPV has to complete in order to enter the competition.

3.2.2.3.3 Existing Design #3: Low Bar Steering

Low bar steering designs refer to handlebars placed below the rider. This creates a steering mechanism that is attached directly to the main frame of the vehicle and does not incorporate the direct drive as the high bar steering does. The two lever arms have tie rods connect to a triangle, with the high point of the triangle directing the steering by leaning the triangle with whichever lever is pulled up. Most recumbent bicycles do not have this design because of the complications during assembly and the continuous maintenance that has to be done to keep them in line.

4 CONCEPT GENERATION

The team has completed multiple iterations of concept generation. These combined concepts are outline in Section 4.1 along with the advantages and disadvantages of each design. This section presents the team's top three designs. Next, Section 4.2 dives into energy storage, steering methods, and braking. This section discusses the various options for the vehicle.

4.1 Full System Concepts

The three full system design concepts are a two-wheeled upright vehicle, a three-wheeled recumbent, and two-wheel recumbent. Based on research carried out by the team, these are the three most common and successful variations of human powered vehicles.

4.1.1 Full System Design #1: Two-Wheeled Upright

This design has the most in common with a standard bicycle. The rider sits upright and uses his/her momentum to maintain balance and steer into turns. This design has numerous benefits. It is very familiar to most people and has been researched extensively. There is a vast amount of information available for the design of upright bicycles. The learning curve of operating this type of vehicle is very low. They are nimble and somewhat stable at high speeds.

Pros:

- Common place
- Easy to operate
- Prior research
- Capable of high speeds
- Highly maneuverable
- Lightweight

Cons:

- Not much room for innovation
- Limited cargo capacity
- Not stable at very high speeds (>45 mph)
- Rider at high risk of injury
- High center of gravity

4.1.2 Full System Design #2: Three-Wheeled Recumbent

This design is the most stable and easiest to use of the three being considered. There is no need to balance in order to mount or dismount this type of vehicle. The three points of contact also distribute loads out over a larger area which reduces overall impact of payload weight on the ride characteristics of the vehicle. Weight and steering systems are common issues with these vehicles.

Pros:

- Very easy to use
- Stable at very high speeds
- Good for hauling weight
- Lowest center of gravity
- Many systems for innovations
- Reduced risk of rider injury
- Comfortable

Cons:

- Heavy
- Difficult to maneuver
- Possibility of rollover

4.1.3 Full System Design #3: Two-Wheeled Recumbent

This design is a compromise between the previous two designs. The recumbent position yields a very low center of gravity along with a comfortable riding position. Steering and tilting is still allowed which greatly increases the maneuverability of the vehicle. This is probably the least intuitive form to operate and will likely take time to master.

Pros:

- Light
- Maneuverable
- Comfortable
- Room for innovations
- Aerodynamic
- Low center of gravity

Cons:

- Hardest to operate
- Rider prone to injury without roll cage

4.2 Subsystem Concepts

In this section, various subsystems that are essential to the performance of a human powered vehicle will be presented. Each subsystem design will be accompanied by a list of pros and cons that will be used and compared against others to determine if the options are viable. Analysis using decision matrices will be used in the future to determine which option, if any, is superior and worth the investment.

4.2.1 Subsystem #1: Energy Storage

4.2.1.1 Design #1: Flywheel

A flywheel can be used to store excess rotational energy that can be utilized by the operator at opportune moments to increase power output or reduce fatigue. Including a flywheel will increase weight and will interfere with steering due to the high angular velocity and gyroscopic precession.

Pros:

- Store useful mechanical energy
- Temporarily increase power output

Cons:

- Heavy
- Hinders steering

4.2.1.2 Design #2: Battery

A battery can be used to operate numerous auxiliary systems. It can be used to drive motors and actuate various devices all around a vehicle without any bulky mechanical linkage. Batteries themselves can be heavy and as per the competition rules, must be charged by the act of powering the vehicle.

Pros:

- Allows the use of lights
- Can be used to charge motors
- Opens use of Arduino, steppers, servos, and switches
- Compact

Cons:

- Must be charged by human power
- Storage is limited
- High output batteries can be heavy and bulky

4.2.1.3 Design #3: Pneumatic/Hydraulic

Pneumatic or hydraulic cylinders can be used to drive different mechanisms such as brakes and motors.

Pros:

- Stores mechanical energy for later use
- Innovative and creative

Cons:

- Low efficiency
- Low return on energy investment

- Can be prone to leaking which renders system ineffective
- Performance effected by ambient temperatures and pressures

4.2.2 Subsystem #2: Steering Method

The different steering methods below are essential to how the rider will convey which way they will want the bicycle to turn. The decision on which steering method will be used relies on the weight of the rider above the handlebars and within reach of the riders' comfort level.

4.2.2.1 Design #1: Crown Steering

Crown steering provides two levers for the rider at either side of their hips. These rods are attached to a crown at the base of the front of the frame. When one lever is pushed forward, this turns the crown and wheel in direction of the lever.

Pros:

- Consistent
- Easy to turn at slower speeds

Cons:

- Uncomfortable
- Mounting is harder
- Start off takes more practice
- Harder to manufacture
- More maintenance

4.2.2.2 Design #2: Standard Bicycle Handlebars

The standard bicycle handlebars come off as a T from the head tube. It provides the ability to sit upright and to reach the brakes and gear change easily and steering is made of small arm movements. This method is in line with the head tube and fork.

Pros:

- Cheap
- Easy assembly
- Brake easily available
- Gear selector easily available

Cons:

- Less control turning
- Uneven weight distribution of rider
- Rider prompted to sit upright

4.2.2.3 Design #3: Racing Handlebars

Racing handlebars lean over the front of the bicycle and help to distribute the weight of the rider to become more aerodynamic. This method is shaped in a Y formation with both handles curving down to provide the rider with comfortable rests for the forearms.

Pros:

- Built for comfort
- Rider weight distributed easier
- Steering is more fluid
- Easily manufactured
- Easy mounting
- Cheap
- Brake easily available
- Gear selector easily available

Cons:

- Enables the rider to sit forward
- More components

4.2.3 Subsystem #3: Braking

There are several methods of applying braking torque to a human powered vehicle. However, because the vehicles tend to be heavier than standard bicycles, higher torques are needed in order to come to a complete stop. Additionally, these systems must be redundant because the consequences of failure at high speed are likely to cause severe injury.

4.2.3.1 Design #1: Rubber Friction Brakes

Common on inexpensive bicycles. These brakes consist of rubber pads that ride on the rim of the front and rear wheels. The provide moderate braking forces and function well when dry. They are also the simplest and cheapest option.

Pros:

- Cheap
- Simple

Cons:

- Ineffective when wet
- Braking torque is low
- Can overheat and melt

4.3.2.2 Design #2: Rotor and Caliper Friction Brakes

Rotor and caliper brakes utilize a rubber pad like the previous design but are actuated on a rotor that is separate from the wheel and a much smaller diameter. These are much more effective in wet conditions and are less affected by heat.

Pros:

- Medium braking torque
- Effective when wet or dirty
- Higher temperature tolerance

Cons:

- Rotors can be damaged or bent

4.3.2.3 Design #3: Hydraulically Actuated Rotor and Caliper Brakes

These are the most powerful brakes available on most human powered vehicles. Complexity and price are the deterring factors for these systems but oftentimes the benefits are worth the cost. They are driven by a hydraulic piston similar to brakes on a car.

Pros:

- Highest braking torque
- Effective when wet or dirty
- Higher temperature tolerance

Cons:

- Expensive
- More complex
- Hydraulic fluid can leak and render system ineffective

5 DESIGNS SELECTED – First Semester

Chapter 5 is a discussion of the technical selection criteria, and rationale for design selection. For this, a Pugh Chart and Decision Matrix are used and detailed in section 5.2.

5.1 Technical Selection Criteria

The main technical criteria used in comparing the designs are the turning radius, innovation, ergonomics, time to mount/dismount, and safety. The turning radius is important to the design selection since the vehicle must be able to turn within 8 meters and handle the endurance race turns (Commitee, 2020). The turning radius determines one aspect of the maneuverability. Next, the innovation is important due to the ASME HPVC allows points for innovation. Any various aspects of our design compared to previous designs allow us to stick out for originality. Subsequently, the ergonomics of the design are essential since the design needs to cater to a human. This criterion becomes important in the endurance race since the vehicle must be operated for two hours (Commitee, 2020). On a similar note, the time to mount and dismount becomes important when the rider must stop and go to pick up cargo and transport it (Commitee, 2020). Any extra time the rider has to spend mounting and dismounting counts against our design because that is time wasted where the vehicle could be gaining speed and distance. Lastly, safety is imperative to the list of criteria and is a large aspect of this project. The safety aspect refers to the operation of the vehicle as well as the safety in case of an incident. This point is further highlighted where the ASME HPVC rules ask each team to perform an analysis for the roll cage and stored energy system (Commitee, 2020). Both the competition and customer ask that the design be built safely and explained through the report.

5.2 Rationale for Design Selection

Decision matrices represented in figure 5.1, 5.2 and 5.3 were used to select between tandem vs single rider, designs based on wheel count and between upright and recumbent designs. Single rider, 2-wheel recumbent concepts scored the highest points in each decision matrix.

Criteria	Weight	Tandem	Single	
Speed	12	9	9	
Uphill climbing	7	1	3	
Braking	15	9	9	
Weight	7	1	9	
Length	7	3	9	
Position of Riders	5	3	3	
Stability	12	3	9	
Acceleration	9	3	9	
Innovation	15	9	1	
Mounting Time	11	3	3	* could be rated the same as acceleration or even lower than acceleration
Total	100	44	64	
Weighted Totals		0.44	0.64	

1	Poor
3	Average
9	Good

Figure 5.1: Decision matrix created to evaluate tandem and single rider designs

		Metric	Weight	2WD-1-1	3WD-1-2	3WD-2-1	Design Idea 4
Weight (1, 3, 9)	1	Stationary Balance	6	3	9	9	
1 - poor	2	Turning Radius	10	9	3	3	
3 - average	3	Ackerman Angle	3		3	9	
9 - good	4	Safety	9	1	3	3	
	5	Steering	8	9	1	3	
Blank Cell = N/A	6	Leaning	7	9			
	7	Braking	10	1	3	9	
	8	Straight Stability	8	3	1	9	
	9	Contact Area	9	3	1	3	
	10	Mounting (getting on the design)	7	1	3	9	
	11	Innovation	10	9	3	3	
	12	Weight	9	9	3	3	
	13	Drag	4	9	1	3	
	14						
		Raw Score		527	257	483	0
		Relative Rank		1	3	2	4
		Sum	100				

2WD-1-1	2 Wheel Design, 1 tire in front, 1 tire in back
3WD-1-2	3 Wheel Design, 1 tire in front, 2 tires in back
3WD-2-1	3 Wheel Design, 2 tires in front, 1 tire in back

Figure 5.2: Decision matrix used evaluate designs based on wheel count

		Upright	Recumbent	Upright	Recumbent
Criteria	Weight	Unweighted Scores		Weighted Scores	
Rolling Stability	10	3	3	30	30
Braking Stability	11	1	9	11	99
Mounting	10	3	3	30	30
Payload	9	3	9	27	81
Weight	10	9	1	90	10
Innovation	11	3	9	33	99
Safety	10	1	9	10	90
Turning Radius	10	9	9	90	90
Hill climbing	9	9	3	81	27
Acceleration	10	9	9	90	90
Total	100	50	64		
Weighted Totals		492	646		

Scale	
1	Poor
3	Average
9	Good

Figure 5.3: Decision matrix used to decide between upright and recumbent concepts.

A Pugh chart (Figure 5.4) was then used to evaluate the three main design concepts, namely, two-wheel upright, two-wheel recumbent and three-wheel recumbent. The datum selected for the analysis was the two-wheel upright design as it can be defined as the most neutral concept. The criteria used were derived from the customer and engineering requirements. The positive sign conveys that the design performs well in specific criteria compared to the datum. The “S” symbol was used represent same performance in its respective criteria’s relative to the datum. Lastly, the negative sign was used to convey criteria that were expected perform poorly compared to the datum.

Criteria/ Concept	Two wheel Recumbent	Two Wheel upright	Three Wheel recumbent
Durable and robust	+		+
Aerodynamics	S		S
Reliability	+	D	-
Low cost	-	A	-
High Speed	S	T	-
Maneuverability	+	U	-
Cargo space	+	M	+
Field of view	+		+
Weight	-		-
Fits multiple riders	S		S
Ergenomics	+		+
Saftey of the rider	+		+
Final Score	7		5

Figure 5.4: Pugh Chart

As stated in section 4, three-wheel recumbent design allows space for a payload, reduce the risk of rider injury, allows wide view for the rider and the shape allows the design to have lower drag. Therefore, it scored positives for cargo space, field of view, safety of the rider and durability. The two-wheel recumbent design scored positives for being more durable, reliable, for being spacious (cargo), maneuverable and for having a greater field of view (the recumbent seating position gives driver the comfort to have a wider field view). In conclusion, two-wheel recumbent design was chosen as the final design concept as it scored the highest points in the Pugh chart analysis.

REFERENCES

Hadland, T., & Lessing, H.-E. (2014). *Bicycle Design.* Cambridge, Massachusetts: The MIT Press.

Azman, A. M., Haziq, A. R., Zakwan, A. M., Anuar, S. S., Redza, R. F., & Nizam, S. M. (2016). Ergonomic study on human-powered vehicles. *MATEC Web of Conferences.*

Balasubramanian, V., Mohan, J., & Kanagasabai, A. (2014). Muscle fatigue based evaluation of bicycle design. *Applied Ergonomics, 45*(2), 339-345.

Hsiao, S.-W., Chen, R.-Q., & Leng, W.-L. (2015). Applying riding-posture optimization on bicycle frame design. *Applied Ergonomics, 51*, 69-79.

Kato, M., Tsutsumi, T., Yamaguchi, T., Kurakane, S., & Chang, H. (2011). Characteristics of maximum performance of pedaling exercise in recumbent and supine positions. *Journal of Sports Science and Medicine, 10*(3), 491-497.

Hart, B. (2019, October 30). *Gears Galore: A Look At Current Drivetrain Options*. (Rodriguez Bike News) Retrieved June 18, 2020, from http://www.rodbikes.com/blog/gears-galore-a-look-at-current-drivetrain-options/.

CeramicSpeed. (2018, July 9). *World's most efficient' bicycle drivetrain unveiled at Eurobike*. (New Atlas) Retrieved June 18, 2020, from https://newatlas.com/ceramicspeed-driven-shaft-drive/55364,

Technology, N. (n.d.). *Fallbrook Technologies Inc*. (Fallbrook Technologies Inc) Retrieved June 18, 2020, from https://www.fallbrooktech.com/nuvinci-technology/

Headset Standards. (2015, August 17). (Park Tool) Retrieved July 18, 2020, from https://www.parktool.com/blog/repair-help/headset-standards

Yeager, S. (2019, May 14). *What Should Your Ideal Cadence Really Be?* (Bicycling) Retrieved July 1, 2020, from https://www.bicycling.com/health-nutrition/a27454779/cycling-cadence-ideal/

R. G. Budynas, J. K. (2015). *Shigley's Mechanical Engineering Design.* New York: McGraw Hill Education.

Stott, S. (2018, August 17). *The Ultimate Guide to Bike Geometry and Handling*. (Bike Radar) Retrieved from https://www.bikeradar.com/features/the-ultimate-guide-to-bike-geometry-and-handling/

Wikstrom, M. (2018, November 28). *The Geometry of Bike Handling: It's All About the Steering* . (Cycling Tips) Retrieved from https://cyclingtips.com/2018/11/the-geometry-of-bike-handling-its-all-about-the-steering/

Lignoski, B. (2002). *Bicycle Stability, Is the Steering Angle Proportional to Lean?* Wooster, Ohio: Physics Department, The Colleger of Wooster.

Bicycle Frame & Component Failures - Expert Article. (2015, July 7th). (The Experts Robson Forensic) Retrieved from https://www.robsonforensic.com/articles/bicycle-frame-component-failures-expert-article

Toll, M. (2018, 4 24). *Regenerative braking: how it works and is it worth it in small EVs?* (electrek) Retrieved July 4, 2020, from https://electrek.co/2018/04/24/regenerative-braking-how-it-works/

EBikes, P. (2017, 3 26). *Regen braking on eBikes - is it worth it?* (Panda Ebikes) Retrieved 7 8, 2020, from https://www.pandaebikes.com/regen-braking-ebikes-worth/

Greenemeier, L. (2011, 6 24). *A Bike That Uses Its Brakes For a Speed Boost (and Other Student Engineer Inventions)*. (Scientific American) Retrieved 7 14, 2020, from https://blogs.scientificamerican.com/observations/a-bike-that-uses-its-brakes-for-a-speed-boost-and-other-student-engineer-inventions-video/

Matthews, D. (2020, 3 13). *Flywheels 101: Choose teh Best Flywheel for your Engine and Application*. (Summit) Retrieved 7 14, 2020, from https://www.onallcylinders.com/2020/03/13/flywheels-101-choose-the-best-flywheel-for-your-engine-and-application/

Tang, N. (2000). Plastic-deformation analysis in tube bending. *Pressure Vessels and Piping, 77*, 751-759.

Raymond Kozak, M. S. (1996). DESIGN AND FABRICATION OF A COMPOSITE HUMAN POWERED LAND VEHICLE . *Proceedings of the 41st International SAMPE Symposium and Exhibition*.

Supat, B. K. (2010). *ASME Human Powered Vehicle* . San Luis Obispo.

H. K. Epemaa, S. v.-J. (2012). Bicycle Design: A different approach to improving on the world human powered speed records . *9th Conference of the International Sports Engineering Association (ISEA) , 34*, 313-318.

D'Aluisio, C. P. (2011, October 25). *U.S. Patent No. US 8,042,822 B2* .

Commitee, A. H. (2020). Rules for the 2021 Human Powered Vehicle Challenge. American Society of Mechanical Engineers.

(2015). *2015 ASME East Coast HPV Challenge.* Rose Hulman Institute of Technology.

Cruzbike. (2019, April 29). Retrieved July 19, 2020, from https://cruzbike.com/blogs/blog/introducing-magic-carbon-fiber-front-wheel-drive-racing-recumbent

HPVC, A. (2020, January 30). *Human Powered Vehicle Challenge.* Retrieved July 19, 2020, from https://efests.asme.org/competitions/human-powered-vehicle-challenge-(hpvc)

M. Alan, P. Aumann and T. Helmann, (2015*),"Human Powered Vehicle Frame Design"*, Digitalcommons.calpoly.edu

B. Warren, *"The Recumbent Bicycle and Human Powered Vehicle Information Center*", Recumbents.com, `

R. Nelson, (2010), *"Aerodynamic Fairing for a Human Powered Vehicle"*, Rich Nelson

Smith, R. Canta, T. Rajala, M. Rice and D. Paquin (2010), "2010 Human Powered Vehicle 2010 Human Powered Vehicle".

M. Gewaily, M. Esmael, A. Atef Diab, M. Hamied, K. Elshayeb and M. Moustafa, M. Faramawy, A. Hassouna, (May 2017*),"CFD analyzing for the aerodynamics of different car models"*, Researchgate