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A Systematic Approach to Human Powered Vehicle Design with an Emphasis on Providing Guidelines for Mentoring Students

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A SYSTEMATIC APPROACH TO HUMAN POWERED VEHICLE DESIGN WITH AN EMPHASIS ON PROVIDING GUIDELINES FOR MENTORING STUDENTS

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Mechanical Engineering

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by
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ABSTRACT

The objective of this research is to provide guidebook that approaches the design of a human powered vehicle (HPV) from a systematic view for an ASME competition. The guidebook introduces students to design and enhances their current understanding related to design, general engineering principals, and engineering principals specific to HPVs. In terms of the design process a combination between the traditional design process and the systems engineering design process is discussed. From here the design process in broken into six main sections for the guidebook, and an evaluation section used to emphasis the usefulness of the guidebook.

First an overall view of the traditional and system engineering design processes are given, along with an overview of the human powered vehicle competition (HPVC). This is followed by details of project planning and problem development. Next the conceptual stage is introduced where concept generation and evaluation methods and examples are discussed. Embodiment design is given in the following section, where solution variants are modeled in a preliminary layout. Next, methods of how to create a more defined preliminary layout are given in the detail design section were a definitive layout is established. Finally prototyping, testing, redesigns, and final design recommendations are outlined in the last section.

In addition, the guidebook provided is meant to serve as a method that can be used to mentor students in the design process of an HPV. As such, the guidebook has been developed through a literature review of design theories, managerial, organizational, and engineering practices that have had beneficial impacts, and past experiences with designing HPVs. In terms of past experiences, the interactions with students involved in a creative inquiry at Clemson University have used as a subjective means to outline some of the important design considerations needed to be discussed. Additionally, Clemson’s HPVs have primarily consisted of tadpole tricycles and as such, a more in depth analysis is included for this particular HPV style.

ACKNOWLEDGEMENTS

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CHAPTER ONE: INTRODUCTION TO DESIGN

Engineering design is the iterative process of creating a product to solve a defined problem through the use of concept development, analysis, prototyping, and product realization. The paper will focus on the “traditional” engineering design process and a systems design process [1,2]. The traditional design process includes the basic steps of formulating a problem, creating requirements for a solution to the problem, concepting solutions, developing those solutions into a final product, and evaluating the final design. The system engineering design process is similar to the traditional design process, but focuses more on thorough documentation and detailed planning to ensure system collaboration and timely product completion.

This paper will focus on a detailed design process through the subject of human powered vehicles, or HPVs. HPV design is the design of a transportation device that is powered by human energy. Bicycles, kayaks, paddle boats, human powered aircrafts, and skateboards are all examples of HPVs. To narrow the range of topics the paper focus more on bicycle and tricycles designs. HPVs were chosen as a focus area because they represent a complex system, which is understandable and relatable.

The goal of the paper is to create guidelines for HPV design. The guidelines will be used to mentor students in the design process and assist in developing an understanding for HPV design. The system aspect of HPVs will allow for the introduction to systems design. Design tools used throughout the process will be explained to impart additional understanding of the different stages of design, the importance of those stages, and a method of how to approach those stages. The guidelines provided are the result of research combined with hands on experience while designing and manufacturing HPVs. The subsequent chapters will discuss the design phases more comprehensively, to allow for a full understanding of the design process and the aspects of HPV design throughout the process.

Lastly, the guidelines presented were created to assist students in the annual human powered vehicle challenge (HPVC) sponsored by ASME. The HPVC allows universities to race HPVs against each other and compete for the best designs. Student teams competing are judged on their vehicle design, their design process, and their racing efforts. In summary, the research goals and accompanying objectives of this paper are presented in table 1.1.

Table 1.1 Research goal and objectives

Goal	Provide a guideline for the HPV system design process that helps mentor students in systems engineering design and traditional design methods
Objective 1	Give an understanding of traditional and systems design methods
Objective 2	Provide discussions and examples for each the design stages
Objective 3	Outline useful design tools and methods for students
Objective 4	Discuss an evaluation system for the design process established in the guidelines

1.1 Traditional Design Methodologies

Pahl *et al* summarize the traditional design process in figure 1.1 [1]. The main phases of the design process are planning and task clarification, conceptual design, embodiment design, and detailed design. The planning and task clarification phase is comprised of the problem definition, requirements, and project planning. Problem definition is creating the objective or mission statement for a project. For example, designing a bicycle that allows users to commute to work. Requirements structure the way the problem needs to be solved. For example, a requirement stating the bicycle must cost less than $300 to produce, means the solution must be affordable.

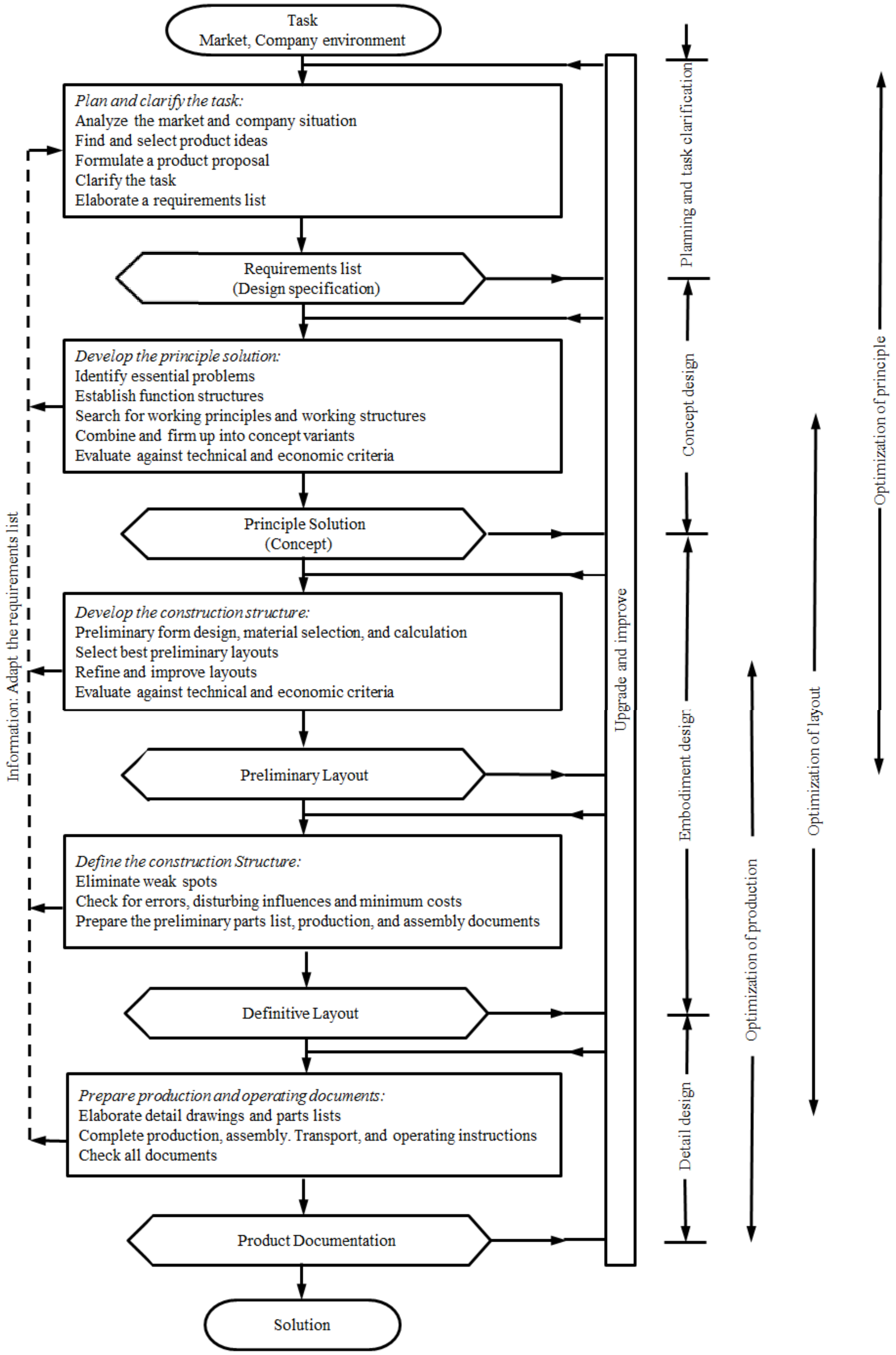


Figure 1.1 Traditional Design Process [1]

Project planning gives management to how the problem should be solved. Elements of planning include scheduling, resource allocations, and estimating product costs.

The conceptual design phase involves creating solution variants or concepts to satisfy the design problem. Different concepting methods can be used to produce solution variants. Commonly used methods include brainstorming, using morphologically charts, the gallery method, functional models, and the 365 method. All of the methods are explained with more detail in chapter three. Concept selection methods are used to identify the solution variants that have a substantial likelihood of optimally completing the design process. The selected solution variants are then used in the embodiment design phase.

During embodiment design selected solution variants are modeled into detailed solutions. A preliminary layout is created to establish a general form of the solution variant. For example, a preliminary layout for a bicycle could include two wheels, a frame between the wheels, a seat attached to the frame, pedals for movement, and handlebars for steering. This is accomplished by reviewing the available information including but not limited to requirements, known geometrical sizes, and interfacing abilities, while adapting the solution variants for appropriate spatial considerations. Through extensive analysis the preliminary layout becomes more defined and a definitive layout is created. The result of the definitive layout is a fully developed idea which can be analyzed for prototyping, production, and project viability. For example, the definitive layout for the frame of a bicycle would include the geometric layout of the frame, all dimensions, structural analysis, material selection, manufacturing, and further analysis that have been conducted.

Once the embodiment phase has been completed, the detail design phase involves completing the necessary documentation for a realized product solution. Examples of documentation include assembly drawing, configurations, part drawing, budget analysis, requirements evaluation, product safety evaluations, and manufacturing details.

1.2 System Engineering Design Process

The systems engineering design process is similar to the traditional design process, but with additional focus on product realization and technical management. The life cycle process of systems engineering is shown in figure 1.2. The pattern of problem formulation, concept development, design embedment, and detailed design still apply through the phases between A and F, but in systems engineering product approval does not begin until after most of the embodiment and detailed design has occurred. After this point, product realization begins, when product fabrication, performance assessments, and eventual discontinuation or decommission occur.

Table 1.2 describes the purpose and outcome of each of the phases. Figure 1.2 shows how the role of technical management impacts the systems engineering process through the technical development and technical management rows. The numbers in the boxes of those rows indicate different technical documents that require completion. Throughout the process specific documents are required to verify the product is being analyzed properly and all details of the design process are documented. The technical documents and preliminary design required for approval minimizes the risk associated with the product prior to product is launch.

To further the approval process figure 1.3 maps out the systems engineering engine used to define the stakeholders, or customer expectations, by creating technical requirements using expectations, and establishing a design solution based on those requirements. The proposed design solution should then meet the established expectations. Throughout the design process reviews should occur to assess the quality of the product design in its current state and verify it is meeting all necessary requirements. Figure 1.4 outlines some of the reviews NASA requires throughout the design process and when the review should occur in relation to the product life cycle. Some of the more common reviews include peer, mission, systems requirements, and systems integration reviews.

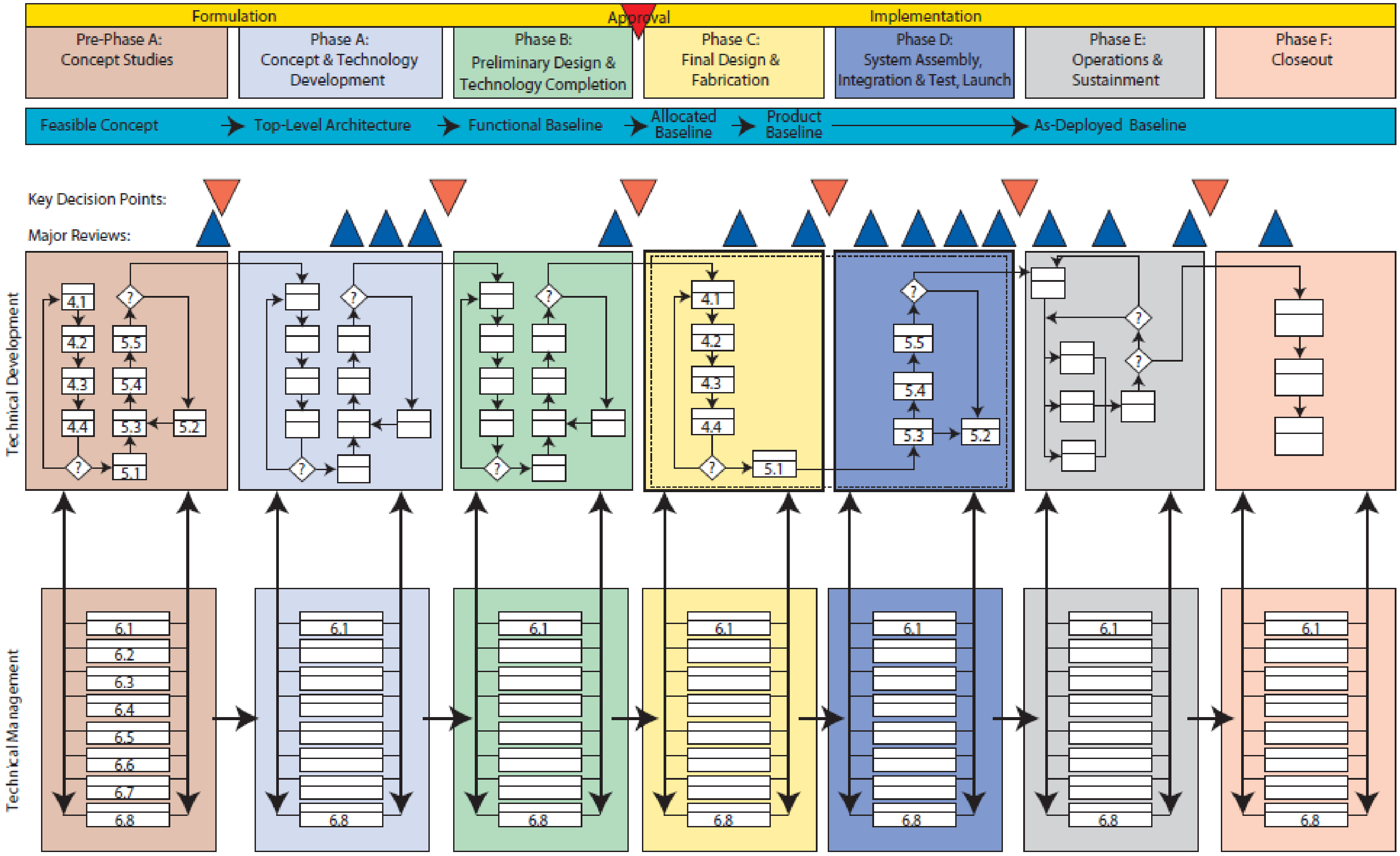


Figure 1.2 Systems engineering life-cycle process flow[2]

Table 1.2 Systems engineering phases and purpose [2]

Phase		Purpose	Typical Output
Formulation	Pre-Phase A: Concept Studies	To produce a broad spectrum of ideas and alternatives or missions from which new programs/projects can be selected. Determine feasibility of desired system, develop mission concepts, draft system-level requirements, and identify potential technology needs.	Feasible system concepts in the form of simulations analysis, study reports, models, and mockups
	Phase A: Concept and Technology Development	To determine the feasibility and desirability of a suggested new major system and establish an initial baseline compatibly with NASA's strategic plans. Develop final mission concept, system-level requirements, and needed system structure technology developments.	System concept definition in the form of simulations, analysis, engineering models, and mockups and trade study definition
	Phase B: Preliminary Design and Technology Completion	To define the project in enough detail to establish an initial baseline capable of meeting mission needs. Develop system structure end product (and enabling product) requirements and generate a preliminary design for each system structure end product	End products in the form of mockups, trade study results, specification and interface documents, and prototypes.
Implementation	Phase C: Final Design and Fabrication	To complete the detailed design of the system (and its associated subsystems, including its operations systems), fabricate hardware, and code software, Generate final designs for each system structure end product.	End product detailed designs, end product component fabrication, and software development
	Phase D: System Assembly, Integration and Test, Launch	To assemble and integrate the products to create the system, meanwhile developing confidence that is will be able to meet the system requirements. Launch and prepare for operations. Perform system end product implementation, assembly integration and, transition to use.	Operation-ready system end product with supporting related enabling products.
	Phase E: Operation and	To conduct the mission and meet the initially identified need and maintain support for the need. Implement the mission operations plan.	Desired System
	Phase F : Closeout	To implement the systems decommissioning /disposal plan developed in Phase E and perform the analyses of the returned data and any returned samples.	Product closeout

In the systems engineering design process the final product is actually a combination of products joined together to create a complete system. To organize the products throughout the design process a product hierarchy is created as shown in figure 1.5. The different tiers of the

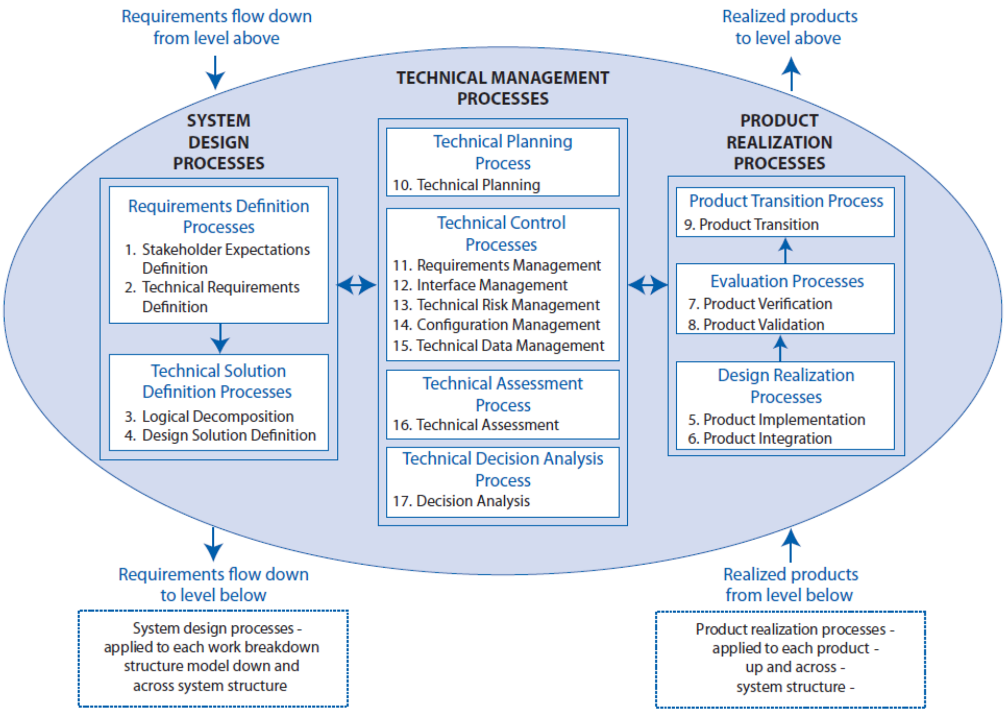


Figure 2.1-1 The systems engineering engine

Figure 1.3 Systems engineering engine [2]

CDR	Critical Design Review	PLAR	Post-Launch Assessment Review
CERR	Critical Events Readiness Review	PRR	Production Readiness Review
DR	Decommissioning Review	P/SDR	Program/System Definition Review
FRR	Flight Readiness Review	P/SRR	Program/System Requirements Review
KDP	Key Decision Point	PSR	Program Status Review
MCR	Mission Concept Review	SAR	System Acceptance Review
MDR	Mission Definition Review	SDR	System Definition Review
ORR	Operational Readiness Review	SIR	System Integration Review
PDR	Preliminary Design Review	SRR	System Requirements Review
PFAR	Post-Flight Assessment Review	TRR	Test Readiness Review
PIR	Program Implementation Review		

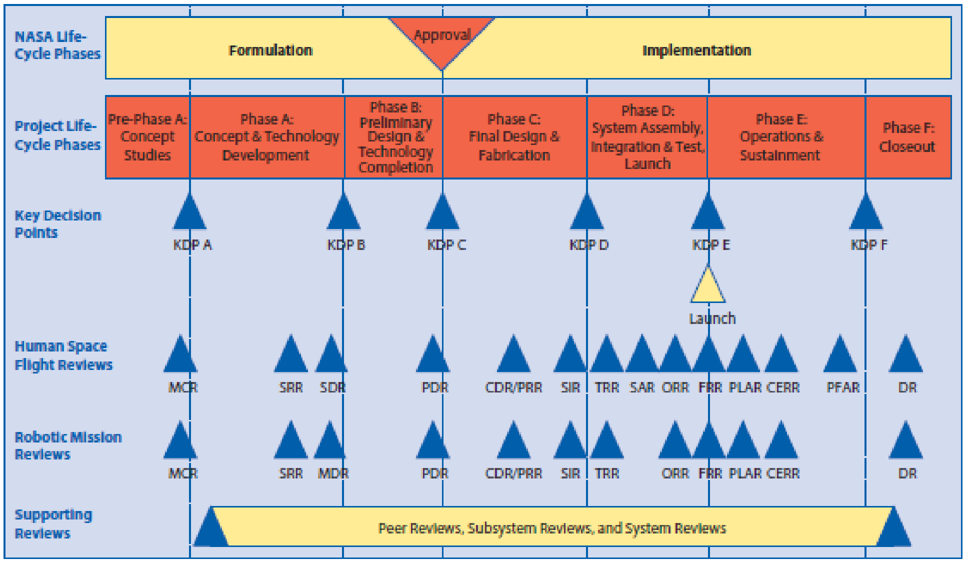


Figure 1.4 Project life cycle [2]

product hierarchy reflect the level of assembly and component details. Components in the highest numbered tier are detailed components such as circuit boards. Elements in the lower numbered tiers are sub-assemblies of the system, such as the avionics system of tier 2 in figure 1.5. Elements in tier 1 could be considered sub-systems, because they are the high level subassemblies of the overall system. Creating the product hierarchy helps to detail the functionalities involved with the system and methods of incorporating them. Additionally, the product hierarchy allows for a division of resources. Meaning task resources can be allocated to components, sub-assemblies, or sub-systems according to predicted amount of effort required. Upgrades in components or sub-assemblies lead to new developments in the overall systems. It may also require design changes to corresponding components and sub-assemblies.

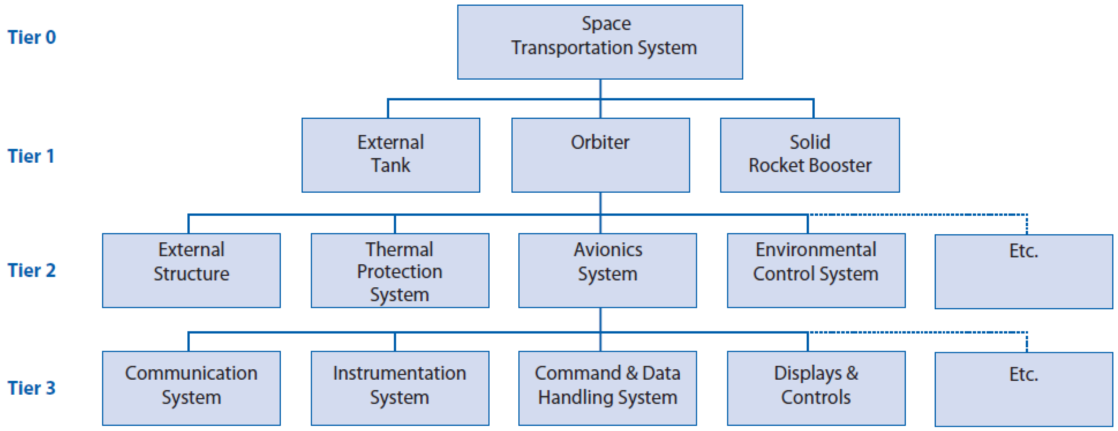


Figure 1.5 High level product hierarchy example of space transportation system [2]

1.3 Introduction to Human Powered Vehicle Design

Human powered vehicles are relatively simplistic systems. As a result, the HPV design process recommended will include elements of the traditional design process and the systems engineering design process. To begin explaining an HPV System the high level product hierarchy is outlined in figure 1.6. The four main subsystems of HPV design are the structure, the controls, the power supply, and performance factors.

The structure entails the body of the vehicle, including the wheels, the general layout, connections for the other subsystems, a roll protection system if required, and the seating for the rider. The general layout, number of wheels, and wheel locations can be useful in determining the types of HPVs. Common HPV designs include three or two wheeled designs. These designs are preferred, because additional wheels add more complexity to the design. Four wheeled vehicles are the most stable stationary, but when turning there is a greater chance of problems occurring, unless the steering alignment is highly accurate and the two non-driven wheels can rotate at different speeds. This can also be true for three wheeled vehicles, but in tricycle design one wheel is typically centered in the vehicle which simplifies the overall design. Different structural layouts include the traditional bicycles, recumbent bicycles, two front wheeled tricycles (tadpole trike), two back wheeled tricycles (delta trike), velomobiles, and tilting trikes [3].

The main structure is responsible for providing seating support for the rider. More accommodating seating supports allow for various adjustments to address the difference in rider body styles. Harnesses can be added to secure the rider in place. A roll protection system, RPS, can be added to protect the rider in the event of a roll over or vehicle collision. Harnesses and RPSs are required for the ASME HPVC events.

The power supply subsystem accounts for how the vehicle is powered and how energy is generated. Most HPVs use a crank system for the power supply which is typically powered using a rider’s feet and legs. Other types of power supply systems include the use of hand cranks or rowing systems. The transmission of the HPV involves a power modification to change the ratio of the wheel rotation to the crank rotation. Typical transmission systems can involve a cassette and crank, both of which are a combination of different sized gears. The gears are connected using a chain. Changing the gears connected to the chain effectively changes the amplification of the transmission system. Energy recovery systems can also be added to the power supply subsystem. Some of the more commonly used recovery systems include a flywheel mechanism, regenerative braking, and electric motors.

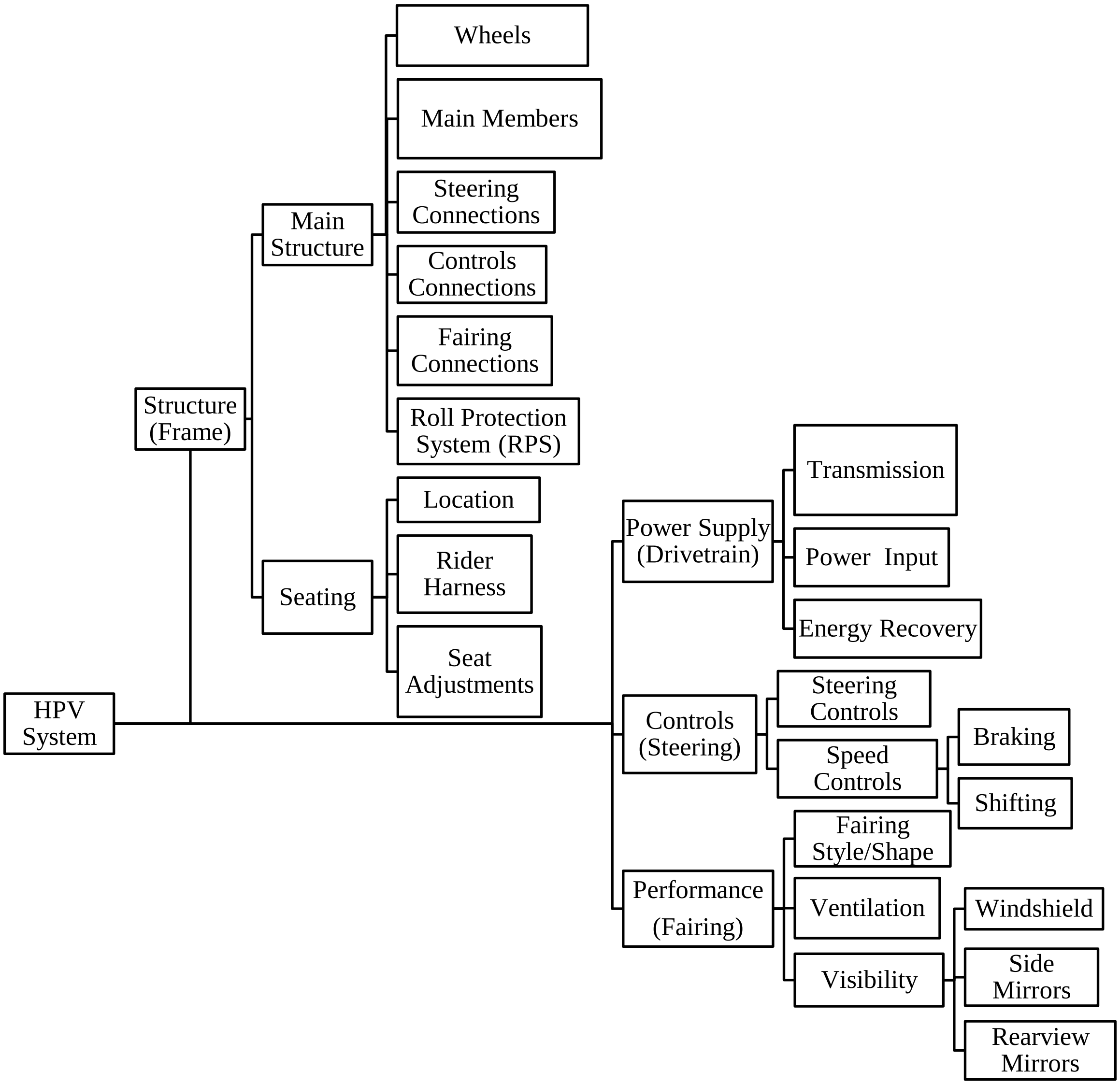


Figure 1.6 High level product hierarchy HPV

The controls of HPV design involve the user's ability to steer the vehicle, adjust the transmission, and being able to apply the brakes. The steering controls have a range of different methods that can be applied towards HPVs. The most commonly known method is the use of handlebars for bicycles or some unique handlebar configuration. In other words, bicycle designs often involve a rotating handle that is connected directly to the wheel. The steering designs for tadpole tricycles are often more complicated. Under seat steering, direct knuckle steering, and the use of steering linkage systems are common for tadpole tricycle designs [4]. Steering linkage systems involve a combination of tie rods and drag links to allow for one control arm (i.e. handlebar) to control the steering of both front wheels. More details on steering configurations will be discussed later. Depending on the design, delta tricycles may be able to make use of a handlebar steering configuration similar to a common bicycle.

Transmission adjustments are controlled using shifters. Shifters come in different styles as well. For example there are bar-end shifters, twist grip, trigger shifters, shifter integrated with brake levelers, and electronic shifters. Similarly brake controls come in different styles and types. Rim brakes, drum brakes, disc brakes, and coaster brakes are the main braking methods used in HPV design [5]. For bicycle designs it is highly recommended both wheels have brakes. Some exceptions include track bicycles where only one brake is required, tandems bicycles where three brakes are recommended from the high weight, and tricycles. Some tadpole trikes are recommended to have independent front brakes and no rear brake, for better performance in cornering. Delta tricycles have been seen with two hand brakes on the front wheel. Delta tricycles may have one driven real wheel and only have brakes on that wheel. Regardless, there should always be brakes on the front wheel(s). Controls for the brake often include pulling a lever to apply cable tension, thus applying the brakes. Lastly, if energy recovery systems are added users controls may be required, such as a control for engaging a flywheel by connecting a jack shaft or pushing a button to disperse energy from an electric motor. On the other hand power assistance methods could be used to automatically assist the pedaling of the user, which is commonly done for hybrid vehicle designs.

The performance subsystem includes adding elements for aerodynamic advantages or ergonomic benefits. Fairings can be full or partial structures that cover the vehicle in order to reduce drag. Common materials involve plastic, sheet metal, or carbon fiber. Fully enclosed vehicles are also known as velomobiles. In addition to providing drag reduction, fully covered vehicles may provide weather and collision protection. Wheel wells, human position, helmets, and general vehicle configurations can also be used to reduce aerodynamic drag. Appendix A outlines a more in depth review concerning human power, ergonomic factors, safety considerations, aerodynamic benefits, ventilation, and visibility.

The ASME HPVC is an annual event in which students from various universities design HPVs and compete. There are four major parts to the event; a design portion, an innovation portion, a speed event, and an endurance race. ASME provides a detailed discussion of ASME design requirements, innovation details, and race specifications [6]. Table 1.3 summarizes the design requirements given by the ASME rules. To win the competition student teams must obtain the highest combined score. The scoring breaks down as shown in figure 1.7. Details regarding scoring of specific events can be found in the ASME HPVC rules with the scoring guides provided [6–8]. Winning 1st place teams at US competitions have typically earned about 88% or more of the possible points, as seen in table 1.4. The design event is based on creating a design report and presentation that documents the student team's results, testing, analysis, and major aspects of the design report. The design report is required before the competition and a design presentation is required during the HPVC event. During the presentation student teams discuss the testing results, along with changes to the design, and elements missing from the report.

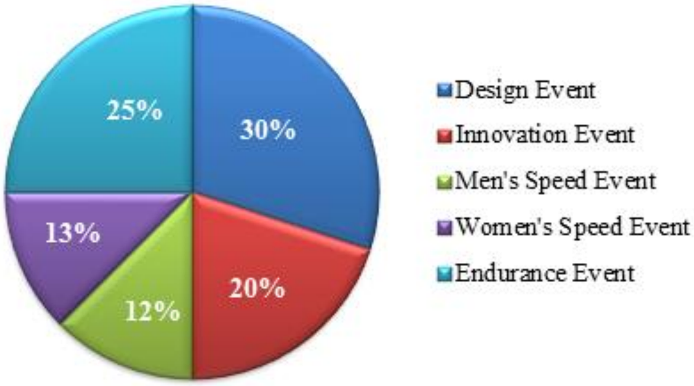


Figure 1.7 HPVC event scoring breakdown

Table 1.3 HPVC Design Requirements

Design Requirement	Justification/Reason
1.) Come to a complete stop from a speed of 25km/hr in a distance of 6.0m	Vehicle has efficient brakes
2.) Can turn within an 8.0m radius	Demonstrates maneuverability
3.) Can travel in a straight line for 30m at a speed between 5 to 8km/hr	Demonstrates vehicle stability
4.) Must include a roll protection system (RPS)	For safety reasons
4a. RPS must absorb sufficient energy and minimize the risk of injury	To protect riders in the case of an accident
4b.) RPS must prevent significant body contact with the ground in the event of a fall or rollover	To protect riders in the case of an accident
4c.) RPS must provide adequate abrasion resistance	To protect riders in the case of an accident
4d.) RPS must be able to take a top load of 2670N, 12° from vertical, with no indication of permanent deformation	To predict the possible damage of an accident and show the RPS is capable of protecting the rider
4e.) RPS must be able to take a side load of 1330N without signs of deformation	To predict the possible damage of an accident and show the RPS is capable of protecting the rider
4f.) RPS must be structural attached to frame and/or fairing for all events	Ensure the RPS is an integral part of the design
4g.) RPS must be above all helmeted riders	Ensure the RPS is large enough
5.) A Harness must be used to secure the rider	To ensure the rider is secure for accidents
6.) Exterior and interior must be free from sharp edges	To minimize risk and injuries
7.) Energy recover systems must be fully depleted before events	To ensure all racers have an equal start

The innovation event requires a separate report that describes an innovative design aspect, design process, manufacturing method, or special feature related to the vehicle. The design presentation is also meant to discuss the innovation aspect to the judges. The speed event consists of either a sprint or drag race event. The sprint event consists of a 400m to 600m run up followed by a 100m timing section, and ending with a 200m run down. The scoring is based on time, with the fastest teams earning the highest scores. The drag event consists of a series of elimination drag races to determine the top teams.

Table 1.4 Recent US HPVC results (Data from [9])

Location	Year	Team Place	University	Score	Average Scores
HPVC East	2015	1st / 33	Missouri S&T	91.52	81.28
		2nd / 33	Alabama	79.19	
		3rd / 33	Akron	73.13	
	2014	1st / 36	Central Florida	89.95	76.96
		2nd / 36	Rose-Hulman	70.83	
		3rd / 36	Olin College	70.09	
	2013	1st / 31	Rose-Hulman	87.24	78.70
		2nd / 31	Missouri S&T	79.35	
		3rd / 31	Toronto	69.52	
	2012	1st / 32	Rose-Hulman	93.50	91.73
		2nd / 32	Missouri S&T	92.30	
		3rd / 32	Olin College	89.40	
HPVC West	2015	1st / 36	Rose-Hulman	88.31	87.35
		2nd / 36	Missouri S&T	87.39	
		3rd / 36	Hawaii at Manoa	86.34	
	2014	1st / 26	Rose-Hulman	90.71	88.80
		2nd / 26	Northern Arizona	90.60	
		3rd / 26	Missouri S&T	85.08	
	2013	1st / 29	Rose-Hulman	85.25	83.53
		2nd / 29	Colorado State	82.87	
		3rd / 29	Missouri S&T	82.46	
	2012	1st / 17	Missouri S&T	86.00	84.38
		2nd / 17	Cal Poly	85.99	
		3rd / 17	Rose-Hulman	81.15	
Scores	1st Place	2nd Place	3rd Place	Total Average	84.09
	89.06	83.57	79.65		

The endurance event is a timed two and a half hour relay race where teams complete as many laps as possible within 2.5 hours. Laps are least 1.5km in length with obstacles. Some obstacles can include speed bumps, stop signs, up and down grades, tight hairpin turns, slalom sections, rumble strips, and quick turns. Additionally, there is a parcel pick-up and delivery required multiple times throughout the race.

One requirement to achieve success in the HPVC is having a respectable vehicle design. To further the discussion on HPV design the remaining contents of the paper will go through design features specific to HPVs. To begin a discussion of the project planning and problem development is provided. Next the conceptual design of HPVs is explained. The following chapter on embodiment design details how to develop the concept into a practical vehicle. The detail design chapter clarifies documentation that should be recorded and its usefulness. Chapter six discusses prototyping and testing to provide insight to the importance of design through fabrication and analysis along with the redesign and final production of the vehicle. Lastly, the final chapters give a method to evaluate the design process discussed, outlines future work, and concluding remarks.

CHAPTER TWO: PROJECT PLANNING AND DEVELOPMENT

In order to begin a design project proper project management and planning is required. This is evident in pre-phase A and phase A of systems engineering design, as well as the beginning stages of the traditional design processes. Some of the main categories of project planning include project management, scheduling, division of resources, problem definition and task clarifications. The beginning stage of the design process is also when problem development and some background research should occur. This chapter presents project planning aspects that have been found to be suitable for HPV design, particularly for student teams.

2.1 Project Management and Goal Setting

For student teams starting from scratch, they may find themselves asking, “Where do we begin?” To establish a foundation in design the group will need to divide into specific areas and begin planning the project. In order to divide the students into task forces, group specialties need to be created. One method on creating group specialties is by looking at the product hierarchy. Figure 1.6 provides four main subsystems for HPV design; the structure, the controls, the power supply, and performance factors. Additionally, the HPV system as a whole could have a single person, or small management group to ensure the subsystems are coordinating together towards a complete design, rather than four individual ideas. Additionally, leadership is required within the subsystems to focus the group’s thoughts and make final decisions. Having three to six students for each subsystem, with a group leader, is suggested for more progress. Having more than two students ensures multiple thoughts are provided, while limiting the number of students ensures everyone is involved and reduces the chances of distractions. When forming groups, the students should consider their backgrounds, interests, planned dedication to the project, and the overall group dynamics. Figure 2.1 provides an example management structure of HPV design.

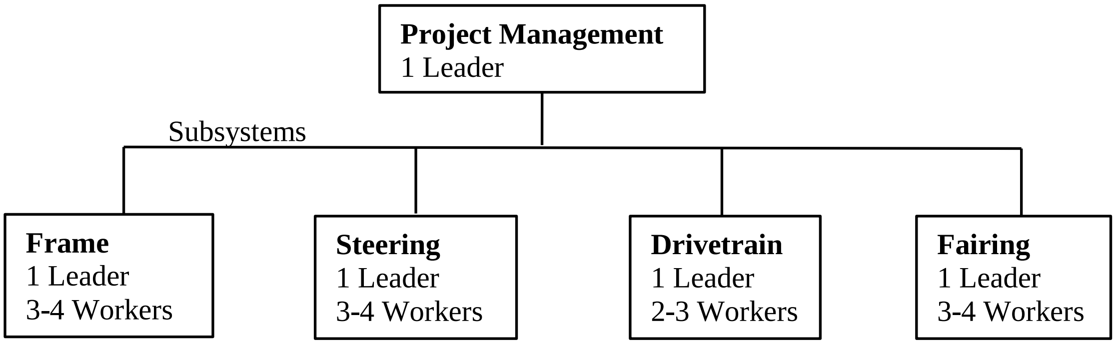


Figure 2.1 Example of HPV team management

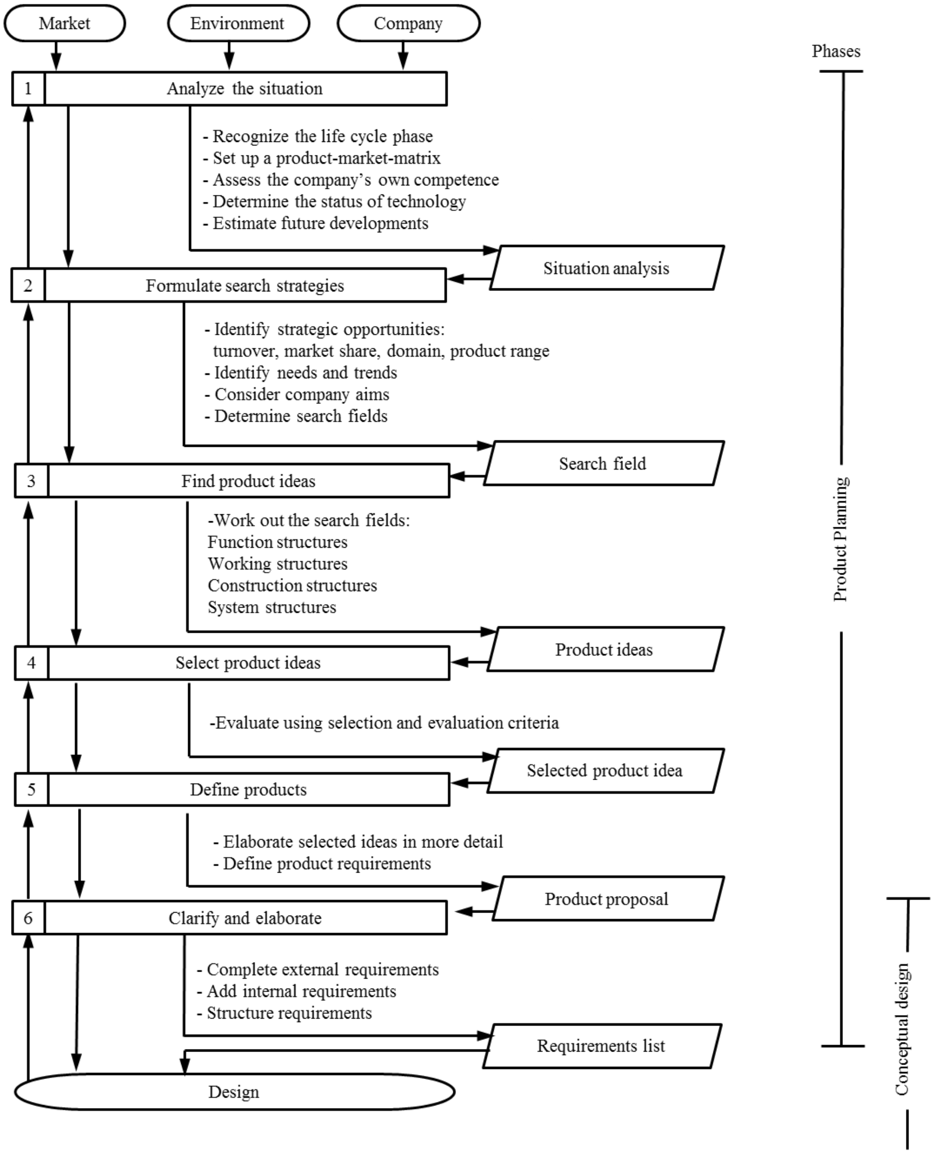


Figure 2.2 Project planning procedure [1]

Figure 2.1 breaks the team down to a format similar to an integrated product team (IPT) structure [10,11]**.** This means the group is divided into different areas of experience or design focuses, with selective leaders from the respective groups collaborating with an overseer to reach a general census on final decisions. The overseer is known as the project manager. The leadership of the project is governed by the team leaders and the project manager. The individual team members are then responsible for completing the tasks assigned to them. The overall responsibilities of the members, for the purpose of student HPV design, are outlined in table 2.1.

Table 2.1 Outline of team member roles and responsibilities.

Group Role	Responsibilities
Project Manager	• Manage the overall project • Manage Gantt chart and/or project schedule • Create weekly objectives for team leader • In project scheduling, task assignment, and meeting requests consider time management and resources available • Manage the budget and make purchases where required. • View the subsystems with systems integration in mind • Obtain progress of groups • Make large system level suggestions for the design • Organize weekly meetings with the leaders • Organize monthly design reviews with all members • Examine system level aspects to be improved on
Team Leader	• Manage the specific subsystem • Report and record progress and current state of the design in the weekly meetings • Create tasks specifically for corresponding design system • Examine aspects of the subsystem to be improved on. • Assign tasks to group member and monitor progress • Report materials and manufacturing requirements. Outline general costs and purchases availabilities. • Report purchases needed at weekly meetings
Team Member	• Complete tasks assigned • Report all problems and progress to team leaders • Record all progress necessary • Report materials and manufacturing requirements. Outline general costs and purchases availabilities. • Make decision appropriately and as necessary • Optimize given design features • Complete required analysis

Once students have finalized the group dynamics, project planning can continue. Initial project planning should be conducted beforehand, while directing the students into groups allows multiple areas to be completed simultaneous, creating an overall more efficient workforce. Additionally, focusing a larger amount of students to one task and organizing everyone's thoughts into a single solution is difficult. Pahl *et al* created a specified procedure for project planning, shown in figure 2.2. Project planning for the systems engineering perspective accomplishes similar goals but also gives more focus to scheduling and project management in terms of resource allocation of individuals, time, budgeting, and materials.

To begin analyzing the situation, as portrayed in figure 2.2, background research will give insight to the current status of technology and market demands. Past design reports, forums, design guidelines, repair manuals, patents, and the HPVC rules are good locations to start collecting ideas for HPV problem formulation. Market demands arises from stakeholders, or who the product will be designed for. For HPV design, the stakeholders are often a combination of the student design team, the judges at the HPVC event, and the demographic the vehicle is designed for. Preliminary research should be first conducted for each subsystem. The subsystem research should include customers' demands, performance expectations, and some basic examples of existing methods or ideas. Appendix B provides basic examples of existing subsystem concepts to give students a base level idea of existing HPV products. Further sources for researching can be found by exploring the references of this paper, especially those associated with the different HPV configurations in Appendix B. Some of the references include video demonstrations for clarity.

After preliminary research completion, each subsystem team will need to present their findings and listen to the other team's research. For this the leaders and project manager should meet to discuss the direction of the project. In addition to obtaining basic knowledge of each individual system the subsystem leaders and the project manager, or "leader team" needs to develop a basic understanding of the system as whole. Additional research may be required. Once all teams have a general understanding of the system, they will need to develop an overall design objective, or mission statement, and basic design criteria. Table 2.2 provides an example a of Seattle's HPVC design problem development.

Table 2.2 Example design objective and basic criteria [12]

<table>
<tr><th colspan="2">Design Objective</th></tr>
<tr><td colspan="2">The Seattle University HPVC Team has the goal to design a bike that can transform from recumbent to upright. The vehicle needs to be able to navigate the hilly terrain and rainy days that are typical when riding in Seattle. Furthermore, to lower the carbon footprint, we used local distributors (i.e. onlinemetals.com, based in Seattle) and as much recycled components as possible (Recycled Cycles, also based in Seattle). The vehicle needs to be user friendly, allowing for daily commute and carrying a load of groceries. Acknowledging our technical failure in 2008, we would like the vehicle to be competitive in the recumbent mode.</td></tr>
<tr><th colspan="2">Design Criteria</th></tr>
<tr><td>1.)</td><td>2 wheeled bike that is capable of switching from long wheel base (LWB) recumbent to upright</td></tr>
<tr><td>2.)</td><td>Serves riders of various sizes (Height: 5'4" to 6'4", Max weight: 250 lbs.)</td></tr>
<tr><td>3.)</td><td>Utility storage (Max storage area - Volume: 450 in3, Weight: 50 lbs.)</td></tr>
<tr><td>4.)</td><td>Safety features to allow for riding at night (front and tail lights)</td></tr>
<tr><td>5.)</td><td>Roll bar and seat belt that meet the requirements to protect the rider in the case of an accident (recumbent mode)</td></tr>
<tr><td>6.)</td><td>Ability to remove parts of the bike (roll bar, fairing, utility bags, etc.), if the rider wants to customize their bike for a given trip</td></tr>
<tr><td>7.)</td><td>Able to achieve a speed of over 30 mph</td></tr>
<tr><td>8.)</td><td>Kick stand for self-standing purposes</td></tr>
<tr><td>9.)</td><td>For the rain, equip the bike with fenders and water repellent on the fairing</td></tr>
<tr><td>10.)</td><td>Use cross/road tires for smooth rolling on streets and deep grooves for sipping water away from the tread in wet conditions</td></tr>
</table>

In creating the design objective students may find it helpful to complete a high level decision matrix. A decision matrix is a tool used for concepting that systematically assesses the pros and cons between multiple ideas. High level decision matrices can be used to help determine the general concept the student team would like to achieve. Appendix C provides a through discussion on decision matrices, their usefulness, and flaws. It is also important to reiterate some conclusions form Appendix C to alleviate misconceptions. First, the decision matrix does not tell the designer, which ideas are the best it simply highlights ideas the users has, because the evaluation scale is arbitrary. Further information may change some of the evaluation perspective, meaning the chosen ideas may not be the best. Lastly, the decision matrix is only a design tool meant to organize the designer’s thoughts. If the designer puts bad information into the tool the conclusions will be lacking as well. Table 2.3 gives high level decision matrix for HPV configurations.

Table 2.3 Example of a high level decision matrix for HPV configuration (Adapted from [13])

	Rule Compliance	Weight	Reliability	Looks	Top Speed	Corning	Comfort	Safety	Ease of Use	Cost	Manufacturability	Maintenance	Simplicity	Total
Importance	5	3	4	2	3	5	2	5	4	2	3	1	3	
2 Wheels	0	2	2	0	2	0	1	0	-1	2	0	2	2	30
3 Wheels Rigid	0	1	1	1	1	1	0	1	0	1	0	1	1	28
3 Wheel Indep. Steer	0	0	1	2	0	2	2	2	1	1	0	0	1	41
3 Wheel Integrated	0	0	0	2	1	2	2	2	2	1	0	0	0	41

Design evaluation tools can assist the decision making process of any of the design criteria, and other high level decisions. For example the first high level design criteria in table 2.2 might have changed if the design matrix on vehicle configuration of table 2.3 was used. As the students go through the design process they will gain more information that will help them make more justified decisions. As a result the decision criteria may slightly change. The design objective should remain unchanged, because it defines the project direction and overall design goals for the team. It should only be changed if the team recognized that their design goals have changed as the design process has progressed.

2.2 Project Scheduling and Communication

To further the project planning process meetings should be established and a project schedule needs to be developed. To have an efficient project, deadlines, reviews, and milestones are needed in combination with a project plan and time schedule. Systems engineering and traditional design methods recommend the use of Gantt charts for scheduling purposes. A detailed project schedule for HPV design is provided in Appendix D. Some elements missing from the schedule are deadlines, resource allocations, weekly objectives, design reviews, milestones, and meeting times. Figure 2.5 and table 2.4 were extracted from Appendix D. They provide high level examples for HPV project planning. A more compressed example of a Gantt chart is included in figure 2.3. The example shows how the timeline of subsystems should be incorporated to the overall system design, when reviews need to take place, outlines the critical path, and highlights milestones.

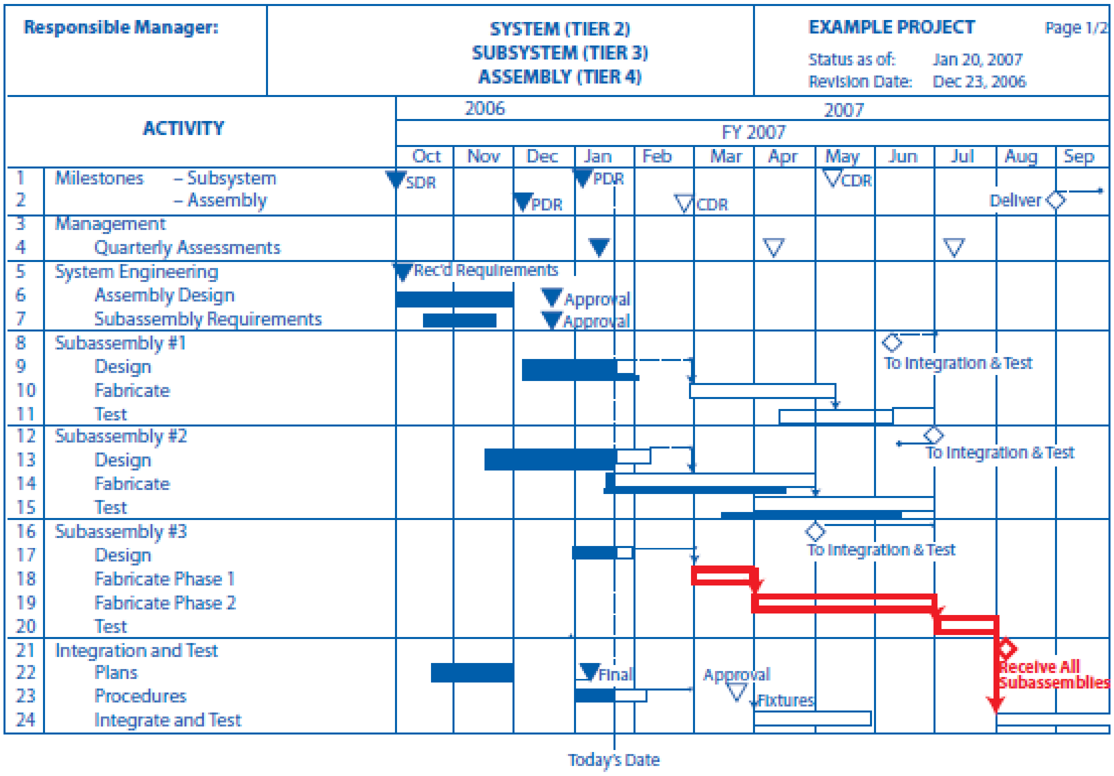
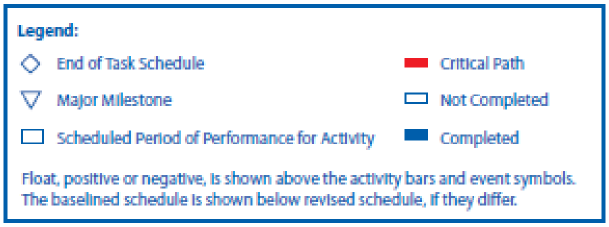


Figure 2.3 General Gantt chart example [2]



Legend:

◇ End of Task Schedule

▽ Major Milestone

☐ Scheduled Period of Performance for Activity

🟥 Critical Path

☐ Not Completed

■ Completed

Float, positive or negative, is shown above the activity bars and event symbols.
The baselined schedule is shown below revised schedule, if they differ.

Figure 2.4 Legend to Gantt chart in figure 2.3 [2]

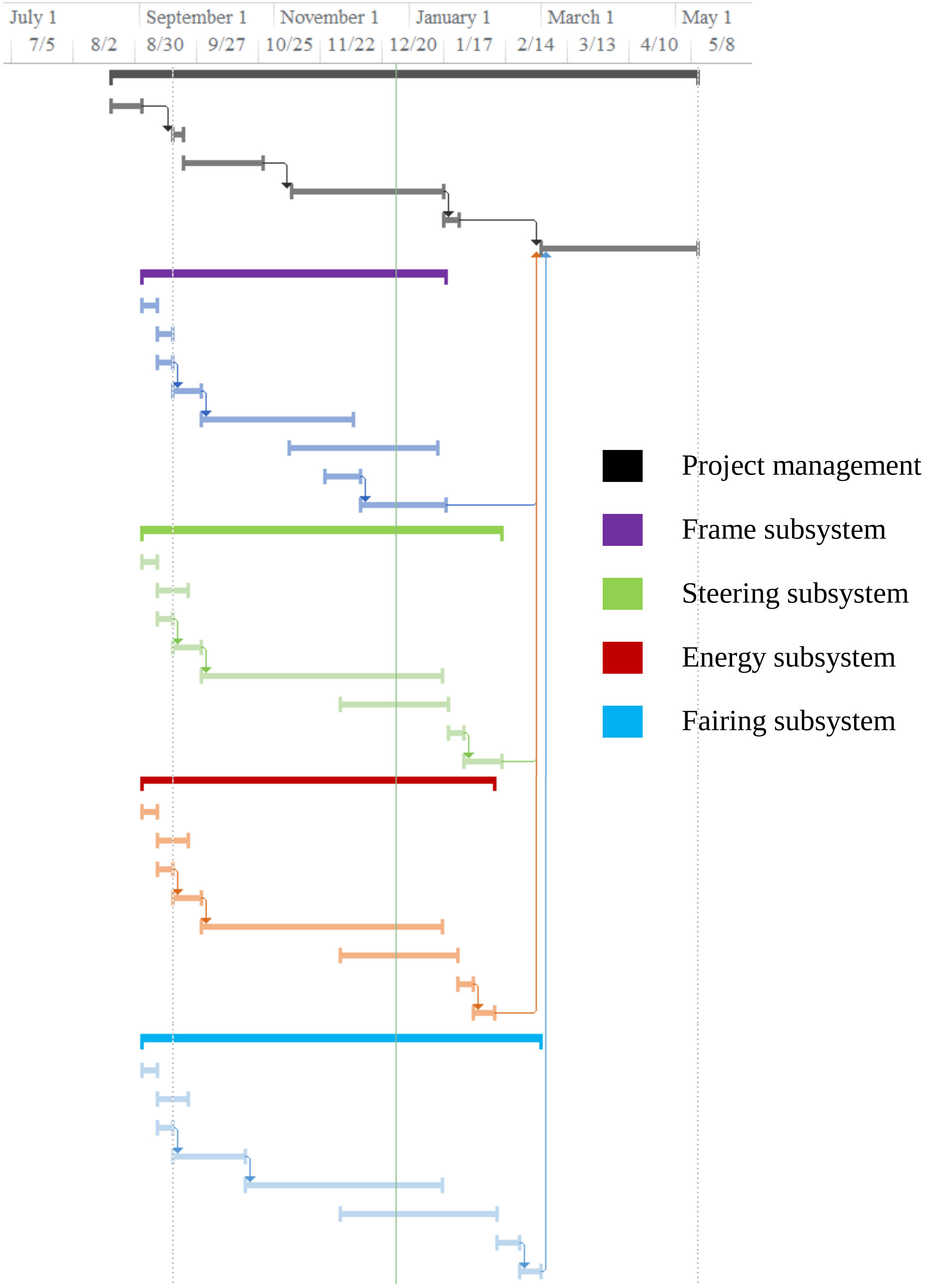


Figure 2.5 Example of HPV Gantt chart corresponding to project planning overview

Table 2.4 HPV Project planning overview corresponding to figure 2.5

Task Name	Duration	Start	Finish
1 Lead Project planning	**220 days**	**Wed 8/19/15**	**Tue 5/10/16**
1.1 Project Initiation	14 days	Wed 8/19/15	Tue 9/1/15
1.2 Structure Product Requirements	5 days	Wed 9/16/15	Sun 9/20/15
1.3 Structure Conceptual Design Selection	31 days	Mon 9/21/15	Mon 10/26/15
1.4 Structure Product Development	33 days	Mon 11/9/15	Sat 1/16/16
1.5 Final Design Details	7 days	Sun 1/17/16	Sat 1/23/16
1.6 Competition and Preparation	66 days	Tue 3/1/16	Tue 5/10/16
2 Structure (Frame) subsystem	**97 days**	**Wed 9/2/15**	**Sun 1/17/16**
2.1 Initialize	7 days	Wed 9/2/15	Tue 9/8/15
2.2 Research Background Information	7 days	Wed 9/9/15	Tue 9/15/15
2.3 Product Definition	7 days	Wed 9/9/15	Tue 9/15/15
2.4 Conceptual Design	13 days	Wed 9/16/15	Mon 9/28/15
2.5 Product Development	60 days	Tue 9/29/15	Sun 12/6/15
2.6 Final Prototype Manufacturing	31 days	Sun 11/8/15	Wed 1/13/16
2.7 Testing and Analysis of Prototype	12 days	Tue 11/24/15	Wed 12/9/15
2.8 Final Product Development	7 days	Thu 12/10/15	Sun 1/17/16
3 Controls (Steering) subsystem	**122 days**	**Wed 9/2/15**	**Thu 2/11/16**
3.1 Initialize	7 days	Wed 9/2/15	Tue 9/8/15
3.2 Research Background Information	14 days	Wed 9/9/15	Tue 9/22/15
3.3 Product Definition	7 days	Wed 9/9/15	Tue 9/15/15
3.4 Conceptual Design	13 days	Wed 9/16/15	Mon 9/28/15
3.5 Product Development	68 days	Tue 9/29/15	Fri 1/15/16
3.6 Final Prototype Manufacturing	17 days	Tue 12/1/15	Mon 1/18/16
3.7 Testing and Analysis of Prototype	7 days	Tue 1/19/16	Mon 1/25/16
3.8 Final Product Development	17 days	Tue 1/26/16	Thu 2/11/16
4 Energy Supply (Drivetrain) subsystem	**119 days**	**Wed 9/2/15**	**Mon 2/8/16**
4.1 Initialize	7 days	Wed 9/2/15	Tue 9/8/15
4.2 Research Background Information	14 days	Wed 9/9/15	Tue 9/22/15
4.3 Product Definition	7 days	Wed 9/9/15	Tue 9/15/15
4.4 Conceptual Design	13 days	Wed 9/16/15	Mon 9/28/15
4.5 Product Development	68 days	Tue 9/29/15	Fri 1/15/16
4.6 Final Prototype Manufacturing	21 days	Tue 12/1/15	Fri 1/22/16
4.7 Testing and Analysis of Prototype	7 days	Sat 1/23/16	Fri 1/29/16
4.8 Final Product Development	10 days	Sat 1/30/16	Mon 2/8/16
5 Performance and Comfort (Fairing) subsystem	**140 days**	**Wed 9/2/15**	**Mon 2/29/16**
5.1 Initialize	7 days	Wed 9/2/15	Tue 9/8/15
5.2 Research Background Information	14 days	Wed 9/9/15	Tue 9/22/15
5.3 Product Definition	7 days	Wed 9/9/15	Tue 9/15/15
5.4 Conceptual Design	28 days	Wed 9/16/15	Sun 10/18/15
5.5 Product Development	53 days	Mon 10/19/15	Fri 1/15/16
5.6 Final Prototype Manufacturing	39 days	Tue 12/1/15	Tue 2/9/16
5.7 Testing and Analysis of Prototype	10 days	Wed 2/10/16	Fri 2/19/16
5.8 Final Product Development	10 days	Sat 2/20/16	Mon 2/29/16

The project plan in Appendix D is created for a two semester student project, using the fall and spring semesters. It only provides the basic tasks to be completed and lacks important information, such as the milestones of the project. Table 2.5 provides a summary of the milestones that should be completed based on the the two semester plan outlined.

Table 2.5 Outline of HPV Milestones

Milestone	**Competition Time frame**	**Approximate time from start of project**
1.) Complete project management and define team roles	Beginning of Fall semester	2 Weeks
2.) Complete basic research and define all subsystem requirements	Early Fall semester	1 Month
3.) Finish drivetrain, steering, and frame concept selection	Mid Fall semester	1.5 Months
4.) Finish fairing concept selection	Mid Fall semester	2 Months
5.) Finalize initial frame design	Late Fall semester	2.5 Months
6.) Finalize drivetrain and steering designs.	Beginning of Spring semester	3.5 Months
7.) Finalize fairing design	Early Spring semester	4 Months
8.) Fabricate frame prototype	Early spring semester	4 Months
9.) Complete drivetrain and steering prototype	Early Spring semester	4.5 Months
10.) Complete frame testing	Mid Spring semester	5 Months
11.) Complete fairing prototype and assembled vehicle	Mid Spring semester	5.5 Months
12.) Complete steering and drivetrain testing	Mid Spring semester	5.5 Months
13.) Complete vehicle testing	Mid Spring semester	6.5 Months
14.) Complete prototype changes and design report	Late Spring Semester	7 Months

Creating a project schedule requires dedication and time, but it results in benefits throughout the design process. The act of project planning forces detailed thinking and provides a goal [14]. Having completed a plan allows the students to know when they are off track, increases productivity, and helps to see problems early. If used properly project planning can reduce delivery time and costs. After creating a schedule it should be updated, changed, and revised throughout the design process as the more information is gathered, breakthroughs happen, or setbacks occur. That being said, deadlines still need to be met, and the schedule should not be drastically adjusted because of lack of effort. To help students stay on track the project managers and subsystem leaders should create weekly objectives. This ensures the students have short terms objectives while also being focused on the long term goals.

Project planning can be improved using project analysis and resource allocation. Examples of project analysis include items such as critical path analysis, to find the more important design tasks, and cost analysis. The cost analysis can be made accurate through the use of resource allocation. In other words, assigning people to tasks with wages, tracking the cost of materials used, and reviewing budget allowances, will give insight to the costs of the tasks and how well they meet a budgeting plan. Software such Microsoft Project, Zoho Projects, and etc. are extremely useful tools that can be used for project planning [14,15]. The software also has elements of resource allocations and project analysis embedded in the programming.

Another element of scheduling is creating arrangements for student meetings, group meetings, design reviews, and overall communication. Scheduling meetings for multiple students with varied schedules can be a challenge. Whenisgood.net provides a free method where students can select their available times and highlights optimal times when the students can meet. For documenting the outcomes of communication, such as meetings and design reviews, system engineering design provides standard documentation practices. The standards are set in place to physically record the important information. Without documenting the outcomes for communication it is impossible to prove aspects of the meeting were discussed and what they were about. Peer review guidelines from system engineering, are provided in Appendix E.

Other communication aspects involve file management, task clarification, team coordination, and information transfer. Email, blackboard, texting, and other mobile applications have worked for communication purposes of the Clemson students. Blackboard and emails provide a more professional foundation for communicating ideas. Texting and mobile applications, such as groupme, allow students to discuss the design process in a more informal environment.

For file management communication, file sharing systems are helpful. While professional product data management (PDM) software, such as Enovia Smarteam, provides excellent file management abilities, they are expensive, require individual installations, and technical computer/licensing skills students may not have. Free file sharing methods, such as Dropbox, and google drive provide a simple and free resource where students can share information. When file sharing between multiple students a standard file system structure should be established for more intuitive file navigation. Lastly, files can only be opened by one person at a time. Recently Google Drive and Dropbox have made efforts to save individual revision for these scenarios, but multiple files with the name lead to confusions. PDM software typically has a check in and check out system for files to account for this, which is an advantage over free software packages. Additionally, depending on the authority of the user some individuals may not have access to certain files. Students can replicate this form of management if desired by creating a shared spreadsheet. The spreadsheet would provide details such as a list of all the shared files, what files are currently in use and by whom, and check in and check out times.

2.3 Problem Development

In addition to creating a project plan, starting a project requires problem development. Problem development is an extension of the criteria created beforehand. Product development more or less is the generation of a set of requirements that limit the design goal. Appendix E provides a brief description of some HPV requirements, ways to organize them, and topics for requirements. Table 2.6, extracted from Appendix F, provides a list of requirement topics adapted from Pahl *et al* [1]. In addition to different types of requirements, there are different sources of demands for requirements, such as customer requirements, developer requirements, manufacturing requirements, etc. To group the needs of different sources there are design tools such as the house of quality [16]. The house of quality is an extension of quality function deployment (QFD) to manage information and map a set of information from one design phase to another. It is often used to map the (customer) needs to requirements. The amount of research and customer surveys can be a determining factor to the amount of requirements developed.

Table 2.6 Topics for requirement generation (Adapted from [1])

Topic	**Examples**
Geometry	Size, height, breadth, length, diameter, space requirement, number, arrangement, connection, extension, surface
Kinematics	Type of motion, direction of motion, velocity, acceleration, dynamic performance
Forces	Direction of force, magnitude, frequency, weight, load, deformation, stiffness, stiffness, elasticity inertia forces, resonance, protection
Energy	Output, efficiency, loss, friction, ventilation, state, pressure, temperature, heating, cooling, supply, storage, capacity, conversation
Material	Flow and transport of materials, physical and chemical properties of initial and final product, auxiliary materials, prescribed materials (food regulations, etc.),
Signals	Inputs and outputs, form, display, control equipment, component and system interactions and adjustments
Safety	Direct and indirect safety systems, operational and environment safety, safety for failures
Ergonomics	Man-Machine relationship, type of operation, operating height, clarity of layout, sitting comfort, lighting, shape compatibility, ease of use, instructional indications
Production	Factory limitations, maximum possible dimensions, preferred production methods, means of production, achievable quality, and tolerances, wastage, number of parts, standardizations
Quality Control	Possibilities of testing and measuring, application of special regulations and standards

Table 2.6 (Cont.)

Topic	Examples
Assembly	Special regulations, installation, siting, foundations, time
Transport	Limitations due to lifting gear, clearance, means of transport (height and weight), nature and conditions of dispatch
Operation	Quietness, wear, special uses, marketing area, destination (sulphurous, topical)
Maintenance	Servicing intervals, inspection, exchange and repairing, painting, cleaning
Recycling	Reuse, reprocessing, waste disposal, storage
Costs	Maximum permissible manufacturing costs, cost of tooling, investment and deprecation
Schedules	End date of development, project planning and control, delivery date

There are different levels of requirements depending on what the requirements are directed at. High level requirements occur at the subsystem and system levels. Detailed requirements define specific demands or wants for components and small sub-assemblies. An example of a high level requirement for the force topic, from table 2.6, would be the frame subsystem must not weigh more than X amount of lbs. A detailed requirement example could be a tie rod from the steering subsystem must not deform under torsion of X amount or less. Requirements can either be demands or wants. A demand means the final design must fulfill the requirement, whereas a want means it would be appealing if the requirement is fulfilled, but it is not mandatory. The above requirements are examples of demands. Figure 2.6 outlines the order in which the requirements should be generated for systems engineering

Initially a large amount of requirements may be developed, but that is not the end of requirement generation. Requirements should be continually generated throughout the design process as new concepts are developed. Requirements can also be updated to provide more details. For example, an initial requirement of “vehicle should not be overly wide” could be updated to “vehicle must be less than 36 inches in width”, in order to fit through a standard doorway. Table 2.7 provides an example to organize the requirements. Appendix F gives additional organizational methods for requirements.

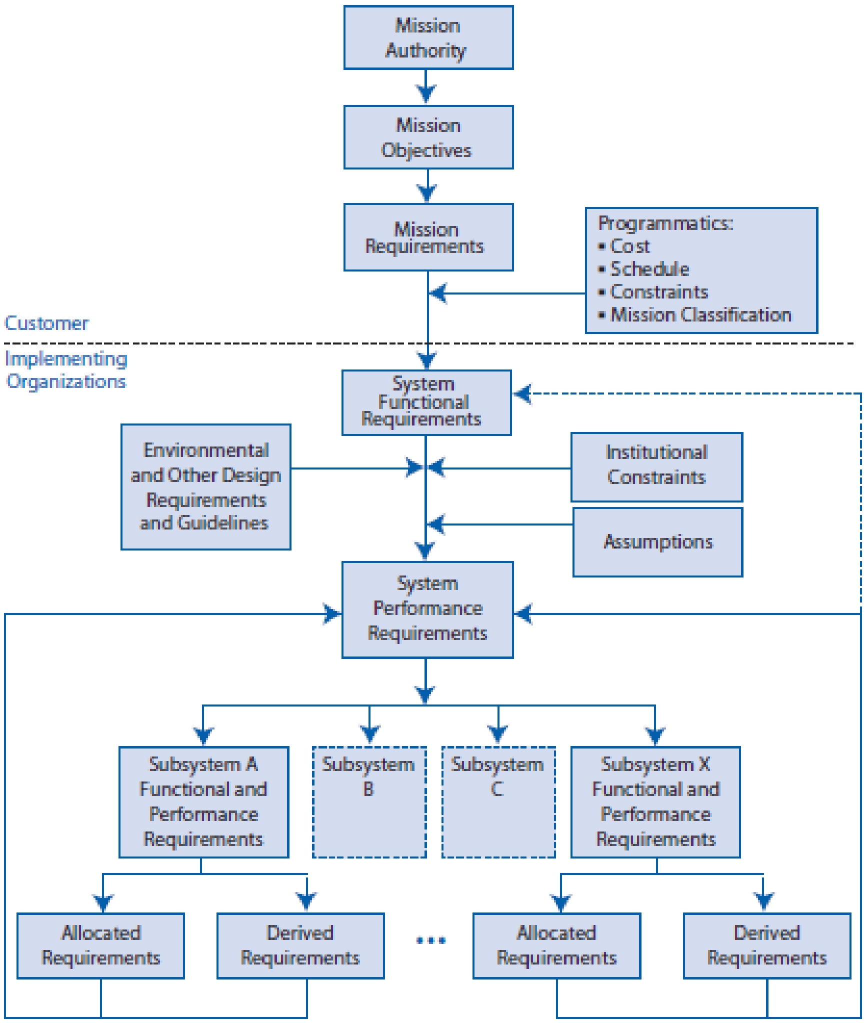


Figure 2.6 Flow down of requirements for systems engineering [2]

Table 2.7 Subset of frame requirements as a formatting example (Style from [1])

ME 431/HPVC (Class/Project)	Requirements List for Frame	10/22/2015 (Date)
D/W (Demand/Want)		Responsible
	1.) Geometry	Frame
D	a. Width must be less than 36 inches	Frame
W	b. Width must be less than 25 inches	Frame
W	c. Length must be less than 90 inches	Frame
	2.) Kinematics	
D	a. Rigid during dynamic performance	Frame
D	b. Stable dynamic performance at high and low speeds	

To make use of requirements they need to be monitored throughout the design process. This allows groups and individuals to be held accountable for specific requirements. By tracking the requirement the designer is able to ensure ensure they are meeting the goals and guidelines outlined. Thus the importance in requirements is the ability to define goals, customer needs, and design criteria, into a documented form that can be evaluated and modified during development validated in the final design ensuring a working final product.

2.4 Project Planning Summary

The beginning stages of design involve group formation, project planning, and problem development. Table 2.8 outlines the suggested order for the initial design process. Group formation is suggested as the first step, because it helps divide the student labor. This allows more focus on multiple tasks and limits disorganization caused by too many students debating on smaller sets of tasks. The second phase includes establishing a standard means of communication and outlining the project with a schedule of design tasks. Communication is ordered in the second phase, because it provides a method for transferring ideas and information. Community is necessary for collaborating complex thoughts and perceptions. Scheduling is important, because it allows the student to plan ahead by creating a timeline that details the fundamental tasks. Doing this gives the students an ahead of their overall progress and allows them to plan for mistakes. The third and last phase involves problem development. Once a foundation has been created through planning and organizing the team students can begin to define the project. In the problem definition students need to define goals, and project requirements. By creating design objectives the students have a baseline source that can also be used to validate their decisions. The contents regarding the different phases are thoroughly discussed in the proceedings of this chapter. To summarize the information presented and to provide some additional resources, table 2.9 has been created.

Table 2.8 Suggested order for project planning and development

Suggested order	**Project Initiation Components**	
Phase 1:	Group Formation	
Phase 2:	Communication	Scheduling
Phase 3:	Problem Development	

Table 2.9 Summary of project planning and development

Project Planning Topics	**Topic Aspects**	**Design Tools and Methods**	**Software programs /Online Resources**
Group Formation	System/Subsystems Formation	Product Hierarchy	
	Leaders/Members	Group Voting or Volunteering Forming, Storming, Norming, and Performing [17]	Personality Tests
Scheduling	Outlining Time and Tasks	Gantt Chart (Appendix D) Documentation (Appendix E)	Microsoft Project, Zoho Project
	Allocating Resources		
	Establishing Meetings and Design Review	Calendar Scheduling	Whenisgood.net, Google Calendar
Communication	File Management Information Transfer	File Sharing	Dropbox, PDM Software, Google Drive
	Information Transfer	Quick Communication	Groupme, Email, Texting
	Meetings	Sharing Calendar Information	Whenisgood.net, Google Calendar
Problem Development	Goal Setting with Criteria (Bench marking)	Research (Appendix A and Appendix B) Decision Matrices (Appendix C)	
	Finding Needs	QFD, House of Quality [16]	
	Generating Requirements	Requirement List, PDS (Appendix F)	

CHAPTER THREE: CONCEPTUAL DESIGN

Conceptual design is the stage in which, concepts are generated to act as solution alternatives for the design goals. Within conceptual design there are two main categories that students need to address, concept development and concept selection. The concept development process includes solution alternatives that are generated, how they were created, and how they are documented. There are several methods to accomplish this, a few of which will be discussed in more detail. The process of concept selection is about how to compare the solution alternatives and how to evaluate the goodness of those based on the design requirements and goals.

3.1 Concept Development

Within the concept development process for systems engineering design there are two main areas to focus. The first is design tools and methods that can be used to concept different ideas. The second area is what ideas need to be developed and at what level.

3.1.1 Concept Development Methods

Figure 3.1 outlines some of the commonly used concept generation methods. Some of the notable methods include morphological analysis, brainstorming, brain writing, 6-3-5 method, C-Sketch, gallery method, design catalogs, and TRIZ. More valuable concept generation methods not mentioned are biologically mimicry and the use of functional diagrams. A brief description of these methods will be given to introduce students to the various ideas of concept generation. Students can explore these methods further outside of this guide for a more detailed description about use of these design tools.

Brainstorming is the act of developing concepts through discussion and cognitive ideas. Brainstorming is commonly associated with groups of individuals coming together and trying to develop ideas based on the discussion that takes place. For a more effective brainstorming session, individuals can first brainstorm on their own and/or individual brainwriting can take place [18]. This indicates individual preparation before group idea generation. Brainwriting is the act of brainstorming, but with drawing and writing taking place to help visualize ideas. Brainwriting is a useful method, because in addition to the ideas discussed, the drawings created automatically document the ideas in visual form. Some concept ideas created from brainstorming are included in Appendix G.

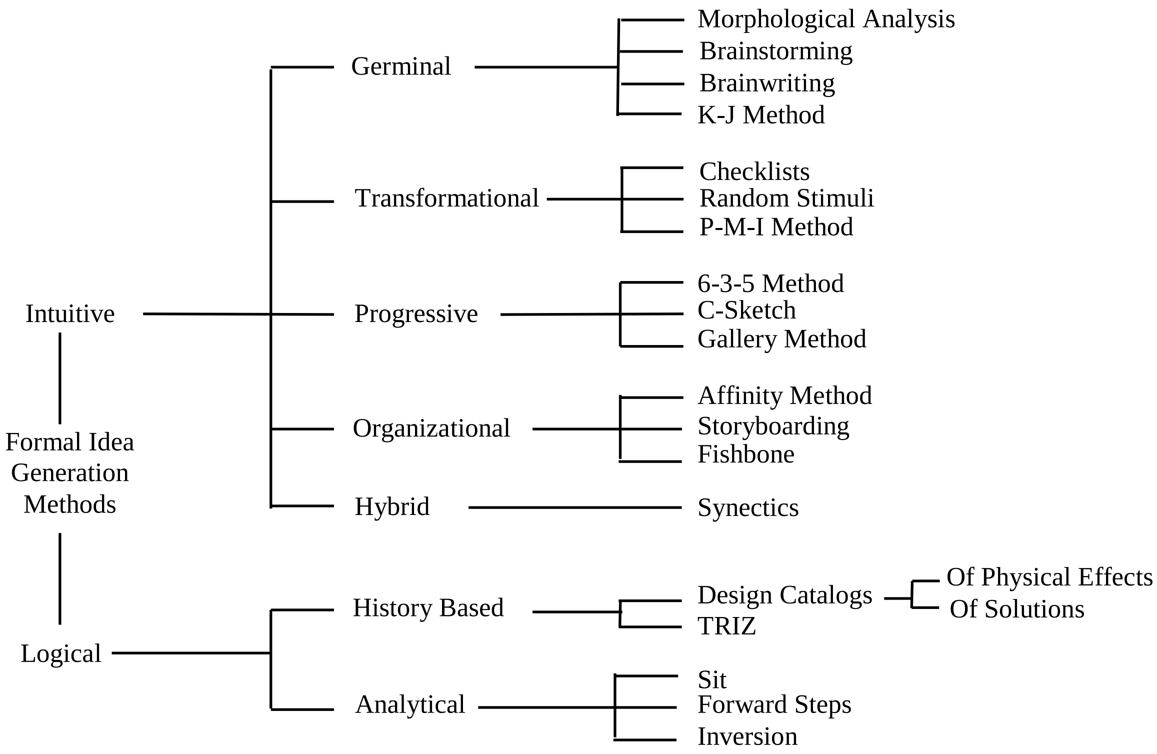


Figure 3.1 Commonly used idea generation methods [19]

The progressive methods of 6-3-5, C-sketch, and gallery involve enhancing concepts throughout use of the design tool. To begin the 6-3-5 method uses six different designers that sit in a circle. Each of the students draws three concepts and passes their ideas to right. Each student looks at the concepts passed to them and draws three new ideas based on inspiration of the passed ideas or reiterations of the ideas seen. This process continues until each idea is passed three times. The C-sketch method is similar, except instead of drawing new ideas students add to the concepts that are passed. In other words the concepts get progressive more detailed throughout the process. Time limits of three to five minutes are recommended for each passed system.

The gallery method involves designers first sketching out their ideas. All of the ideas are then placed on display. The team members then go around and place sticky notes on the ideas they like better, with notes about aspects they like if necessary. The ideas with the most notes are the ideas the team favors more. Additionally, the notes can highlight good parts of otherwise bad ideas that would be neglected, that could be useful in other designs.

Morphological analysis can be used to collect many of the ideas behind concepts using a matrix. Thus, it is more of organizational design tool than an idea generation tool. The functions of a system are placed inside the first column of a matrix. For a given function, possible solutions are proposed in the same row. Complete concepts from the system can be found by using one or more ideas from each row. To make the method more applicable, functional models should be created. To better explain this concept table 3.1 is given. To use morphological charts lines would connect elements from each of the rows to create a complete design. In the table they are removed for clarity of the table contents. More examples of morph chart usage are provided in Appendix G. Typical manufacturing method and materials would not be included in the concept design, but doing so helps give an idea the applicability of the concept. Additionally, students found that having a manufacturing method for the fairing specifically was part of the concepting process.

Biological mimicry, TRIZ, and design catalogs are all examples of design tools that can be used to help outline predefined solutions. Biological mimicry is looking at elements of nature and examining how they solve similar problems. Online tools have also been created to improve this design method [20]. If students searched for elements such as “reduce drag”, using [20], examples such as “wing profile of hawks” are discussed. TRIZ is used to select two contractions to solve within a design and provides methods to accomplish this. Thirty-nine was determined to be the total number of different contractions. Again online resources have been created to make this design tool more useful [21]. An example of TRIZ related to HPV design would be the weight of the moving object and strength (The structure of the vehicle can require more material. The additional weight requires more input power from user). Using [21], some recommendations are creating anti-weight by creating lift, or composite materials to increase the overall strength per weight.

Table 3.1 Morphological chart for the fairing subsystem

Shape (The fairing needs a form)	Overall rectangular shape with rounded edges	Overall tear drop shape	Polygonal type shape	Rounded blunt front section that tapers down to the back	Streamlined shape (narrow and rounded)
Degree of Coverage (How much of the vehicle will be covered by the fairing)	Vehicle is completely encompassed	Only have a front fairing section	Only have back fairing section	Only the top and front half is covered	Complete encompassing shape with viewing area removed
Material (The fairing must be made from something)	Carbon fiber or fiber glass (Composite materials)	Flexible stretching or formable material	Carved Wood	Sheet metal	Rigid cardboard sheets / PVC sheets
Manufacturing method (Somehow the fairing must be fabricated)	Vacuum Forming Process	Blow forming or thermal forming process	Origami assembly with overhangs and faster connections	Composite overlaid on molded foam	Flexible Material stretched over a sub-structure
Structure (How will the fairing be made rigid enough)	Monocoque design	Thin outer structure supported by a rigid sub-structure	Multiple (2 or more) rigid sections	Flexible materials wrapped around the structure (frame)	
Attachment (How will the fairing be attached the frame)	Zip ties or metal wires to wrap another frame	Weld structures (fairing to frame)	Use fasteners to connect the structures (fairing and frame)	Duct tape or other adhesive materials	Custom made bracket connections
Ventilation (The fairing needs to keep the rider at an operating temperature)	No vent needed	Removal of window for vent	Vent in the front section that direction flow of air	Sub/side ducts and exiting ducts for flow	Sunroof and/or side windows
Visibility (The rider must see the road and hazards)	Use entirely clear materials	Have a lower front section	Have back and side panels and a windshield	Adjustable mirrors	
Entering/Exiting (How will it allow riders to get in and out)	Open/no windshield	Hinged door	Hinged windshield	Removable	

Design catalogs give solutions to functional principles or general solutions. Again having a functional model makes the use of design catalogs more useful, because the general functionality of the system is already laid out. Functional models come in two main forms functions trees and function structures. To explain functional models, it is first important to understand a black box model. The black box model represents the system being designed. The inputs to the box are the inputs to the system and outputs of the box are what the system does. Figure 3.2 gives an example of a black box model of a bicycle for clarity.

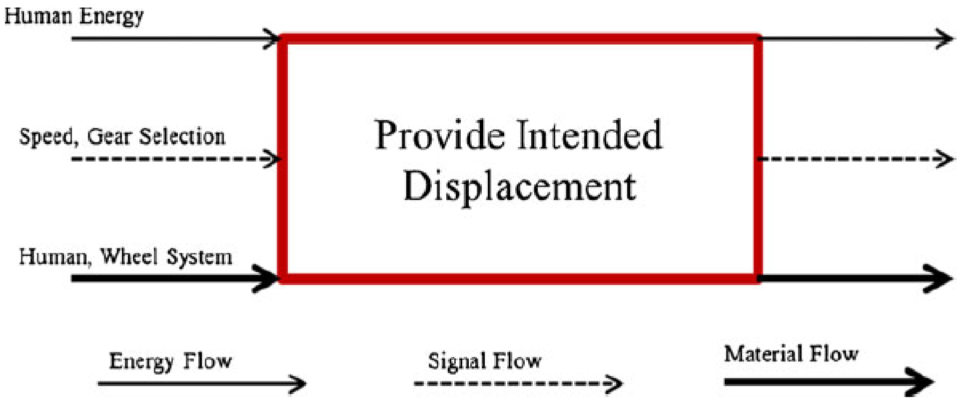


Figure 3.2 Black box model for bicycle [22]

A function structure builds on the black model and maps the functional requirements needed to map inputs to outputs. Figure 3.3 provides an example bicycle function structure for clarity. The function structure uses the idea of material, energy, and information flow to map the various functional requirements. A function basis language is typically used to make the functions more abstract and independent of bias [23]. An example of this is converting human energy to mechanical energy, instead of requiring pedals. Thus, by using the functional basis language the bias of using a pedal is eliminated. While the functional structure does not directly develop concepts it is useful for determining required functions for the system and outlining a path or order for the functions to be accomplished. This is useful for determining the number and type of different components in the system and providing a starting point for concept

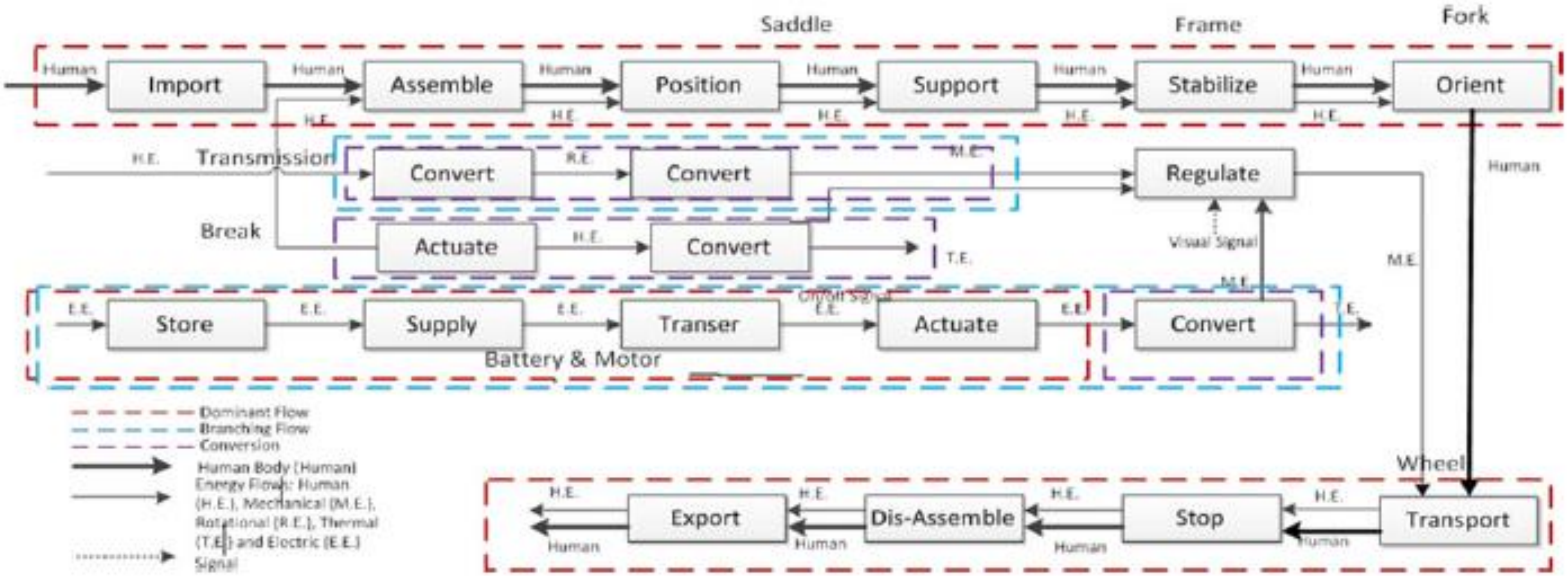


Figure 3.3 Function structure of a bicycle [22]

design tools, such as TRIZ, biological mimicry, and design catalogs. These types of concepting design tools provide solutions based on (functional) needs, thus directly benefit from functional layouts.

Another method of modeling the functional requirements is a function tree, which is demonstrated by figure 3.4. The function tree uses a hierarchy structure where the different levels discuss different hierarchies of function. The first level shows the functions of the system, the second shows sub-functions of the functions, and so on. Note figure 3.4 should be this way but the functions were displayed indiviudally for clarity. This could be considered more relevant to system engineering if the product hierachry, (example shown in figure 1.6) could be mapped to the function tree (example shown in figure 3.4). In other words the product hierachy would layout the elements of the system and the function tree would describe the functions those elements address. This mapping is shown in table 3.2.

Table 3.2 Mapping relationships between product hierarchies and function trees

Tier	Product Hierachry	Function Tree
Tier 0:	System	System
Tier 1:	Subsystems	Functions
Tier 2:	Sub assemblies	Sub-functions
Tier 3:	Components	Sub-sub-functions
Tier 4:	Sub-components	Sub-sub-sub-functions

To improve concepts developed by these methods designers can consider combining concepting methods. As a previously stated example the functional requirements methods can be combined with design catalogs, TRIZ, and biological mimicry to generate ideas. Other examples could include using a morphological analysis to baseline ideas for a c-sketch or gallery method. Brown *et al* mentioned how group storming could be improved by individual brainstorming or brainwriting [18]. Comparing the effectiveness of different methods or combining different methods is outside the scope of this paper, but has been studied extensively by others [19,24]. In short there are four metrics to compare different concepting methods; quantity, quality, novelty, and variety. The best concepting method would result in a large quantity of high quality concepts that cover a large variety of ideas and introduces novel solution alternatives. Examples of the HPV subsystem solution alternatives are provided in Appendix G. The alternatives are based on using a tadpole tricycle configuration that was predetermined in the project planning phase.

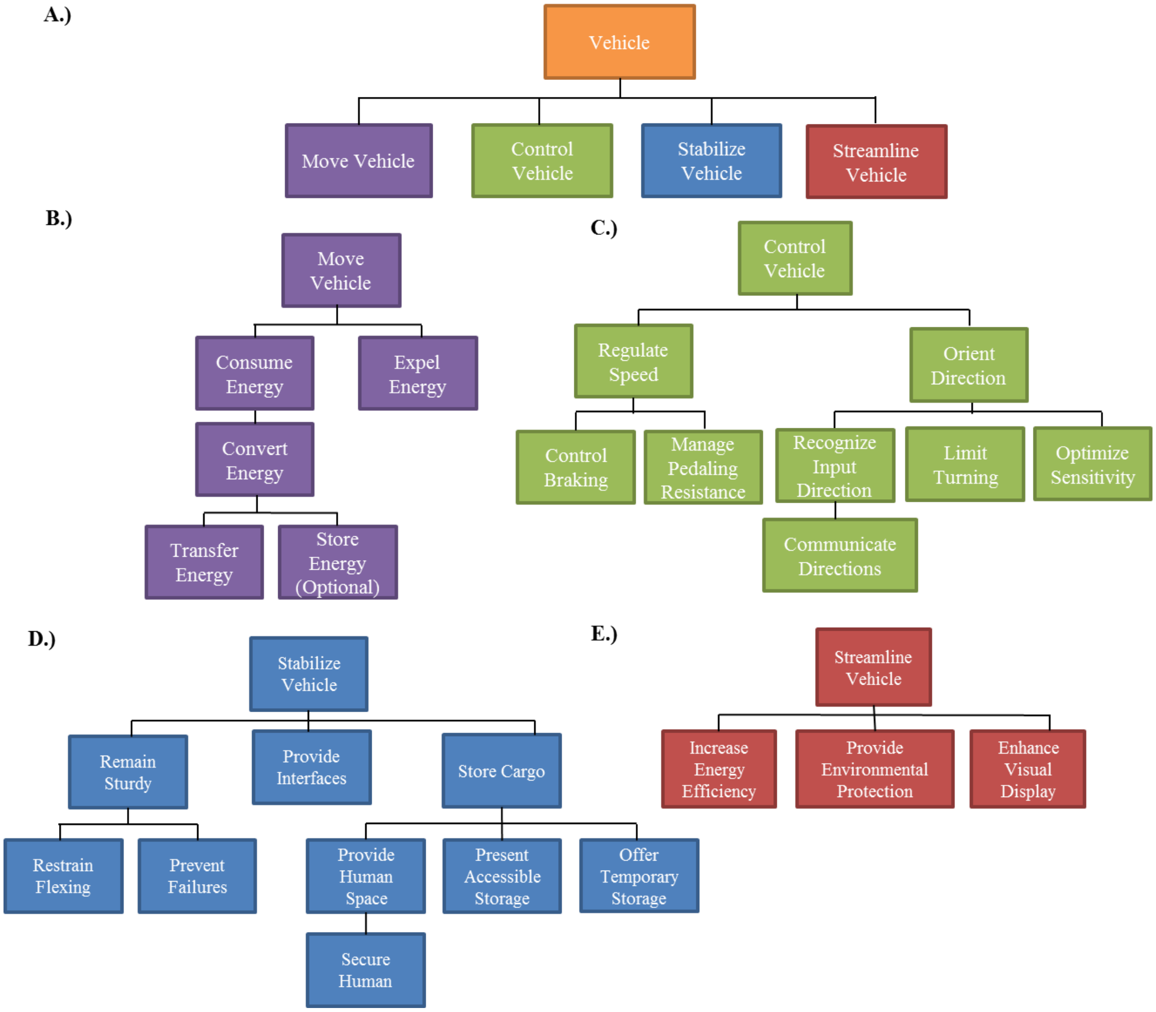


Figure 3.4 Function tree of human powered vehicle A.) Main function B) Move function C.) Control function D.) Stabilize function E.) Streamline function

3.1.2 System Level Concepts

The process of producing solution alternatives, or concepts, can be completed at various system levels. Throughout this paper a top down system level process is used. That means the general configuration of the system was determined, then the subsystems were developed, and so on. The general configuration was discussed in the project planning phase. The subsystems are the next level down and as a result they were the subject matter for the conceptual design phase for the students. It was determined the complexity of the subsystems for HPVs was suitable for the conceptual design phase. In other words, the complexity of the subsystems did not require further concepting at lower system levels, i.e. subassemblies as seen in table 3.2. Depending on the complexity of the system, further concepting and/or more information may be needed. While the frame subsystem was relatively simple, including an energy recovery in the drivetrain, choosing an appropriate steering system, and determining a manufacturing method for fairings were more difficult. In return, more research was required for concepting these subsystems. In other words, designers can concept more complex systems, but more information is required. Component and more detailed level concepts are typical resolved in the embodiment stage of the design process, for systems in complexity similar to HPVs.

An important idea to consider when concepting for engineering systems is the integrality of functions throughout the product hierarchy [25]. Another way to put this is design can either be integral or modular. Modular designs would have a one-to-one or more mapping of functions to components. This means every function has at least one unique component. Integral designs have a more than one-to-one mapping of functions to components. This means a component can be used for multiple functions. Figure 3.5 shows an example of a modular design for a trailer, while figure 3.6 provides an example of a integral design for the same trailer. The benefits of modular designs include replacing parts and maintenance, typically at the cost of weight and/or decreased aerodynamic performance. Integral designs can provide weight and drag reductions while adding the cost of more difficult repairs and or more expensive replacements. The integrality of components or assemblies can be determined at different levels of the system. Regardless of the choice proper justifications should be given.

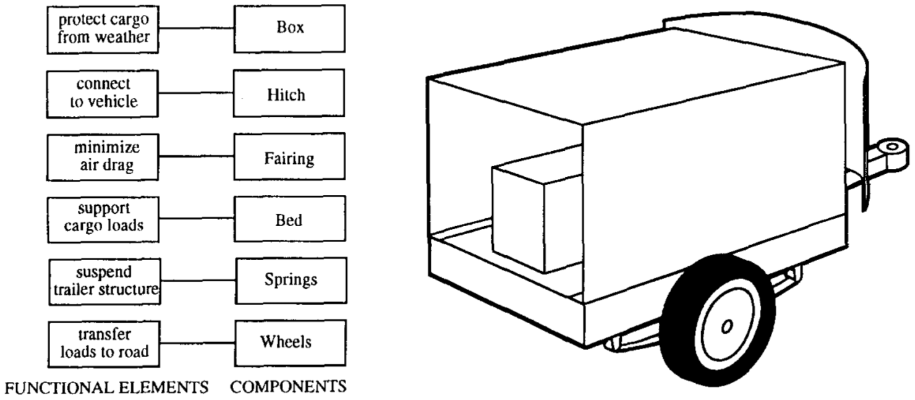


Figure 3.5 Modular design of a trailer [25]

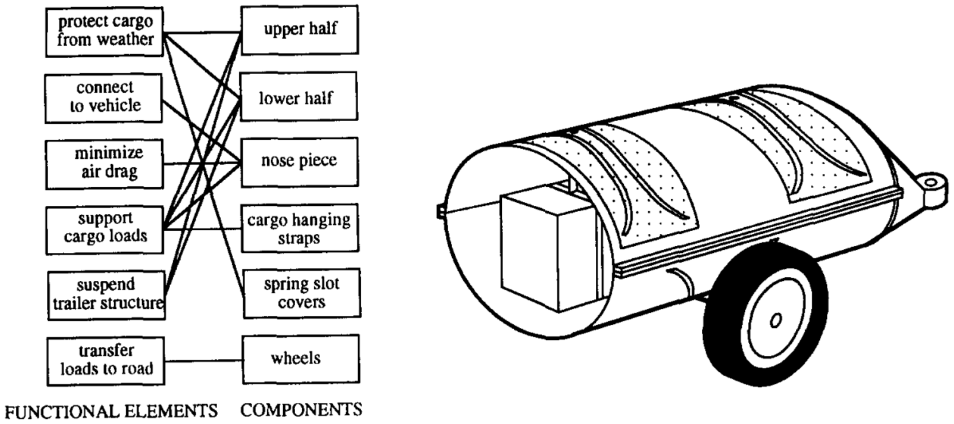


Figure 3.6 Integral design of a trailer [25]

At the subsystem level of HPVs a practical application of an integral design would involve combined aspects of the fairing and frame. If made of composite materials the fairing shape can be made more rigid in specific locations and can act as a frame or frame support, as shown in figure 3.7. Another example could include integrating the steering and frame, such as the design of tilting tricycles, shown in Appendix B.

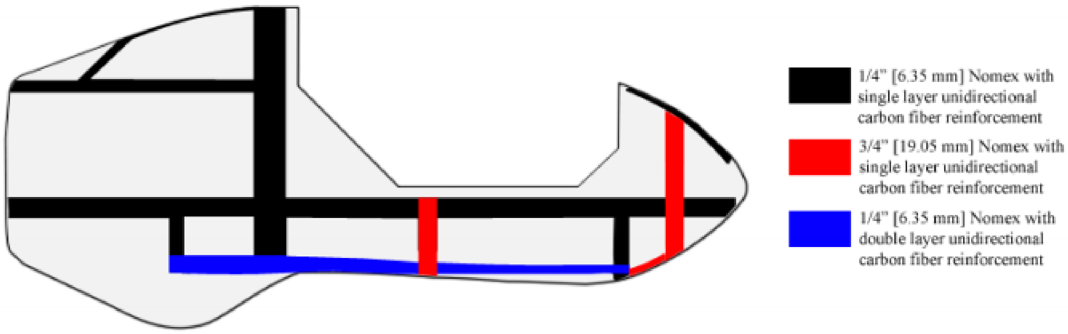


Figure 3.7 Integral subsystem example of frame of fairing [26]

3.2 Concept Selection

After concepting solution variants the designers need methods to navigate through the concepts and evaluate their likelihood and degree of success. The process of evaluating concepts also needs to address how well the concept meets the requirements. An effective evaluation process should highlight the solution alternatives with the best design performance. This is accomplished by using evaluation criteria to assess the quality of solution alternatives. A reasonable source for evaluation criteria is the previously generated requirements. From the requirements designers can generate a condensed group of evaluation criteria, such as the evaluation criteria in table 2.3. When evaluating a design based on a finite set of criteria the expanded requirements can act as basis for how concepts meet evaluation criterion.

There are several methods to evaluate concepts and highlight promising ideas. Evaluation matrices (decision matrices, pugh matrices, weighted analysis and pairwise comparison), QFD, and value analysis are examples of concept selection design tools [27]. There are other developed methods as well, such as the method created by Mistree *et al* [28]. This method is a combination of different types of matrix evaluation methods that tries to combat some of the flaws in other methods. An adapted model from Mistree *et al* is included in Appendix C, with more explanation of the mathematics involved, as well as a more detailed explanation of decision matrices. Examples of the adapted method being used are provided in Appendix H. The recommended evaluation model is outlined in table 3.3. Example outcomes of frame evaluations are provided in tables 3.4-3.6.

Table 3.3 Hybrid evaluation process

Step	**Description**	**Explanation**
1	Create acronyms	Create acronyms for the concepts to be evaluated.
2	Develop evaluation criteria	Create "essential requirements" based on the requirements previously generated. Try to limit the number of essential requirements" between three and five. Additionally create evaluation criteria for those "essential requirements"
3	Set-up evaluation matrix and select a datum	Align the "essential requirements" and concepts in an evaluation matrix. Then select a datum for comparison.
4	Perform evaluation	Compare each of the concepts. This is done by comparing the concepts to the datum. Is the concept is better for an evaluation criteria than the datum a 1 is given, a -1 for worse, and a 0 for the same. The datum receives a 0 for everything. Normalize the results
5	Record justifications for evaluations	Record the justifications for each of the comparisons. This can be used for retrospective analysis and evidence for decision making. Additionally this may be where good features of otherwise bad designs are recorded.
6	Create weighted scenarios	Create a weighting method to compare the importance of the different evaluation criteria.
7	Repeats step for multiple datums	Continue steps 3 through 5 for different datums until the results are independent of the datums used.
8	Combine the results	Combine the results and create a finalized ranking of the different concepts. The top concepts can be now be chosen for further development.

Table 3.4 Sample frame evaluation using SMCR datum

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR	FSMR	FSDM	SMOR	CRCF	TRHF
Structural Integrity										
Stability	0	1	-1	1	0	1	1	-1	0	0
Flexing	0	1	-1	0	1	-1	-1	-1	-1	1
Durability	0	-1	-1	1	1	-1	-1	-1	0	0
Environmental Adaptiveness	0	1	0	0	0	1	-1	0	0	1
Normalized Score	0.600	1.000	0.000	1.000	1.000	0.600	0.200	0.000	0.400	1.000
Manufacturability										
Components	0	-1	-1	-1	1	-1	-1	1	-1	1
Ease of fabrication	0	0	1	-1	1	1	-1	1	-1	0
Assembly	0	-1	-1	0	0	-1	-1	0	-1	0
Cost	0	-1	0	0	0	-1	-1	0	0	0
Normalized Score	0.667	0.167	0.500	0.333	1.000	0.333	0.000	1.000	0.167	0.833
Performance and Ergonomics										
Position and Comfort	0	0	-1	1	0	1	-1	0	0	1
Entering/Exiting	0	1	1	0	0	1	1	0	0	1
Controls	0	0	-1	1	0	0	1	0	0	-1
Weight (Distribution)	0	-1	-1	1	0	-1	-1	-1	0	0
Normalized Score	0.400	0.400	0.000	1.000	0.400	0.600	0.400	0.200	0.400	0.600
Safety										
Harness Support	0	1	-1	1	0	-1	-1	0	-1	0
RPS System	0	-1	-1	-1	-1	-1	-1	-1	-1	0
Visibility	0	1	-1	-1	0	1	1	1	1	0
Normalized Score	0.750	1.000	0.000	0.500	0.500	0.500	0.500	0.750	0.500	0.750
Integratability										
Seat	0	-1	-1	-1	0	0	0	-1	-1	1
Steering	0	1	-1	0	0	1	1	0	0	0
Fairing	0	-1	-1	0	1	-1	-1	-1	-1	1
Drivetrain	0	-1	-1	0	0	1	0	-1	-1	0
Normalized Score	0.667	0.333	0.000	0.500	0.833	0.833	0.667	0.167	0.167	1.000

Table 3.5 Sample frame evaluation weighting

	Case						
	1	2	3	4	5	6	7
Structural Integrity	2	1	1	1	1	5	1.833
Manufacturability	1	2	1	1	1	4	1.667
Performance and Ergonomics	1	1	2	1	1	1	1.167
Safety	1	1	1	2	1	3	1.500
Integratability	1	1	1	1	2	2	1.333
Total	6	6	6	6	6	15	7.5
						Perceived Weighting	Combined Score

Table 3.6 Sample of combined frame results (Normalized weighted scores shown)

	Concepts					
	SMCR	DMFS	SMRR	RFSR	FSMR	TRHF
SMCR Datum	0.626	0.603	0.663	0.777	0.562	0.851
THRF Datum	0.509	0.607	0.628	0.783	0.676	0.779
SMRR Datum	0.551	0.666	0.744	0.794	0.562	0.835
FSDM Datum	0.817	0.711	0.911	0.817	0.422	0.861
Averages	0.626	0.647	0.737	0.793	0.557	0.831
Final Ranks	5	**4**	**3**	**2**	6	**1**

3.3 Conceptual Design Summary

The conceptual design phase is meant to generate design solutions that could solve a given problem and meet the requirements developed. Generally, concepts are crude and underdeveloped, because they provide a baseline for an idea. Many concepts are needed to limit bias in the final solution from lack of exploring more of the design space. The important aspects of the conceptual design phase are concept development and concept evaluation.

Solution variants can be produced using a variety of concepting methods. Some of the recommended methods for students are morphological analysis, brainstorming, brain writing, 6-3-5 method, C-Sketch, gallery method, design catalogs, and TRIZ. Functional trees are also useful in determining the functional requirements of components for the product hierarchy. This in turn helps develop concepts that better suit the functional requirements.

Within concept development solution variants can be produced for different system levels with varying complexity. Higher system level concepts can allow for optimized ideas, at the cost of larger complexity, such as integral designs. Additionally, systems that are more complex require more information and research to ensure the concepts are practical and feasible. A top down approach is useful for system level concepting, because it allows the designers to get an introductory approach to the system as whole. The concepts can then become more detailed as they are embodied and more information is gathered. System level concepts also force the designers to think about the interfaces between subsystems, which is a functional requirement for all system level designs. Before completing conception generation, it is imperative to understand state of art technology. Therefore students should look at design reports of past vehicles to get a practical understanding of different systems and subsystems that have been used in the past. That being said each student could read through at least five different design reports and the team as whole could examine at least fifteen different entries of past HPVC submissions, with a mixture of successful and unsuccessful designs.

Lastly, concept selection is needed to narrow the concept generated into a small group that shows more promise. There are several methods that can be used for evaluating concepts. Of those evaluation matrices are straight forward, easy to use, and provide reasonable results. Examples of concept generation and proper use of evaluation methods are provided in Appendices C, G, and H. To summarize conceptual design more, table 3.7 is provided.

Table 3.7 Conceptual design summary

Design aspect and purpose	Design Tools	Comments
Conceptual Development: Create different solution variants for various aspects of the design including system and subsystem configurations.	Brainstorming	Used in a group setting to compare, contrast, and build many ideas off each other. Widely used and accepted.
	Brainwriting	Drawing visuals for concept ideas. Can be used in an individual or group setting. Very useful and effective for recording solutions
	Morphological	Great method for organizing different considerations for solutions. Able to product the greatest amount of ideas the quickest.
	Progressive methods	C-sketch, galley, and 6-3-5 method. Ideas continue to grow and develop throughout the concepting session
	History based solutions	Design catalogs, TRIZ, and bio mimicry. May be more useful after a set of solutions is already established.
	Functional modeling	Function structures and function trees. Descriptive tool of system components and their functionality. Should be combined with other concepting tools for more benefit.
Concept Evaluation: Selecting the most suitable solution variants	Decision Matrices	Quick and easy. Generally effective but can give misleading results based on subjective scales and evaluations
	Pair wise comparisons	Possible datum choice biasing. Great for comparing the solutions directly to each other
	Hybrid evaluation using datum analysis	Similar to pair wise comparison, but with datum biasing removed.

CHAPTER FOUR: EMBODIMENT DESIGN

Embodiment design is the step in which the top leading concepts are expanded on, narrowed to one solution, and modeled for further analysis. There are two stages for embodiment design; preliminary and definitive layout. Preliminary layout is where the form, fit, and functions of the concepts are modeled. By doing so size approximations, interface relations, and general shapes are better defined. Complications that arise highlight areas that need to be addressed, such as completing functional requirements, size restrictions, and intersecting components. The definitive layout overlaps with detailed design. In the definitive layout more in depth analysis is conducted to ensure the different subsystems, subassemblies, and components meet the functional requirements. For example, FEA and fatigue life-cycle analysis may be conducted on a rotating shaft to ensure the design is adequate for the lifetime of the product.

4.1 Preliminary Layout

The preliminary layout begins by creating initial models of the concepts. Models can be prototypes, computer aided models, schematic layouts, engineering diagrams, and so on. The models are created to help define the form, fit, and function of a design. Creating initial models gives definition to sizing and shapes. For example, figure 4.1 demonstrates how the sizes and shape of a frame concept changed once estimated dimensioning was created. By dimensioning elements of the concepts independent features are spaced more appropriately. For the preliminary layout the majority of dimensions from the model can be reasonably approximated. Once initial dimensions are given, the designers can examine standards, available resources, design requirements, and similar designs to adjust the preliminary model.

Models may consist of virtual representations; using computer aided drawing (CAD) programs, such as SolidWorks, CATIA, and Ansys. CAD model the most common models, likely

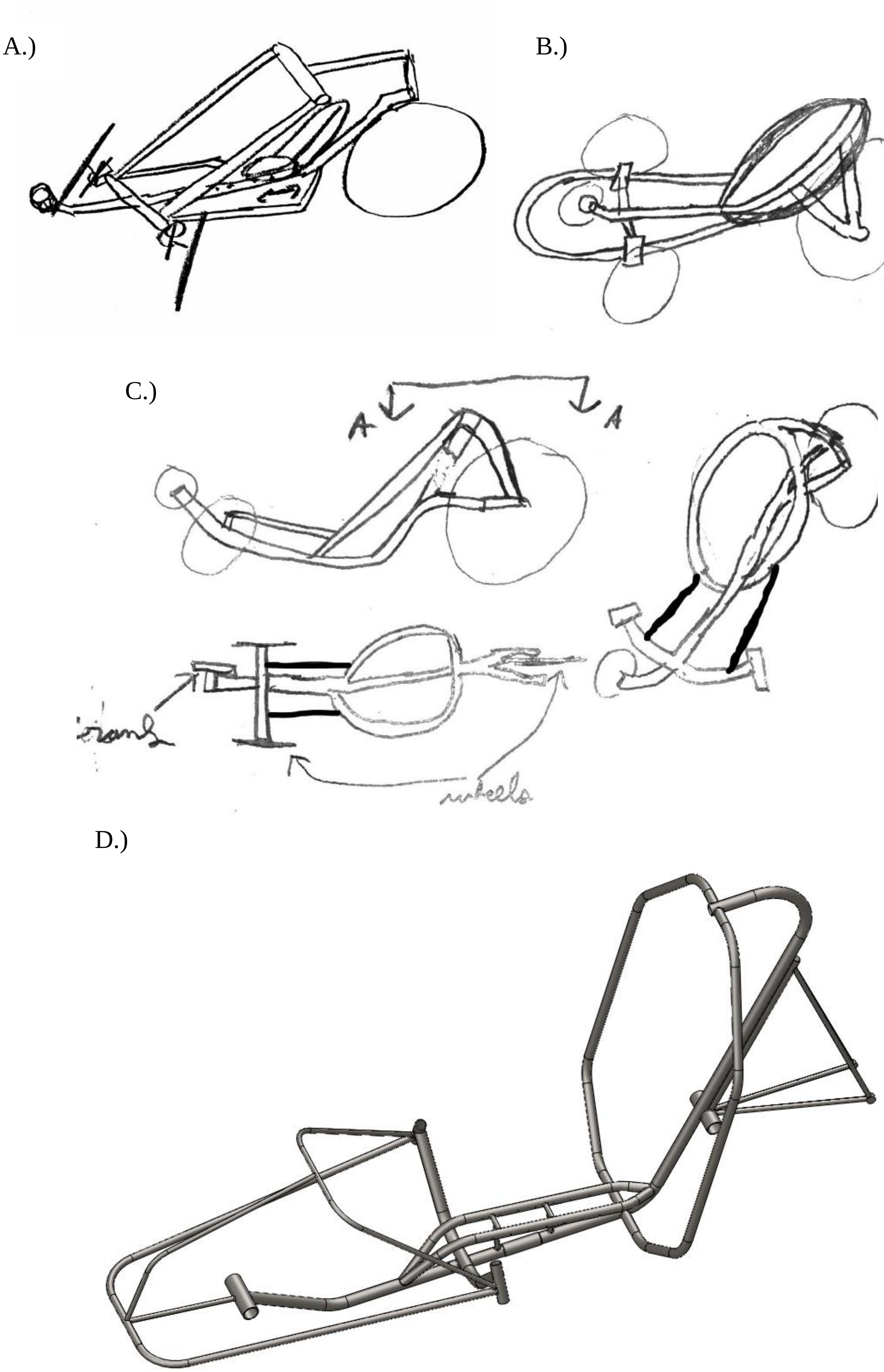


Figure 4.1 Example of transforming multiple frame concepts into a single preliminary CAD model A.) top leading concept B.) Second leading concept C.) Third leading concept D.) Preliminary CAD model of combined concepts

due to their ability to give one-to-one scaling and three dimensional viewing from any angle. CAD programs are often incorporated with tool packages to allow for fast and reliable evaluations, manufacturing plans, bill of materials, and assembly layouts. Lastly, CAD programs allow multiple users to easily combine and compare models, which allows for a greater division of labor. In other words, multiple designers can create geometrical models of different systems and components. The models can be combined to help with visual interfaces between the different models, possible sizing problems, interactions between dynamic features, assembly complications, and so on. Without CAD models, some of these complications and problems might go otherwise unnoticed.

Prototypes are another form of modeling. They can be used to physically demonstrate dimensions and help show interactions between components. This can be seen in figure 4.2 where a student led steering team was determining the practicality and functionality of a highly ranked coupled lean steering and turning concept. From the prototype the team determined many changes were required as the modeling progressed. Of the changes required for further development the most demanding changes were the interactions between the tie rod and the frame connection, the rotation pins, properly locating the steering assembly, and the rotation between the steering assembly and the frame. Some of the problems between the frame and the tie rod connection include moments and compression forces causing the pins connecting the components to bend and deform. Additionally, when tilting the frame in relation to the steering arm the connection between the tie and frame caused misalignments between the frame and steering arm. The pins used to connect rotating components needed further development, because they were unstable. The pins translated within the material and gradually changed their axis of rotated. For the connection between the frame and the steering arm it was determined an additional locating mechanism was needed to relieve stress from the tie rod connection. Lastly, a more precise hole and bearing would be required to make the tilting action of the frame more reliable.

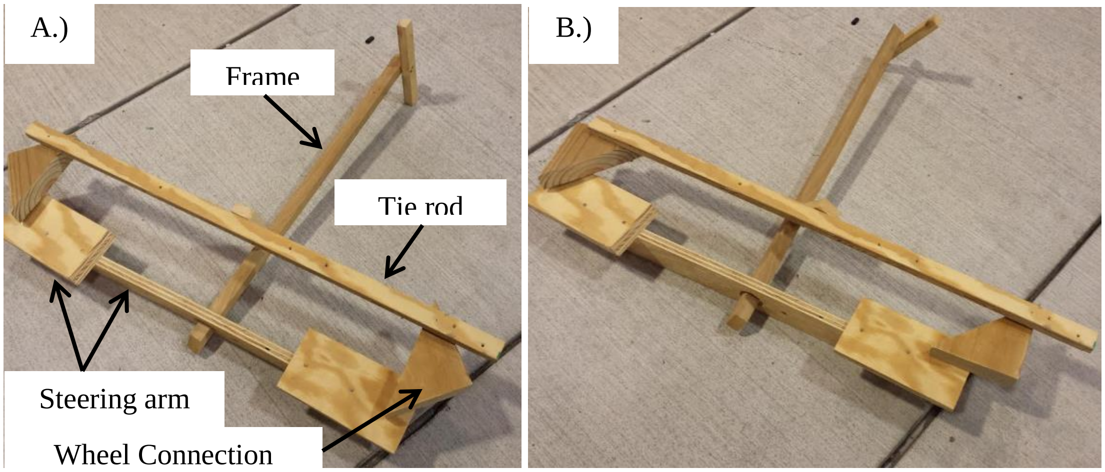


Figure 4.2 Prototype model of lean steering mechanism to determine practicality and function A.) Neutral position B.) Turned position

Another example of prototype modeling is shown in figure 4.3. The prototype was used to determine how well a geometrical CAD model compared to a physical rider. In doing so it was determined that the location of the bottom bracket needed to be extended. With the previous bottom bracket location it was uncomfortable for the rider, the knee angles and knee angle range limited the power available, and the range of riders height was limited.

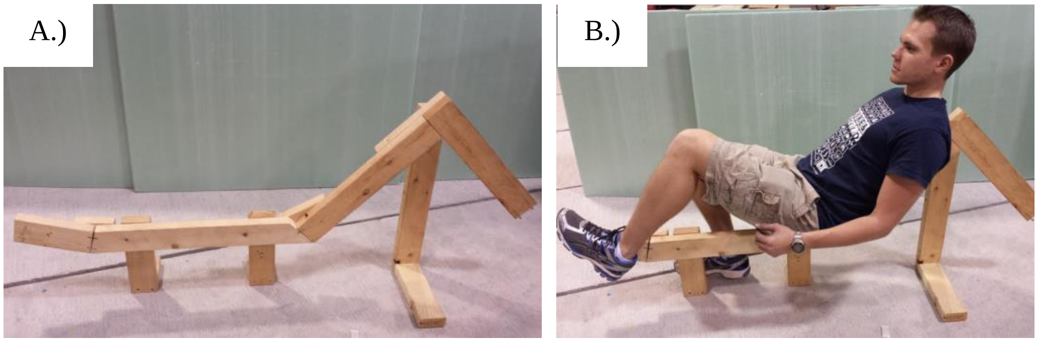


Figure 4.3 Prototype of frame geometry to determine ergonomics for drivetrain subsystem A.) Basic frame shape B.) Frame with rider

After initial modeling geometrical CAD modeling and prototypes the form, fit, and function of the design becomes better defined. In the process complications arise and refining the design is required. In the refining process more detail can be allocated towards design aspects such as ergonomic spacing, using standard components, lowering manufacturing complexity, and creating easier assemblies. These types of incorporations are known as DFX, or design for X, such as design for ergonomics. The individual aspects can be more heavily analyzed in detail design, but incorporating changes in the early preliminary layout allows for a more optimized design. This is because by the time the design reaches the detailed design phase many aspects are defined and simple changes are required to propagate throughout the entire system, making them more difficult to incorporate.

In terms of ergonomics, the design should be user friendly. HPV designs in particular should be extremely ergonomic because their sole propose is transforming human energy. In order to design for ergonomic spacing, designers can use anthropometric information. A summary of common anthropometric data can be found in Appendix I. Appendix A provides a literature review of how to apply different ergonomic aspect, such as anthropometric data. Figures 4.4 and 4.5 and table 4.1 (copied from Appendix A) demonstrate how the anthropometric data could be used for HPV design. In the preliminary layout, the anthropometric data is important, because it helps define the general spacing and dimensions of the vehicle.

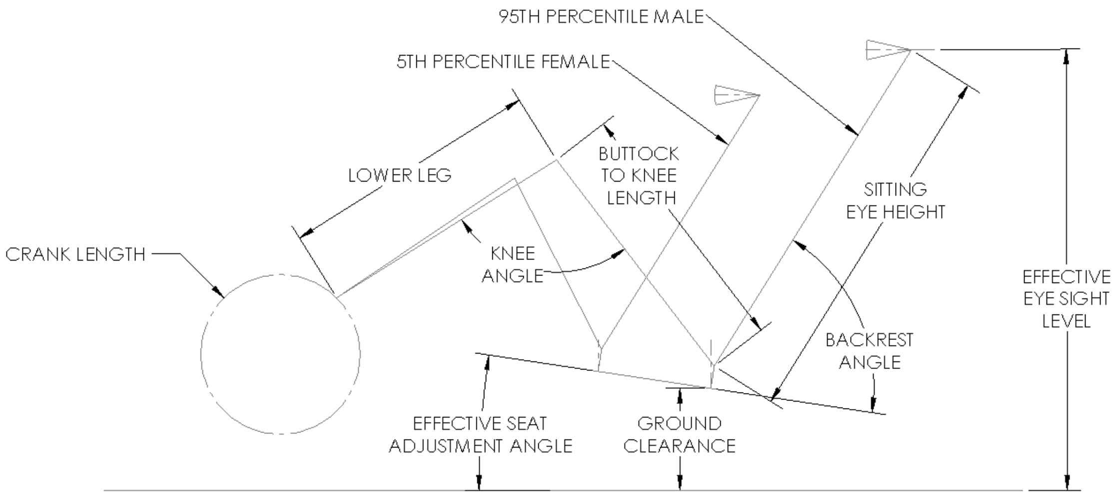


Figure 4.4 Example Sitting Configuration

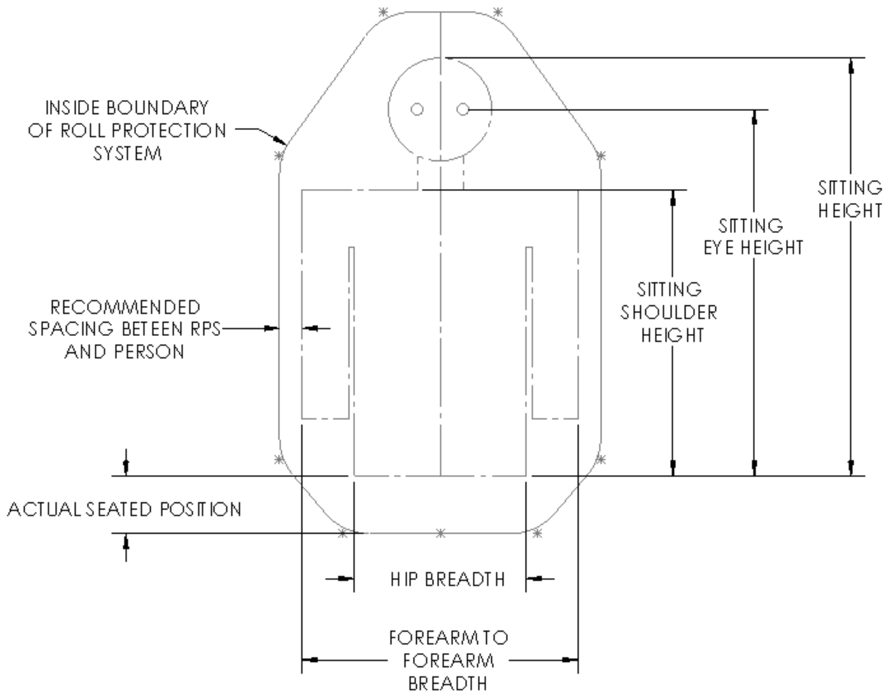


Figure 4.5 Example Roll Protection System

Table 4.1 Summarized Anthropometric Dimensions [29,30]

Dimension	Female (Percentiles in inches)				Males (Percentiles in inches)			
	1st	5th	95th	99th	1st	5th	95th	99th
Buttock to Knee Length	20.54	21.34	25.19	25.99	21.68	22.40	26.28	27.04
Forearm to Forearm Breadth	15.52	16.33	20.80	22.03	17.76	18.80	24.43	25.70
Hip Breadth	11.65	12.12	15.05	15.75	11.67	12.19	14.82	15.48
Lower Leg	15.73	16.40	19.78	20.58	17.44	18.15	21.72	22.37
Sitting Eye Height	26.14	26.95	31.27	32.23	28.02	28.94	32.92	34.23
Sitting Height	30.50	31.31	35.84	36.74	32.59	33.67	38.26	39.03
Sitting Shoulder Height	19.38	20.04	23.76	24.54	20.68	21.59	25.44	26.16

Selecting standards is another aspect in the preliminary layout. Using standards greatly reduces the total amount of design work needed. For example, trying to design a car and the engine would require much more work than necessary. Examples of standards for HPVs include, but are not limited to brakes, wheels, cassettes, chains, bottom brackets, steering tubes/forks, head tubes, dropouts, handlebars and accessories, some frame tube sizes, seat mounts, and brake mounting methods. Depending on the design of a HPV many aspects could be modified in the preliminary layout to include a greater use of standards. In turn, the amount of work would greatly reduce design work and may be more reliable. In terms of reliability, trying to create new brakes versus incorporating a form of bicycle brakes would require extensive testing, specialized and costly fabrication, and greater design work. In other words, adapting a design to fit standards, such as brake standards, saves time and money.

Preliminary analyses, like back of the envelope calculations, are useful for determining the reasonableness of design aspects. For example, equation (1) outlines the energy storage capabilities of a flywheel, where E_f is the kinetic energy of the flywheel [Nm (Joule), ft lb], I is the moment of inertia [kg m^2, lb ft^2], and ω is the angular velocity [rad/s] [31]. Common materials, moments of inertia, and flywheel energy storage examples, can be found using the reference associated with the equation. A basic stress analysis as shown in figure 4.6 demonstrates how the size of a frame tubing could be selected. Depending on the steering configuration it might be possible to use a simple four bar mechanism model to determine elements of the steering sensitivity and limit the turning radius. A basic gear analysis could be conducted to determine what combination of gears would be optimal, based on the radius and/or number of teeth from standard gears. An example of basic gear analysis and use of standard bicycle gears is shown in figure 4.7. Given the diameter of the wheels and the cadence ranges of the rider, simple calculations could also be performed to determine the upper and lower speed limit capabilities of the drivetrain. Basic calculations allow for simple evaluations of the preliminary layout and indicate the feasibility of a design. Thus, they are useful to incorporate early on to give a better understanding of design changes that need to occur, before proceeding with further testing and analysis.

$$E_f = \frac{1}{2} I \omega^2 \qquad (1)\ [31]$$

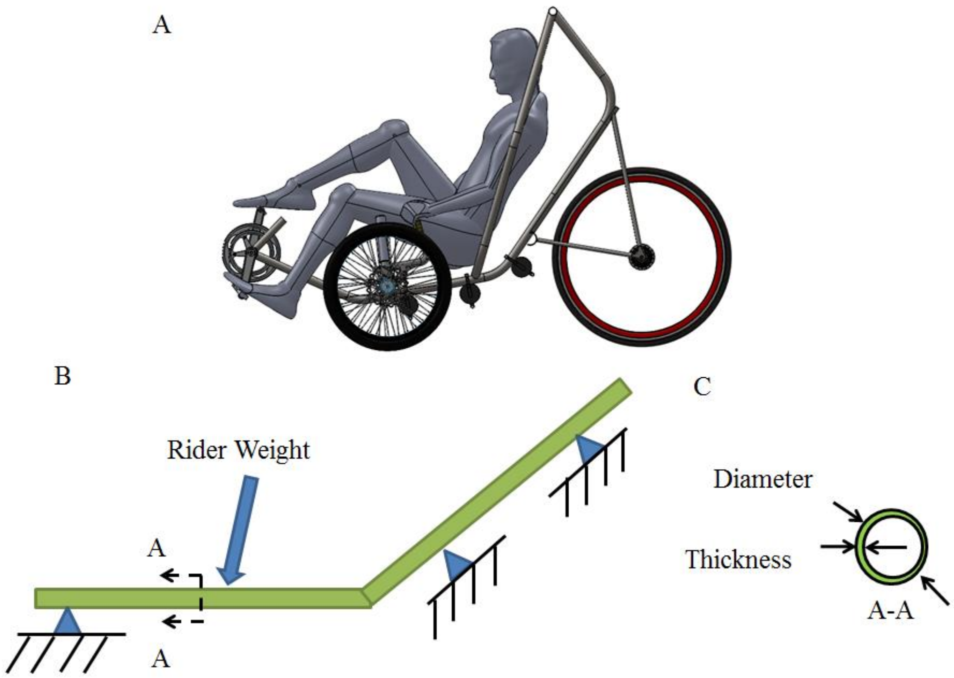
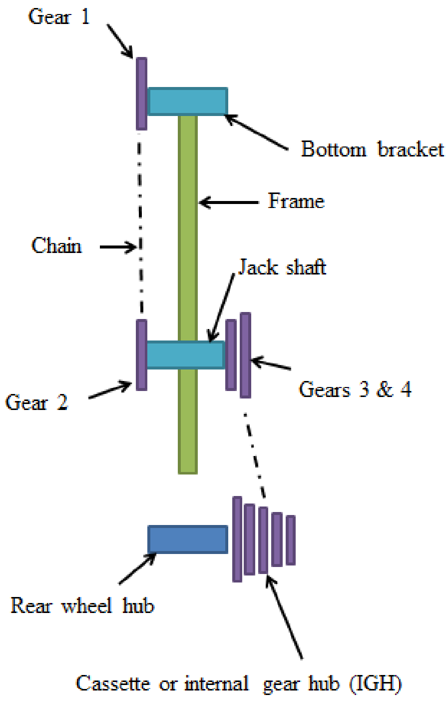


Figure 4.6 Example of basic stress calculations and how to create an engineering problem from a design A.) Original layout B.) Engineering description of problem C.) Cross section of frame



Given:
1.) Minimum gear ratio <= 1.25
2.) Maximum gear ratio >= 4.5
3.) IGH gear range 408% (11 speed)
Gear ratios range from .527 to 2.15
18T gear attached to internal gear hub

Problem:
Select gears 1-4 such that the given criteria is true. Due to sizing constraints gears 2-4 must be less than 3.8 inches in radius

Assumptions:
1.) Only standard crankset gears will be used;
Some available standards (in number of teeth)
52/42/30 (Road bike), 50/34 (Compact gear set) , 42/32/22 (mountain bike)
2.) Gear 3 and 4 must be from the same crankset

Plausible Solution:
Gear 1 = 52
Gear 2 = 32
Gear 3 =32
Gear 4 =22

Max gear ratio = 52/32 * 32/18 * 2.15 = 6.21
Min gear ratio = 52/32 * 22/18 * .527 = 1.04

Figure 4.7 Example of basic drivetrain analysis given a preliminary layout

As the preliminary layout becomes more defined, the designers gain a deeper understanding of the overall system, the subsystems, assemblies, and components. The preliminary layout could be determined to be finished once an overall anatomy of the design can be given. Figure 4.9 gives an example anatomy of a bicycle, while figure 4.8 gives an example anatomy of a tadpole tricycle. A completed anatomy demonstrates the system as a whole has been completed and thought was given to features at the lowest level of the system. It also means the design is ready to move forward to definitive layout for more in-depth analysis. In definitive design, in-depth analysis and more details will help validate the design, determine manufacturing plans, layout the materials and parts to be purchased, and so on. As the anatomy is defined a preliminary parts list could be created. From the preliminary parts list some supplies could be ordered, such as standards or items that may require additional shipping times. The preliminary parts list also gives the design group a better idea of the budget needed.

Figure 4.8 Anatomical view of a typical recumbent tadpole tricycle [32]

Figure 4.9 Anatomical view of a typical road bike [33]

4.2 System Level Embodiment

In the preliminary layout, it was mentioned many times that different system level aspects need to be considered. The preliminary layout would be determined finished once the lowest system level components were modeled and a complete system anatomy could be given. The system anatomy of the design could then be related to the original product hierarchy. The original product hierarchy would then be updated to provide a more detailed representation of the system, in relation to the preliminary layout. Likewise, the function tree would be updated based on the preliminary layout to detail the functional significance of each system level aspect. Depending on the functional descriptions of every feature, the total number of features could be reduced for more of an integral design, or increased for more modularity. This idea of functional analysis allows the students to evaluate why every feature is included in the overall product hierarchy and help determine the necessity of the features created. Additionally, students may find that functional requirements of the system are missing and as a result more features need to be included in the design.

Aside from maintaining organization of the system through product hierarchies, system anatomy, and function trees, interface management can be used to track the interactions between various system level features. Figure 4.10 provides a guideline to the interface management process. To summarize students need to develop requirements for the interfaces between features and document the changes that occur. By doing so the interfaces become controlled, regardless of what component a system is in. For example, say a bracket for an idler gear for the drivetrain subsystem, is required to be welded to the frame. In doing this, a location requirement for the bracket and geometrical limitations for the bracket is specified. Documentation of some kind (could be a CAD model and an update to the requirement's list), is created to designate where the location and size of the bracket is. From then on, both the drivetrain and frame subsystem agree to have that desired interface of a stated location and size. Changes to the interface require the approval of both subsystems in order to ensure the functionality of each subsystem is unaffected by the change. Another method to document the interface management is by using a N^2 diagram, as shown in figure 4.11. The N^2 diagram is used to quickly demonstrate how different system level features are related and how that relation occurs. This interface management styles can be combined in a way that CAD models and requirement lists detail the interfaces, while the N^2 diagram visually documents those requirements into a single chart.

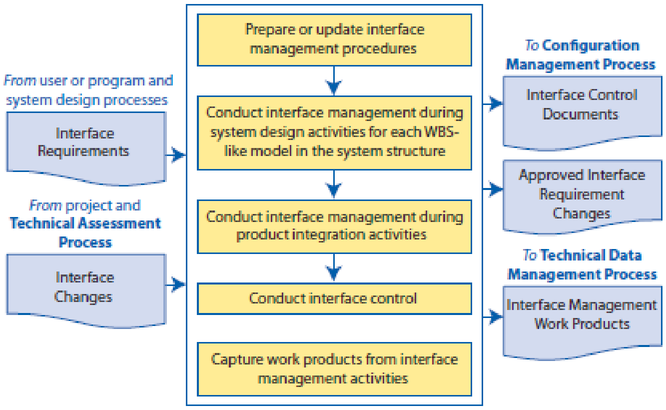


Figure 4.10 Interface management process [2]

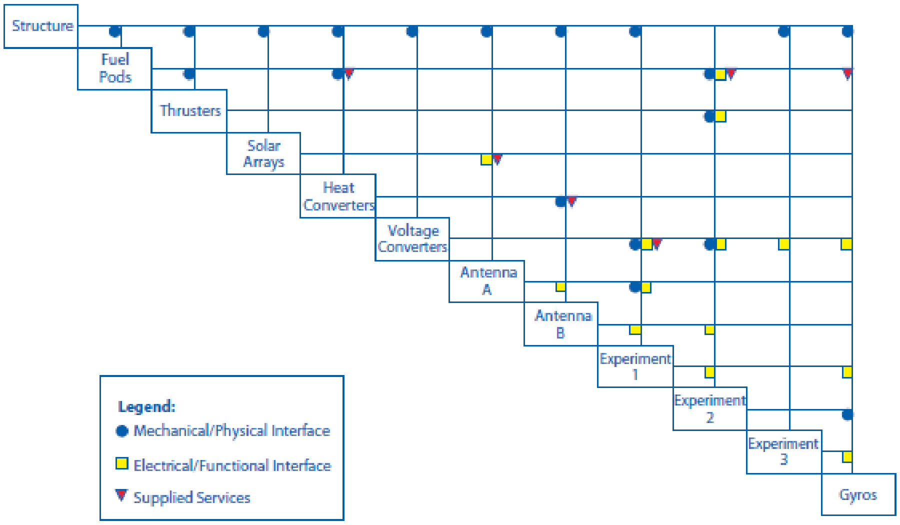


Figure 4.11 Example N^2 diagram of orbital equipment [2]

4.3 HPV Specific Guidelines

Each of the four main subsystems and the system as a whole have specific guidelines, standards, manufacturing methods, analysis, and assembly features that can be followed. This section aims to discuss many of those aspects. Here the majority of the focus is given towards tadpole trikes, with limited details about other HPV configurations. The reasoning is because tadpole trikes are more complex and most designers have limited knowledge of the design aspects. Additionally, the scope of this paper is limited to providing guidelines in HPV design, thus not every detail of every type of HPV can be explored. By providing specific guidelines about tadpole tricycles, designers may examine some design considerations and observe aspects that can be extended to different HPV configurations.

4.3.1 Frame Configurations

First, frame subsystem details will be given. Frames typically come in a select number of materials; steels, aluminum, wooden or bamboo, and composite tubing. The shape of the tubing varies, but most shapes are either circular (typical aluminum and steel tubing), square (custom tricycle builds), rounded polygons (composites), or teardrop (triathlon bicycles). To connect different tubes together welding, lugs, and monocoque designs are often used. Lugs are standard connections where tubes of different length, but the same cross sections can be connected. Cheaper carbon fiber and composite frames use lugs coated with a layer of paint, to hide the use of lugs, often giving the deceptive appearance of a monocoque design. As an example of how the frames construction can vary from the mentioned features, during the 2015 HPVC east event, one team’s innovative aspect was the frame being completely made of bamboo, with 3D printed, carbon reinforced lugs as connections.

In tricycle design the frame determines different aspects of the vehicle, such as weight distribution, wheel configuration, center of gravity, and wheelbase. Table 4.2 outlines some of the outcomes of frame styles and these vehicle dynamics. Due to surplus of tadpole configuration advantages over delta styled tricycle, recommendations for tadpole designs will solely be given. The horizontal weight distribution determines how well the trike handles and how stable it will be [4]. More weight towards the front provides better cornering and leads to less over steering. Too much weight on the front will cause the rear wheel to be useless, especially during hard cornering. A more optimized weight distribution is 70/30 with more of the weight being on the front wheels. The vertical weight distribution or center gravity greatly affects handling as well. Lower centers of gravity, such as below the wheel axle heights, allow for excellent handling at the cost of visibility, safety, comfort, and practicality. Lower center of gravity also reduces the importance of horizontal weight distributions. The wheelbase is the distance between the front and the rear wheels. Changing the wheelbase effects the weight distribution, on the wheel, the vehicles turning abilities, steering, stability and overall comfort. The wheel track is the distance between the two front wheels. Wider wheel tracks help prevent roll overs during cornering. Bike lane widths and doors make wheel tracks that are too wide impractical. Between 29” and 32” are general recommendations that allow for excellent handling. Reduced wheel tracks can be used, if other features are incorporated, such as negative camber. Smaller wheel tracks and larger wheels may interfere with the rider's legs. In general, as the wheel track decreases so does the space and comfort for the rider.

Table 4.2 Brief discussion on frame configuration and wheelbase (adapted from [4])

Configuration	Pros	Cons
Delta tricycle 	• Easy to design and follows ideas of a standard bicycle. • Lower costs to manufacture	• Quick moment of inertia causes excessive roll (could be corrected using lean steering) • Majority of braking relies on single front wheel • Greater chance in oversteering and loss in handling performance, due to greater momentary acceleration of the front end
Tadpole tricycle 	• Uses the same steering principles as an automobile • Two front wheels offer an excellent braking • Has overall excellent handling • Allows for greater cornering and stability	• Steering systems are more complicated and require more unique parts. • Design is more complicated and dependent on more features
Wheel base	Pros	Cons
Short wheelbase (under 40") 	• Tighter turn radius • Faster and sportier handling • Smaller and more compact frame	• Rider's position has more effect on weight distribution • Reclining of the seat is limited
Long wheelbase (over 40") 	• Seat has more room for reclining • Rider's position has less effect on weight distribution	• Longer frame leads to higher weight and more flexing • Creates a larger turn radius

Another aspect of frame design is the general frame design. In terms of the general shape that needs to be created in such a way that is increasing rigidity to prevent flexing, accounts for ergonomics, gives an approximate weight distribution, limits unnecessary weight, and provides structural support. Some ideas include integrating features to reduce weight and increases rigidity, such as a combined seat support. In designing the rear end, or connection to the rear wheel, some structural considerations are the weight loading, chain loading, and torsional loadings from dynamic forces. Full triangulated stays, shown in figure 4.12, are the most recommended rear end design and have excellent performance for weight, chain, and side loading.

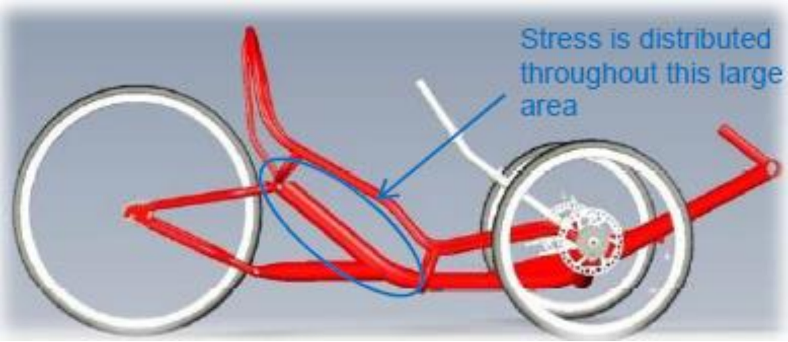


Figure 4.12 Example of full triangled stays [4]

4.3.2 Steering Systems

For the steering geometry there are many considerations [4]. To begin, wheel caster is the angle between tire contact patch and the kingpin axle, as shown in figure 4.13. The wheel rotates on the kingpin axle and as wheel is placed on the vehicle, caster causes the wheels to point inwards. Increasing the caster increases the force applied. The caster for standard automobile is four to five degrees, while go-cart caster gets much steeper.

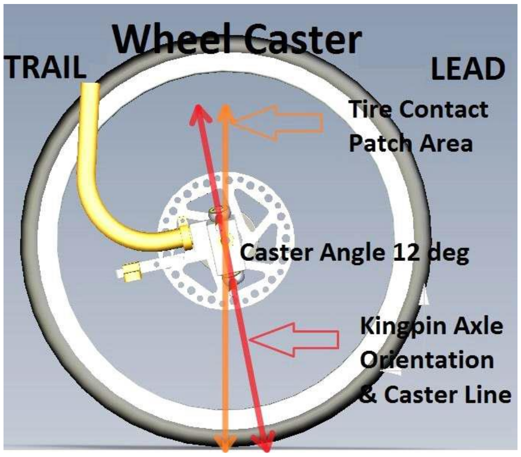


Figure 4.13 Caster angle orientation [4]

Another steering consideration is camber, the angle between the front wheels. Wheels perpendicular to the road have neutral camber. Negative camber is when there is less distance between the tops of the wheels than the bottom and positive camber vice versa. Neutral or negative camber is generally preferred. In addition to camber toe-in is another steering geometry that needs consideration. Toe-in is the angle at which the front wheels point towards each other. Positive toe-in is where the front wheels point towards each other and away from the rear wheel. Toe-in is often a desirable trait, because it provides great straight line stability at the cost of efficiency and sluggish cornering. That being said a little toe-in, if any, is often required.

One major consideration for steering is Ackerman compensation. This steering compensation was created to prevent the wheels from skidding when the vehicle turns. When the vehicle turns the inside wheel of the steered direction must turn sharper than the outside wheel. Figure 4.14 provides a visual representation of Ackerman compensation for clarity. To prevent skidding, the wheels could also rotate at different rates, instead of different angles. For this reason, delta tricycles and the rear wheels of four wheeled HPVs make sure of rear differentials. To implement Ackerman geometry, controls arms attached the wheel axles should point towards the rear wheel, as shown in figure 4.15. Controls arms are extensions of the king pin housing that is also connected to linkage systems that moderate turning of the wheels.

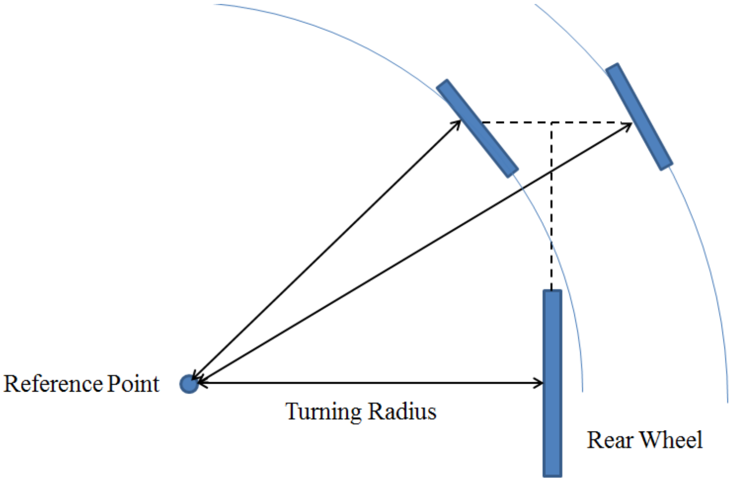


Figure 4.14 Visualization of Ackerman compensation

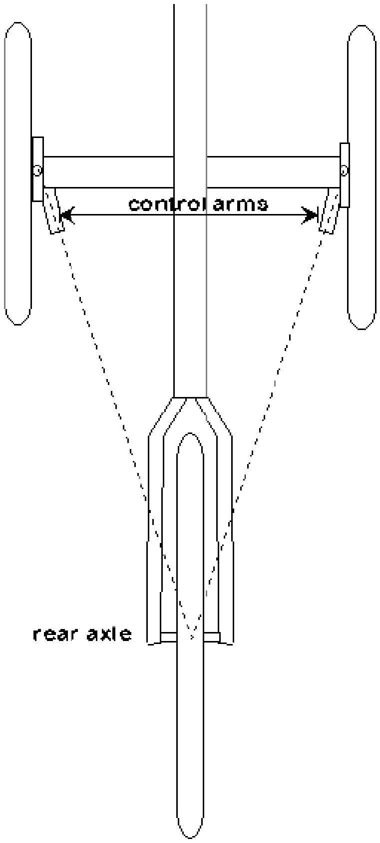


Figure 4.15 Ackerman implementation [4]

The Ackerman geometry does not guarantee the best performance and in some cases it is desirable to reduce Ackerman geometry in large radius turns, for steering that is less sensitive and less prone to over-steering [4]. The Anti-Ackerman prevents oversteering at high speeds and acts as a partial Ackerman implementation. It allows slight tire skidding with large radius turns and follows full compensation for tight turns. The final result is slower cornering, without steering instability at larger speeds.

The placement of the kingpin has more implication on the steering geometry. As shown in figure 4.16, the kingpin should align with the center patch of the tire, which is otherwise known as center point steering. Doing so makes the steering less affected by road defects and reduces “bump steering”. The relationship between caster and the kingpin inclination also allows the wheels to lean into the corner, which in turning slightly enhances the handling. Automobile designers deviate from the kingpin inclination and let the intersection line fall short of the center patch for enhance road feel. This reduces brake pull, but can cause over steering. Some manufacturers do not implement center point steering, because the king pin is close to the wheel and as a result the king pin center line is close to the tire patch.

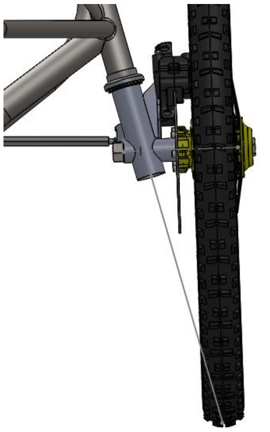


Figure 4.16 Kingpin alignment [4]

In terms of steering mechanisms there are many different types, but the three basic configurations are over seat steering, direct knuckle steering , and under seat steering [4]. An assessment of these different steering configurations is provided in table 4.3. Over seat steering gives a similar feel to traditional bicycle steering. A “Y” or “T” shaped handle is turned, which causes the wheels to rotate. The handle rotates about a joint and linkages are then used to connect the rotation of the handles to the rotation of the wheels. Higher end designs make use of U-joints, while cheaper design use a fixed or restricted single axis movement. Direct knuckle steering uses the head set assembly and head tube from a bicycle. A bicycle steam and handle can then be attached directly to each wheel and the user directly controls the wheels. A tie rod connecting the control arms in figure 4.15 is recommended to ensure the wheels rotate correctly in relation to each other. Under seat steering uses a U-bar under the seat which is connected through linkages to the front wheels. The different linkage systems connect to the control arms attached to the king pin.

Table 4.3 Assessment of steering configurations (adapted from [4])

Steering System	Pros	Cons
Over seat steering	• Lower Weight than under seat steering • Lower Complexity • Allows for narrow wheel tracks • Lowers frontal area (Aerodynamic improvements)	• Rider cannot use handles for support, which requires a seat with lateral support to keep the rider from falling out • Not popular, due to arm fatigue and/or lack of intuitive design. • Fatigue level is higher than under seat steering
Direct knuckle steering	• Simple and cheap. Use a single tie rod system • Provide comfortable support for arms • Gives rider support during high speed turns, precludes use of lateral seat support • Lowest weight • Use existing bicycle components	• Side to side motion counter intuitive to some • Increases frontal area (Less aerodynamic) • Places rider's hands dangerously close to wheels or ground • Requires ample room for handles
Under seat steering	• Intuitive control makes it easier to use. • Provides comfortable support for arms • Gives rider support during high speed turns, precludes use of lateral seat support	• Heavier weight compared to over seat steering • Increases frontal area (Less aerodynamic) • Places rider's hands dangerously close to wheels or ground • Requires ample room for U bar clearance

There are main different steering linkage systems. Of those some common ones will be explained here [4]. One linkage configuration that can be used with under or over seat steering is a single tie rod and drag link system is shown in figure 4.17. Ackerman compensation can be used by adjusting the control arms to the proper alignment. Although the configuration uses more links than some other it allows for superior adjustability and adequate Ackerman compensation. The dual drag link system, shown in figure 4.18, is another linkage system, which offer near perfect Ackerman compensation. The positioning of the bell crank can be changed, but keeping the drag link almost parallel is needed. Thus a position of the bell crank that is not aligned with the kingpins could be used, but it would have to be either shorter when moved aft or longer when moved forward. Adjusting the bell crank alignment does effect the overall Ackerman compensation. The linkage becomes complicated when adapting to under seat steering, because of the second bell crank and additional tie rod.

To understand the figures of the linkage systems better it is necessary to consider which parts are fixed and which parts moved. In both figures 4.17 and 4.18 the kingpins are fixed and free to rotate. The wheel axles and control arms rotate with the kingpin. The tie rod and drag link are of fixed length and are free to rotate at their connection points. In the under seat steering configurations the rotation of the U-bar is in the center of the bell crank (rectangle mount with four circles). It is also important to note for the under seat steering (figure 4.17B) the distance between the connection to the drag link from the bell crank and the bell cranks rotate together, which allows the rotation of the U-bar to move the drag link. For the over seat steering the handle is connected to the top circle on the bell crank. In other words, the bell crank rotates about the top circle, due to the rider turning the handle.

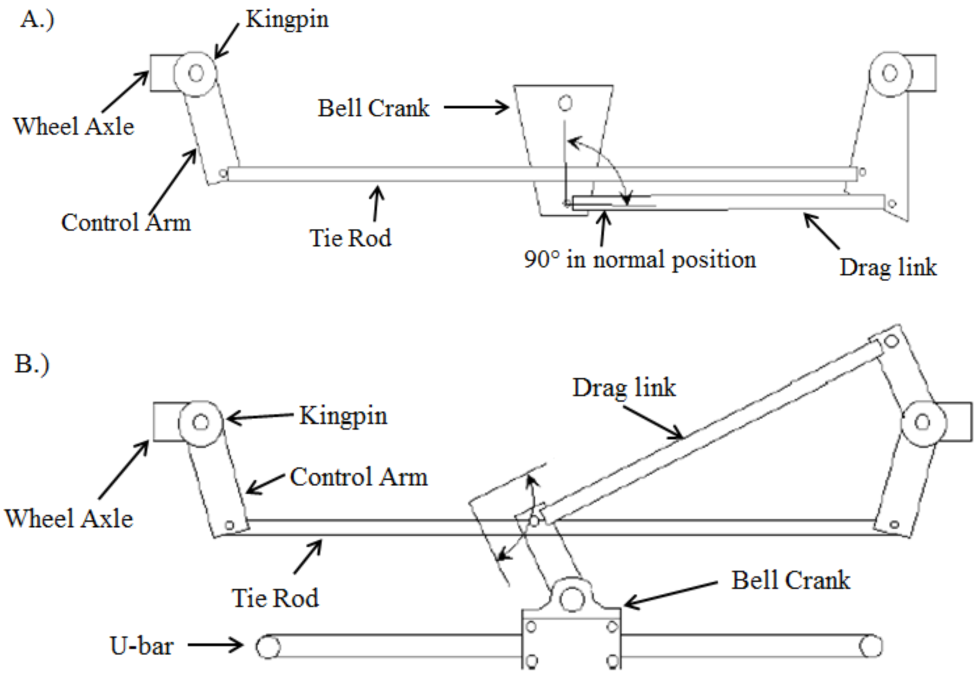


Figure 4.17 Single tie rod with drag link system A.) Over seat steering configuration B.) Under seat steering configuration (Adapted from [4])

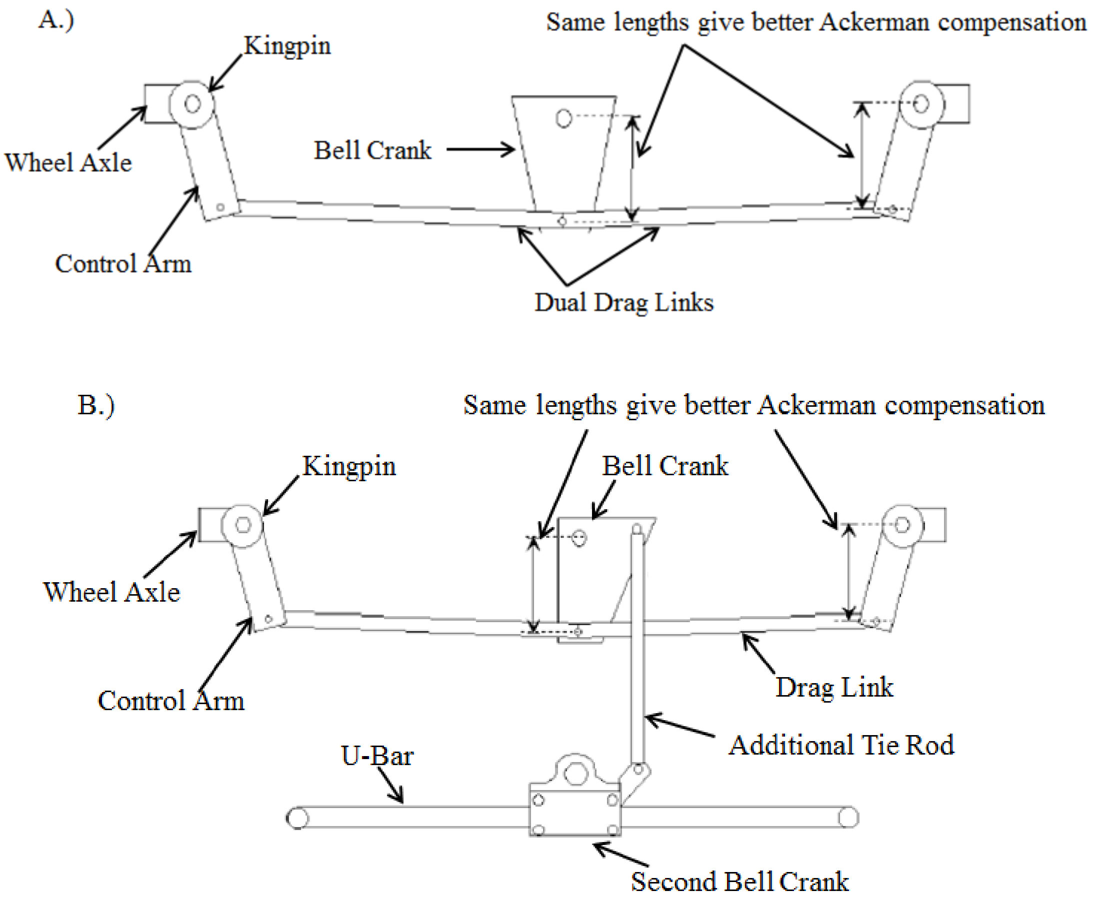


Figure 4.18 Dual drag link system A.) Over seat steering configuration B.) Under seat steering configuration (Adapted from [4])

Lastly, the crossed dual drag link system, shown in figure 4.19, is another common linkage system [4]. It has been optimized for under seat steering, because the bell crank is placed behind the kingpins, meaning the steering knuckle does not follow the typical Ackerman geometry. The linkage system can be adapted for over seat steering by moving the bell crank forward, but an aft lever duel drag link system is better suited for over seat steering configurations. This linkage system is an application of the right angle rule, which requires the tie rod to be orthogonal to the bell in the neutral position. For more Ackerman compensation, to prevent tire scrubbing, the mounting on the bell crank was angled further back.

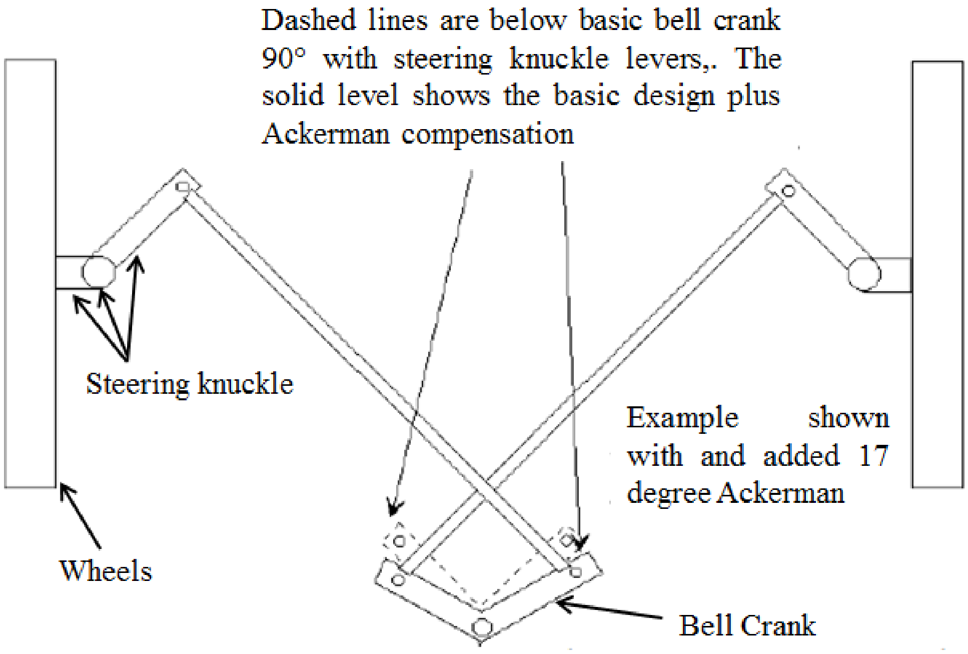


Figure 4.19 Crossed dual drag link system (Adapted from [4])

Understanding standards such as bicycle head tubes, crown races, and headsets will help designers understand methods of how to create a rotating axle for the front wheels. Brown and the Park Tool company do a great job of explaining this [34,35]. To give an example, a head tube could be welded to a tricycle frame in position of the desired king pin alignment. Next a steering tube from a bicycle fork can be cut and used as the rotating shaft. A headset assembly can then be installed with the steering tube to allow for a smooth rotating shaft. An axle can later be added to the steering tube at the desired angle. The other steering considerations, such as kingpin alignment can be used to determine the proper angle. Lastly, other needed elements such as the connection for the tie rod can be added to the steering tube as well. To give a better understand of how bicycle standards could be used, figure 4.20 gives a visual representation of the discussed example. To add suspension, springs could be added around the steering tube.

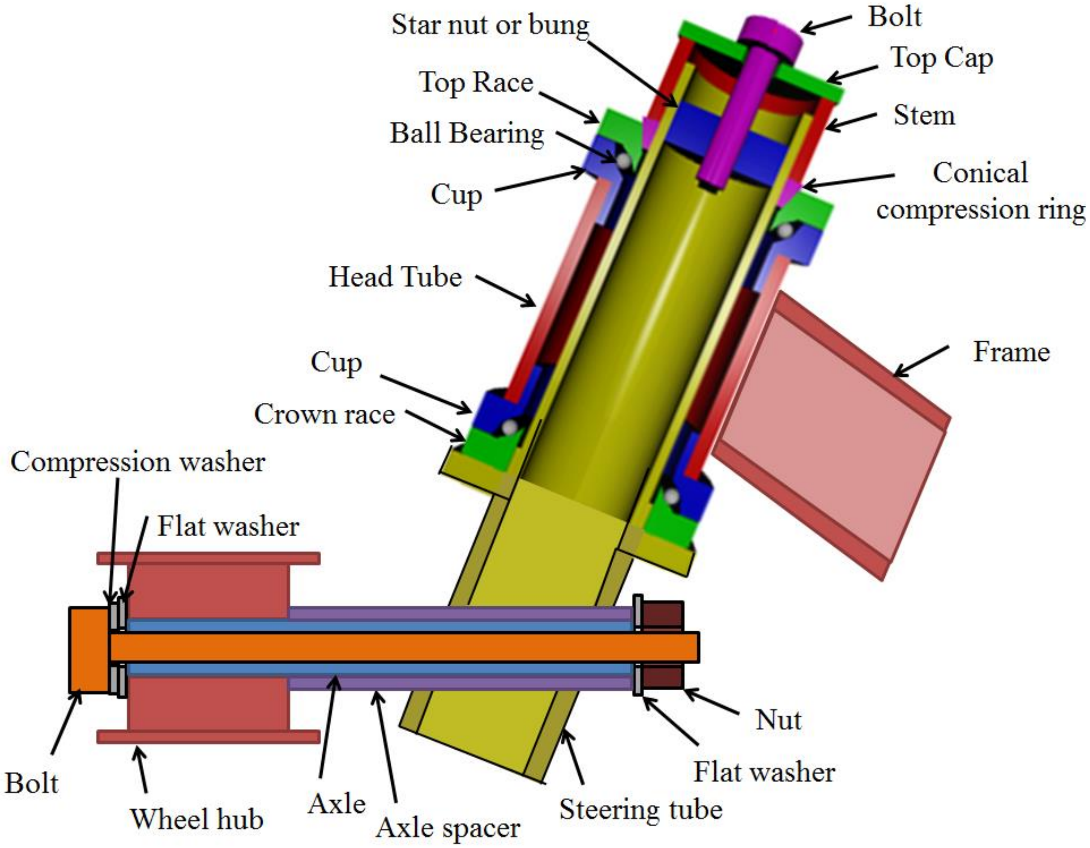


Figure 4.20 Example cross section of possible angle steering axle solution

4.3.3 Drivetrain Considerations

The drivetrain of tadpole tricycles can range from simplistic to relatively complex systems. The main function of the drivetrain is to transfer power from the rider to the wheels. The tool used to absorb the power is typically a crankset. The energy is transferred using chains and is absorbed by rotating the rear wheel. From this the main concerns of the drivetrain are often chain management, gearing analysis, user interfaces, and standard compatibilities.

To begin the gearing analysis is used to determine the available gear ratios the drivetrain will use. This in turn affects the step sizes, total gear range, and number of usable gears. Larger gear ranges allow for more variation in pedaling resistance. For overall adequate pedaling resistance Small gear ratios are needed for steep uphill and large gear ratios are needed for maximum speeds on flats and downhill sections. Typical road bikes have a minimum gear ratio of about 1.4 and maximum of about 4.7 to give an idea of how pedaling resistance can vary based on gearing and slope of the road, which also gives a gear range of 336%. This is accomplished from a 52/39 crankset and an 11/28 10-speed cassette. Using the same components, table 4.4 shows the step analysis. Based on the wheel size and rider cadence, the gearing can be used to back out speeds estimates of the HPV, as shown in table 4.5**.** Different drivetrain gearing configurations and parts can change the step sizes, mean step, usable gears, gear range, min/max gear ratios, as shown in table 4.6. Some systems will still use a single speed system for simplicity and/or to force more (average) pedaling resistance to the rider.

Table 4.4 Gear analysis of 52/39 crankset and 11-28 10-speed cassette

Crankset (52/39)		**Gear Ratios**		**Usable Gears**	**Gear Ratio**	**Step Size**
		52	*39*	*52/11*	4.73	
Cassette	*11*	4.73	3.55	*52/12*	4.33	9.2%
	12	4.33	3.25	*52/13*	4	8.3%
	13	4	3	*52/14*	3.71	7.8%
	14	3.71	2.79	*52/15*	3.47	6.9%
	15	3.47	2.6	*52/17*	3.06	13.4%
	17	3.06	2.29	*52/19*	2.74	11.7%
	19	2.74	2.05	*39/15*	2.6	5.4%
	21	2.48	1.86	*39/17*	2.29	13.5%
	24	2.17	1.63	*39/19*	2.05	11.7%
	28	1.86	1.39	*39/21*	1.86	10.2%
				39/24	1.63	14.1%
				39/28	1.39	17.3%
					Mean Step	**10.8%**

Table 4.5 Speed analysis of various gear ratios [36]

Gear	Front/ Rear	60 rpm		80 rpm		100 rpm		120 rpm	
		mph	km/h	mph	km/h	mph	km/h	mph	km/h
Very high	53/11	22.3	36	29.7	47.8	37.1	59.7	44.5	72
High	53/14	18	29	24	38.6	30	48.3	36	57.9
Medium	53/19 or 39/14	12.5	20	16.6	26.7	21	33.6	25	40
Low	34/23	7.2	11.6	9.6	15.4	11.9	19.2	14.3	23
Very low	32/42	3.5	5.6	4.7	7.6	5.9	9.5	7.1	11.4

Table 4.6 Gearing analysis of different bicycle transmissions. [36]

Gear Range	Transmission (Gearing)	Usable Gears	Mean Step
180%	3-speed hub gears	3	34.2%
250%	5-speed hub gears	5	25.7%
300%	7-speed hub gears	7	20.1%
307%	8-speed hub gears	8	17.4%
327%	Typical 1 chainring derailleur setup (1x10, 11-36)	10	14.1%
327%	Road 1 chainring derailleur setup (1x11, 11-36)	11	12.6%
350%	NuVinci continuously variable transmission	Continuous	N/A
409%	11-speed hub gears	11	15.1%
420%	Extreme 1 chainring derailleur setup (1x11, 10-42)	11	15.4%
428%	Road 2 chainring derailleur setup (2x10, 50-34 x 11-32)	13	12.9%
441%	Road 3 chainring derailleur setup (3x10, 52/39/30 x 11-28)	15	11.2%
518%	Mountain 2 chainring derailleur setup (2x10, 38-24 x 11-36)	14	13.5%
526%	Rohloff Speedhub 14-speed hub gear	14	13.6%
630%	Mountain 2x11 derailleur setup (24/36 x 10-42)	14	15.2%
636%	18-speed bottom bracket gearbox	18	11.5%
655%	Mountain 3 chainring derailleur setup (3x10, 44-33-22 x 11-36)	16	13.3%
698%	Touring 3 chainring derailleur setup (3x10, 48-34-20 x 11-32)	15	14.9%

Chain line management is one concern for drivetrain systems. The simplest configuration is one chain connecting the cassette of a rear wheel to the crank set. For longer drivetrain systems this simple configuration would give problems of too much slack in the chain, the chain rubbing against the frame and/or ground, shifting concerns, and a greater chance of chain derailment. There are several features that can be added to control the chain path. One possible add on is the use of chain tubing. To use chain tubing, the tubing is mounted to the frame and the chain is guided through the tubing. The tubing material allows for manageable wear with the chain. The use of chain tubing creates a path the chain is forced to follow. Chain tubing is considered advantageous because of its cheap cost.

To manage chain slack one consideration is the use of idler gears. Idler gears are costly, but act as an additional control point for the drive system. As a control point the chain is tensioned more and is allowed to change direction. Figure 4.21 gives an example drivetrain using two idler gears with limited frame geometry. As seen the idler gears are helpful for managing the chain around the frame. If choosing to use idler gears make sure the mounting is properly secured to the frame. In the past Clemson drivetrain clamp mounts failed because of the chain tension causing forces and moments to the mounts. This caused the idler mount to rotate around the frame tubing and resulted in drivetrain failure. The problem was solved by welding custom brackets to the frame for the idler gear to attach to. The brackets had a properly sized nut weld on one side and the idler gear connected had a corresponding threaded axle. Idler gears consist of different styles, such as a power gear (normal geared teeth), Teflon roller (for friction resistance rubbing), single gear (for one chain), and a double idler (for "two" chains using two idler guides on a single idler, as shown in figure 4.21).

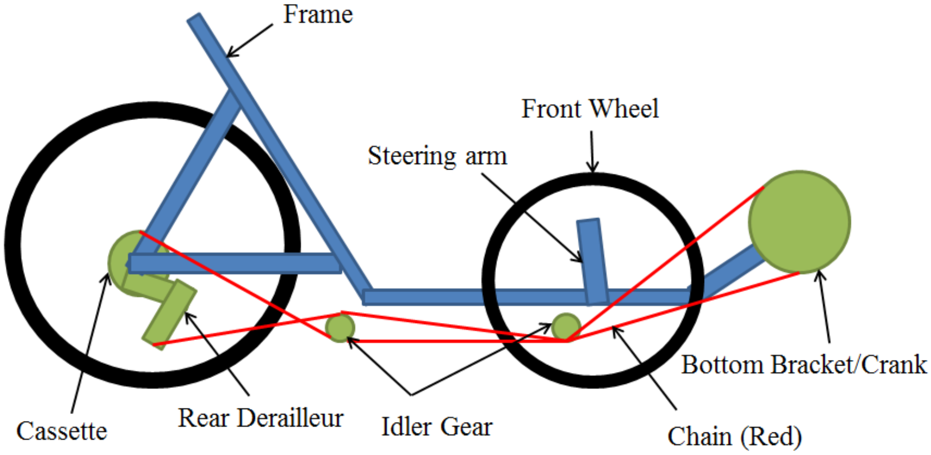


Figure 4.21 Drivetrain example using idler gears

Another method to manage slack is by using a chain pulley. The chain pulley works similar to a derailleur that can be placed at any position. Figure 4.22 displays how the chain pulley could be used with a drivetrain. Lastly mid drive systems, such as the jackshaft shown in figure 4.7 could be used. The jackshaft allowed for multiple smaller drivetrain systems. In figure 4.7 a single speed is used to connect the crank to the jackshaft and a shiftable drivetrain from the jackshaft to the rear wheel. This was advantageous because the distance for the rear drivetrain section is similar to a bicycle drivetrain, meaning issues concerning slack, chain derailment, and shifting are more manageable. The front drivetrain was a single speed, which requires the chain to be properly tensioned. In one Clemson design this was accomplished using an idler gear, which was also needed for a change in the chain path. Another solution to tensioning the chain could have been using an eccentric bottom bracket on the crank set. If the single speed portion was on the rear drivetrain the chain could be tensioned by a different shape in the rear dropouts, which is typical for low cost single speed bikes.

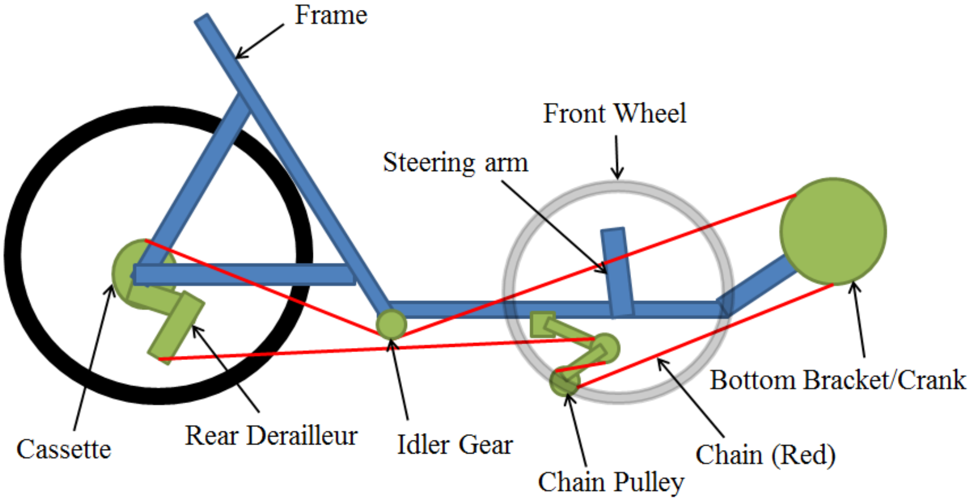


Figure 4.22 Drivetrain example using chain pulley

For the rear wheel section of the drivetrain most designs use a cassette and rear derailleur. The cassette consists of a series of several different sized gears, or cogs. The cassette is cheap and gives a gear range of about 250% (28/11), by itself. Cassettes are also commonplace which makes maintenance, repair, and upgrades simple. The rear derailleur helps tension the chain, allows for shifting between different cogs, and sets maximum and minimum shifting limits. If the cable connecting the derailleur and shifter is not tensioned properly, the shifting can be off, which could make the chain push against the derailleur and/or not change gears when desired. If the Limits are wrong the chain can fall off the cassette. If this occurred on the side between the wheel and the cassette the chain could fall in that space, which could cause damage to the HPV system as a whole. In some cases the rear wheel can be entirely destroyed. If this occurred while the HPV is being ridden the rider is much more likely to crash, which could potentially injure the rider and damage the vehicle further.

Another rear wheel consideration would be an internal gear hub (IGH) and a chain tensioner. The IGH can offer a larger gear range than a cassette (as shown in table 4.6), encloses all of the shifting components, supposedly gives more reliable shifting, and won't cause extreme damage in the cause of failure. On the down side, IGHs are typically more expensive, they can require special installation and maintenance, add more dynamic weight to the center of the rear wheels, and require specialized shifters. A single gear is fixed to the same axle as the IGH to allow for a drivetrain connection. The chain tensioner is optional, but makes managing changes to the chain slack simple. The chain tensioner acts like a derailleur that doesn't move inward and outward for shifting. Commonly the chain tensioner will use the same holes as a derailleur on rear dropouts.

Shifting and braking are the main concerns of user interface for the drivetrain system. Shifters are commonly use friction of index shifting [37]. Friction shifting consists of pulling a lever to change the cable tension which in turn causes a shift in gears. Using friction shifting the rider can shift from the lowest to highest gear and vice versa with one motion. Some examples of friction shifting include stem and lever shifters. Index shifting uses discrete stops that correspond to the derailleur systems. They are not as interchangeable as friction shifters and are often criticized for that. Some index shifting examples include twist shifters, trigger shifter, and STI shifters. STI shifters are commonly found on road bikes. They include the shifting and braking mechanism in one handle for rider simplicity. Some other forms of shifters include bar end shifters, typically found on triathlon bikes and electric shifting, found on higher end bicycles.

In terms of braking coaster and rim (or caliper) brakes are some of the most common. Disc brakes have gained much popularity as well. Additionally, drum brakes are viable option [5]. Rim brakes are the lightest option and require a true wheel for optimal efficiency. They work by having a replaceable rubber piece rub against the rim of the wheel on each side, when a lever is pulled to tension a connected cable. Coaster brakes work by backpedaling and can only be installed on the rear wheel. Disc brakes are similar to rim brakes in functionality, but are more efficient in poor weather conditions, allow for easier wheel changes, and special fittings. Disc brakes operate by having a caliber press against a disc, which is fixed to the wheel axle. Drum brakes are very weather resistant and vary widely in performance. They are prone to overheating on long downgrades. Larger drum brakes commonly offer better braking. Horwitz gives more details about the usage of drum brakes and states they are used on a majority of recumbent trikes [4]. In terms of user interface most braking systems use a lever to apply tension to a brake connected cable.

Using standard components and ensuring component compatibility is a needed aspect of drivetrain systems. This is because the moving parts wear down over time and require maintenance and replacement. Thus, using standard features allows for cheaper consumer costs throughout the lifetime of the product and for replacement of component availability. Some standard examples include cassette interfaces with the rear wheel, chain dimensions and gear teeth profiles, shifting components, brakes and brake pads, cranksets, pedals, pedal and crank interfaces, and so on. Compatibility between features is required to ensure the system operates as a whole. For example, the 11-speed Shimano Nexus internal gear hub has a specialized index shifter made specifically for it. If the designer wanted to use a different shifter, such as an 11-speed STI Shimano Ultegra shifter, they would need to ensure compatibility between the IGH and the shifter. After examining the components the designer will realize the IGH uses indexing with varying cable pulls, which is different than the indexing of the STI shifter. Thus, the components are not compatible. For this specific scenario the designer could try to create a mechanism that relates the different indexing, which has been done at the industrial level in the form of the hubbub. The designer could also consider using friction shifters such as bar end shifters. Another example of component compatibility is the interface between gears and the chain. If the gear teeth and chain profiles do not match, component wear will occur faster, the drivetrain efficiency will decrease, and chain slippage might occur.

Lastly, energy recovery systems can be added to the drivetrain at the cost of complexity. For example, a flywheel can be used to store braking energy, but additional connections are required for the drivetrain to consume and store that energy. One method would be to use a clutch system incorporated into the brakes. Table 4.7 (Copied from Appendix G) outlines a list of possible energy recovery systems (ERS) to give the reader a base level view for some exploratory options. Each ERS requires a unique and relatively complex system for connectivity.

Table 4.7 Energy recovery concepts

Concept Acronyms	Acronym Meaning	Brief description/Notes
FWER	Fly wheel energy recovery system	Is a drivetrain system for transferring energy from the front of the rear wheel and includes a dampened flywheel system for energy recovery and braking. The flywheel is engaged by using a clutch system incorporated into the brake.
SPER	Solar panel for energy recovery	A solar panel, battery and motor would be added to a drivetrain system for additional energy recovery
PEMR	Piezo electric energy recovery	Idea of adding piezo-electric materials to a suspension system to recover voltage from the damaging of the suspension. Would require a motor and battery to make full use of it.
RBSO	Regenerative braking system one	Adding a regenerative braking system to the front brakes to recover energy when braking
RBST	Regenerative braking system two	Adding a regenerative braking system to the rear brakes to recover energy when braking. When used with a design the uses only front disc brakes this method allows for additional brakes that also supply energy.

4.3.4 Aerodynamic Performance and Other Considerations

Aside from adding a fairing there are some additional features that can be adjusted to improve the aerodynamics of the vehicle. To begin decreasing the angle of the seat will increase the aerodynamics in two ways. First a lower seat angle would have less frontal area. Secondly the shape of a lower seat angle is a more streamlined body. Thus, the air flow over the lower seat angle body is more streamlined and the drag is reduced. Figure 4.23 demonstrates how decreasing the angle of a back support decreases the drag, based on these factors. In the model an air flow of 22.4mph (10m/s) was used, the back rest was 2ft in length, the seat support was 1ft long, and the overall seat was 1ft wide. The results indicates the drag force would decrease from 1.535lbf (6.828N) to 0.993lbf (4.420N) by changing the seat angle from an angle of 60° to 30°. That being said, the figure is a very simplified case that does not include the person or other vehicle features that would affect the aerodynamics. One thing to consider is that while decreasing the seat angle would improve aerodynamics, it would also decrease comfort and visibility for the rider. Small frontal areas from other types of changes will also show aerodynamic benefits. This can be accomplished by changing the system steering system, decreasing the wheel track and decreasing the front wheel size.

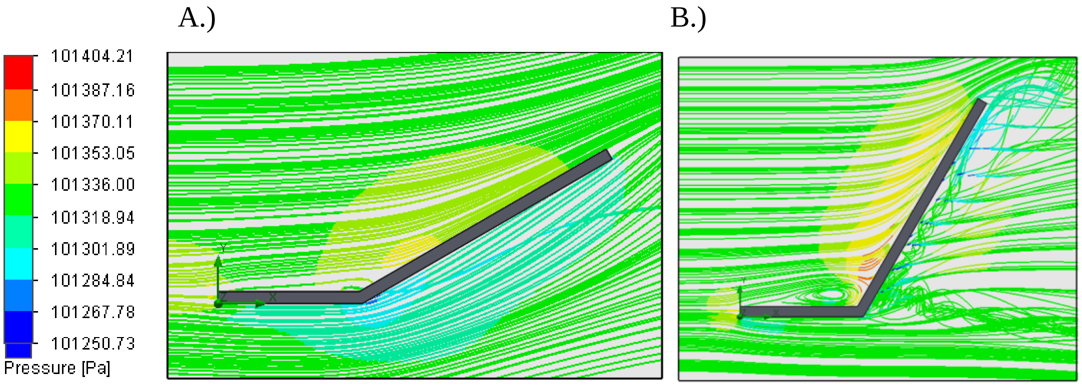


Figure 4.23 Flow over different seat angles A.) 30° seat angle B.) 60° seat angle

Fairings are another method used to decrease drag. In addition to drag improvements, fairings also allow for environmental protection, such as precipitation and wet roads. Often faired

HPV are called velomobiles. Fairings come in different varieties as well, such as fully enclosed, partial fairings (typically front or rear), and fully enclosed fairing with opening (bottom opening and/or opening for the riders head. When considering adding a fairing there are a few main concerns; the shape of the fairing, how to fabricate the fairing, how to attach the fairing, providing an adequate cooling system within the fairing, and how to allow the rider to enter/exit the HPV with the fairing attached. Some solutions to these concerns are addressed in table 3.1.

The shapes of the fairing can widely vary. Table 4.8 shows three common types of fully enclosed fairing shapes. The outline of the bicycle frame is a large sized frame used and given for visual comparison. To examine the aerodynamic benefits of fairings figure 4.24 displays the pressure streamlines of the three different shapes and figure 4.25 plots the differences in drag forces at different speeds. Solidworks flow simulation was used to complete the CFD with the computational volume shown by the grey volumes in figure 4.24**.** The results of figure 4.25 could be made more accurate if the computational volume was expanded and the meshing used was more refined. The results for the drag forces on a bicycle were developed by Science Learning [38]. Additionally there are some inaccuracies in the model, because only the fairing shapes were modeled. For a true evaluation of the drag forces, the complete system would have to be used, along with the rider.

Table 4.8 Example fairing shapes

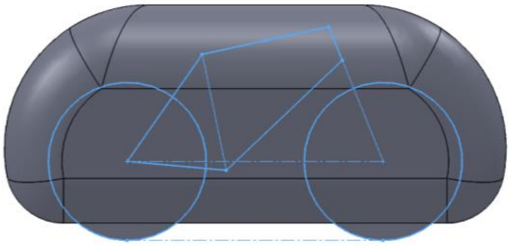
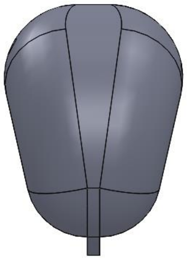
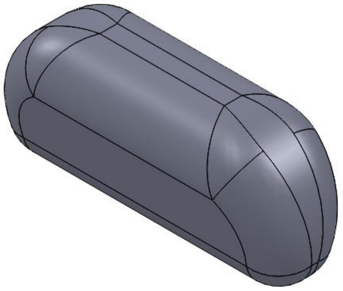
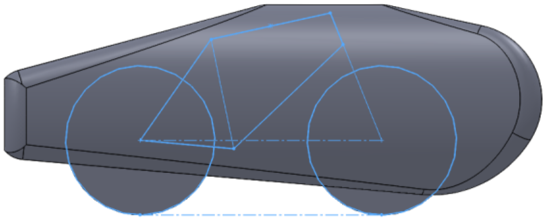
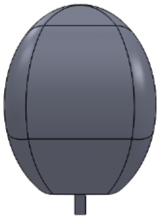
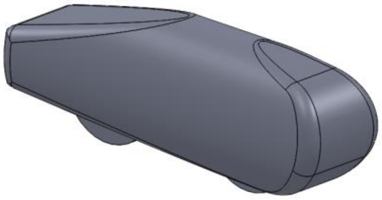
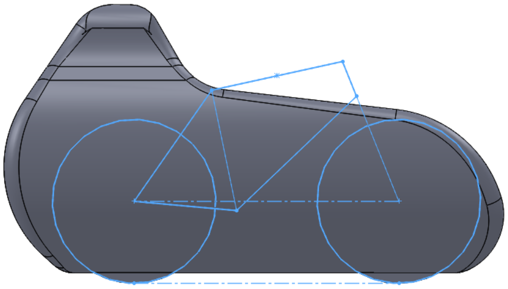
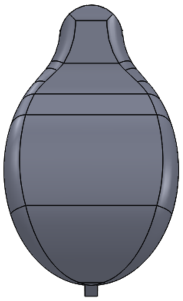
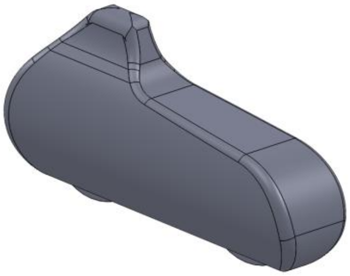
Side view	Front view	Isometric view
		
Streamlined Fairing		

Table 4.8 (Cont.)

Side view	Front view	Isometric view
		
Tear drop Fairing		
		
Upright Fairing		

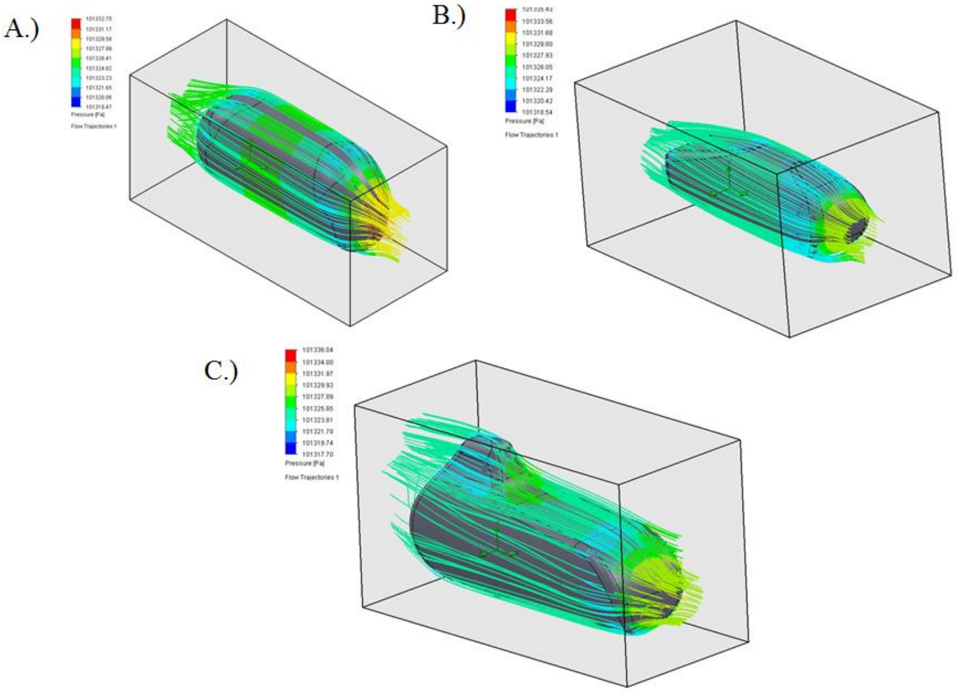


Figure 4.24 Pressure streamlines at 10km/hr A.) Streamlined Fairing B.) Tear Drop Fairing C.) Upright Fairing

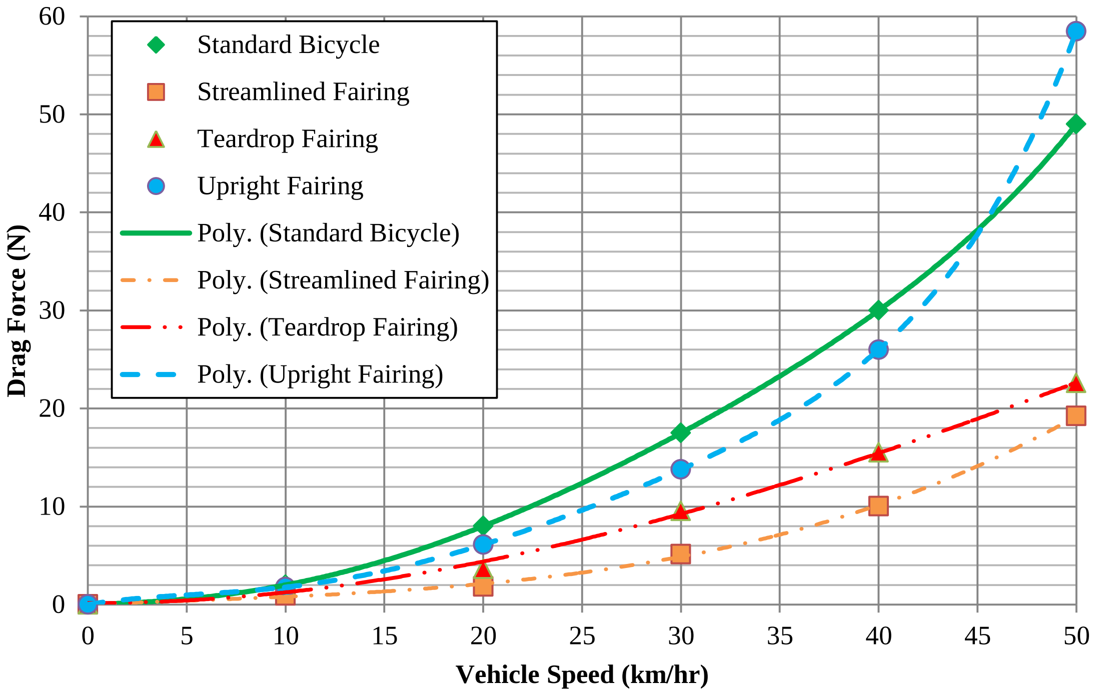


Figure 4.25 Resulting drag forces from different fairing shapes

The manufacturing of the fairing comes in a variation of methods. Of those common methods are a composite layup, thermal formed blow forming, vacuum forming, and assembly style skin on frame designs. Composite fairings require a large mold to be carved and coated. Next polymer woven sheets are placed over the mold, resin is applied, curing occurs, and the process is repeated until the shape is complete. Then a gel coating is commonly applied. The woven sheets consist of polymer chains aligned in a set direction. The orientation and stacking order of the sheets can be optimized to increase the strength and stiffness of the fairing. For higher quality finishes the first composite shape is used as a mold for a second composite layup. To get an example of mold creation figure 4.26 shows a process Rose Hulman has used to save the cost of carving an entire foam block [39]**.** Additional methods could include using foam sheet, cutting cross sections out using a laser cutter for precision, piecing the sheets together and sanding between the transitions.

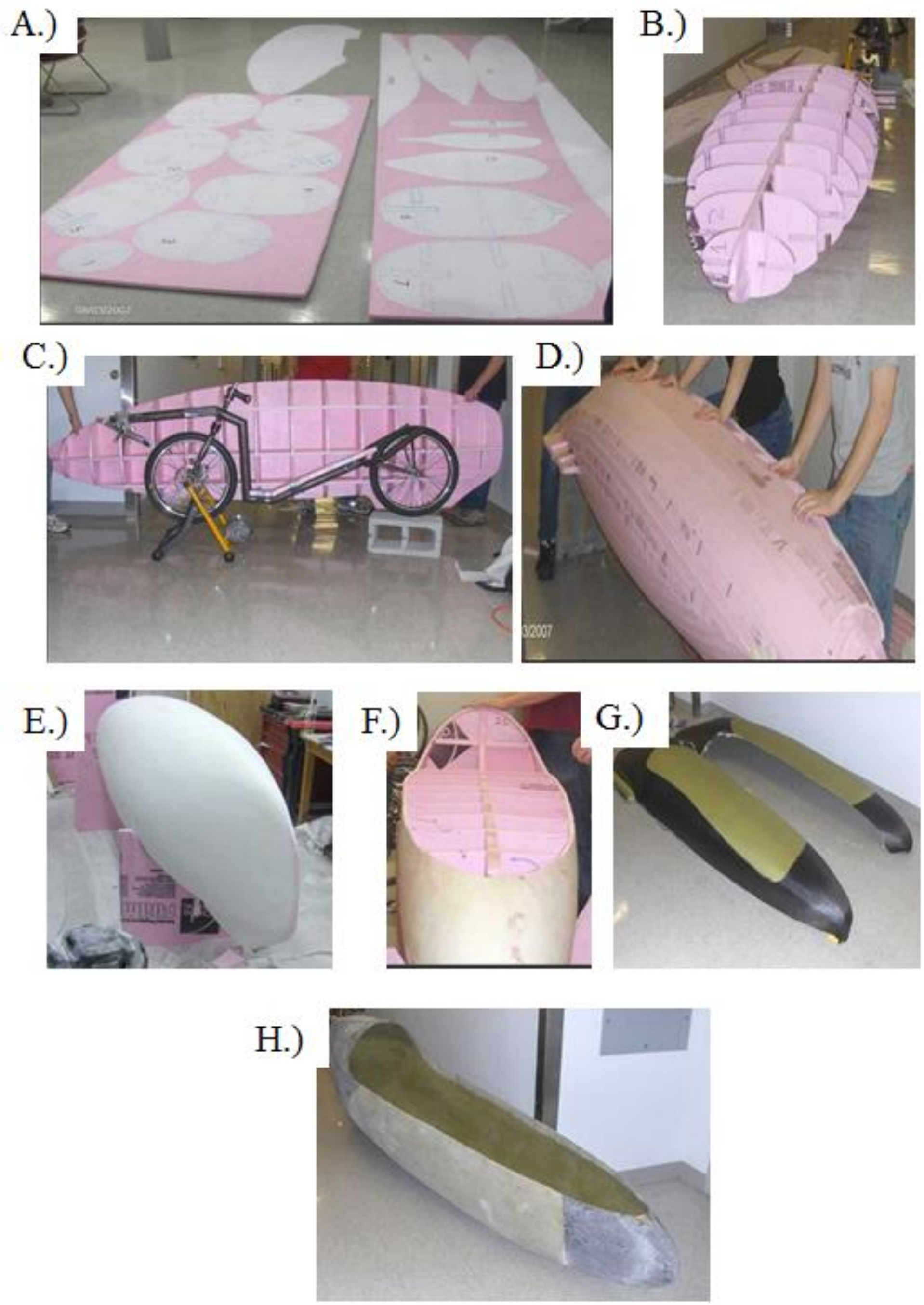


Figure 4.26 Overview of Rose Hulman mold creation 2007 A.) Layout of mold cross sections on foam sheets B.) Assembly of cross section C.) Initial mold to HPV comparison D.) Layering foam strips over mold skeleton E.) Smoothed mold F.) Shaped mold with removal of unnecessary mold sections G.) Composite halves created from mold H.) Combined mold halves and finished fairing product [39]

Vacuum forming can be used complementary to composite forming. In the vacuum forming process suction is used to wrap a material around a mold until it cures. For composite forming, this means the polymer shapes will retain the shape of the mold better after being cured. Blown fairings are created by placed a (clear) polymer sheet in an oven, as seen in figure 4.27 [40]. After the sheet is heated compressed air is used to form the sheet into a bubble like shape. Since the sheet is more malleable at higher temperatures the pressure of the air is large enough to deform the sheet. Skin on frame fairing can consist of wrapping a flexible material around a substructure or fastening rigid material to the substructure.

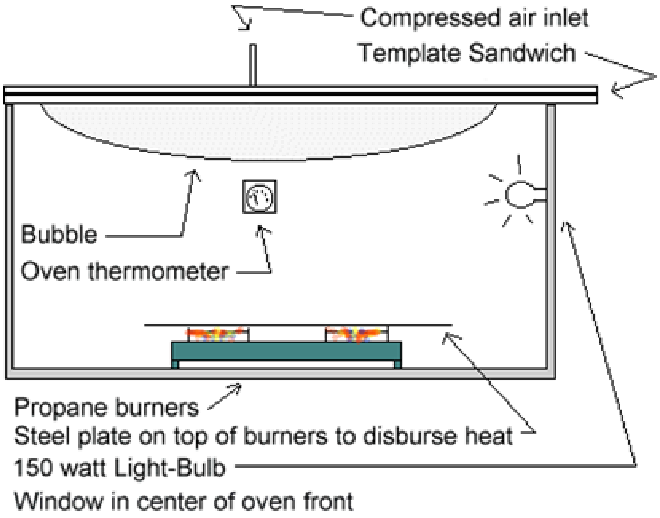


Figure 4.27 Blown fairing manufacturing setup [40]

In terms of attachment methods fairings can be made to permanently attach to the system, semi-permanently, of made to be removable. More permanent methods involve using strong adhesives, permanent fasteners (rivets), or fusing (such as welding), part of the fairing to the HPV structure. If a permeant attachment method is used maintenance and repair considerations need to be well defined. Semi-permanent attachment methods include using ties (zip ties or wire ties) or removable fasteners (nuts and bolts). Removable fairing could use a combination snap fits or special mounts that secure the fairing in place, but also can be uncoupled by a specific directional force applied by a person.

The next consideration of fairing design is the heating and cooling for the rider. If left unchecked, environmental factors such as solar radiation will continually raise the temperature inside the fairing [41]. To combat effects like baking from the sun, ventilation systems can be added. For this inlet ducts are needed. Of the many types of inlets sub-ducts work while providing a low amount of aerodynamic detriment. For more efficient cooling the ventilation should be directed towards the rider's face. For colder temperatures fairings can be insulation to help the rider retain heat.

Lastly, a main consideration for the fairing system is being able to quickly and safely enter and exit the vehicle. Some designs (streamlined and speed testing) have assistants tape the rider in, which requires assistance getting in and out. Fairings with an open top or open side give the rider freedom to access the vehicle at any time. Doors could also be added to allow for accessibility. Other solutions include having parts of the fairing (or the whole fairing) that could be removed by the rider.

Aside from aerodynamics there are other performance factors to consider when designing a HPV. The first is lower vehicle weight. The lower weight allows for faster acceleration and easier climbing. It also means that rider’s position could have more of an impact on vehicle dynamics. Light weights can be achieved by using light components, system with fewer features, and riders with lower weights. Of the overall weight of the vehicle, the dynamic weight is the most important, because it requires energy to maintain motion. This is why parts, such as wheels, can be so expensive. Besides optimizing the weight of parts, like wheels, one method to decrease dynamic weight is using smaller wheels. That being said if this was done on a rear wheel a larger chainring would be required [4]. Before making the wheels too small in the process of wheel selection roll-over resistance should also be examined. Roll-over resistance is the ability to roll over surface, such as a pebble, rock, crank, and flat road. For courser surfaces larger diameter wheels will typically have a better roll-over resistance.

4.4 Embodiment Design Summary

The embodiment design stage involves resolving the form fit and function of the leading solution variants. To accomplish this, a baseline system needs to be established in the form of a model. Virtual models, such as CAD models are great tools to help the designer solve the embodiment needs. To begin, part files can be created to establish the geometrical form and dimensions of components. Next, assembly files can be created to determine the fit between those components. For determining functionality designers can use prototyping, perform preliminary analysis, examining standard parts, and use guidelines, such as the aforementioned details about HPV subsystem designs, for better understandings. Once the model is completed it should include every component outlined in the product hierarchy. Once the model is complete the designers need to verify that the design meets the customer’s needs and established requirements. Much of this documentation and verification will occur in the definitive layout, or detailed design stage.

From the systems engineering process interface management is important. In other words, all of the connections between components in the assembly need to be defined and controlled by documentation. For example, the type of interface between features (mechanical, electrical, etc.), the spatial location of interface, requirements for the interface, method of connection, and changes to the interfaces all need to be recorded. Likewise changes to overall design and components should be recorded as well. When creating a CAD model, large systems are typically too complex for a single person to model the entire product. As a result, it is important to determine which features of the system are coupled. This in turn helps determine how strict the interface management needs to be, especially at the higher levels, such as the subsystems. For example, the steering and frame geometry as outlined in the HPV specific guidelines are highly coupled, because the geometry of the steering angles rely on the structure of the frame. As a result, more interface control is needed. On the other hand, the layout of the drivetrain and the addition of the fairing have little to nothing in common except the possibility of needing a shared space. As a result the interface management isn't as important. That being said interface management is still needed, because there could otherwise be invalid spatial interactions and similar problems. Table 4.9 is given to summarize the HPV embodiment process further.

Table 4.9 Embodiment design summary

Embodiment design elements		**Comments**
Modeling		Use CAD systems, anthropometric data, and prototyping. Goal to create initial model of top leading solution variants.
Preliminary Analysis		Back of the envelope calculations, problem solving for functionality, and design choice justifications.
Interface Management		Can N^2 diagrams and interface management process. Goal is to control and define connections between different design features
Model overview		Examine system anatomy and ensure all components are represented in the model.
HPV specific considerations	Frame	Material and connections (Welding, lugs, etc.) considerations, Determining weight distribution, and providing interfaces for other subsystem connections.
	Steering	Choosing caster and camber angles, king pin alignment, Ackerman geometry, steering systems (over seat, under seat, direct knuckle steering), and linkage systems
	Drivetrain	Overall layout, speed and gearing analysis, brakes and shifting human interfaces., choice of shifting and brakes, selections from standard components, and energy recovery systems.
	Fairing	Shape, size, manufacturing process, ventilation, visibility, subsystem attachment, and vehicle accessibility

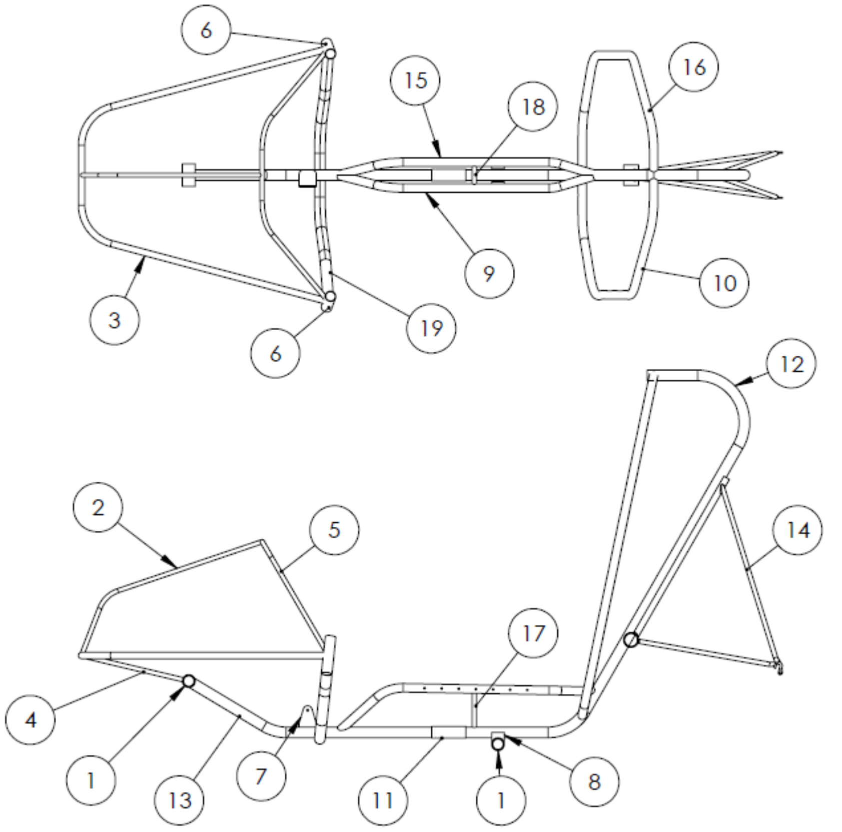
CHAPTER FIVE: DETAILED DESIGN

In the detailed design stage the definitive layout of the solution gets fully defined. In order to complete the definitive layout, the design needs to complete thorough documentation of the design, requirement verification, and fabrication planning. In other words, this is the stage where most of the design validation is explicitly and thoroughly explained. Creating manufacturing plans is one of the first stages to finalizing the design. By creating fabrication plans the design shows the documented preparation to move forward and indicates only small manageable changes are expected to occur to the design, after testing. Design analysis in the form of detailed calculation and computational models will help to verify that the design meets given requirements. Given a detailed model and manufacturing plans a budget analysis can be created to outline a detailed estimate of the design expenses and overall cost of production. Lastly, the design can be reexamined with a focus on a specific design aspect, such as safety, assembly, and so on. By doing so, changes to the design can be made before fabrication to enhance the product to a specific design focus.

5.1 Manufacturing Planning

Manufacturing planning is the process of deciding how the product will be developed. This includes figuring out how all the different parts will be fabricated, what raw materials will be used, different standards to be purchased, choosing the methods of fabrication, determining the integration between the parts when they are assembled together, and detailing the assemblies of the different parts. A first step in manufacturing planning is creating part and assembly drawings. Part drawings establish the dimensions and document a standard for fabrication. Assembly drawings outline how the different parts come together. Figures 5.1-5.4 give examples of a frame assembly and part drawings. A complete examine frame is included in Appendix J.

ITEM NO.	PART NUMBER	QTY.
1	Bottom Bracket Shell	2
2	Bumper and Fairing Support Connection	1
3	Front Bumper	1
4	Front Bumper Support	1
5	Front Fairing Support	1
6	Head Tube	2
7	Idler Connection Bracket	1
8	Jackshaft Connection	1
9	Left Seat Rail	1
10	Left Roll Bar	1
11	Main Member Extension Connection Piece	1
12	Main Member Section 1	1
13	Main Member Section 2	1
14	Rear Triangle	1
15	Right Seat Rail	1
16	Right Roll Bar	1
17	Seat Rail Support	1
18	Seat Rail Width Support	1
19	Steering Arm	1



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DATE 3/26/2016
CLEMSON UNIVERSITY
TOLERANCES: ASME Y14.5M
Tricycle Frame - Frame Assembly
COURSE ME 893
SECTION 001
MATERIAL CroMoly 4130
SIZE A
ASSIGNMENT NO. N/A
SCALE: 1:16
UNITS: English
SHEET 1 OF 19

Figure 5.1 Frame assembly drawing (BOM and callouts)

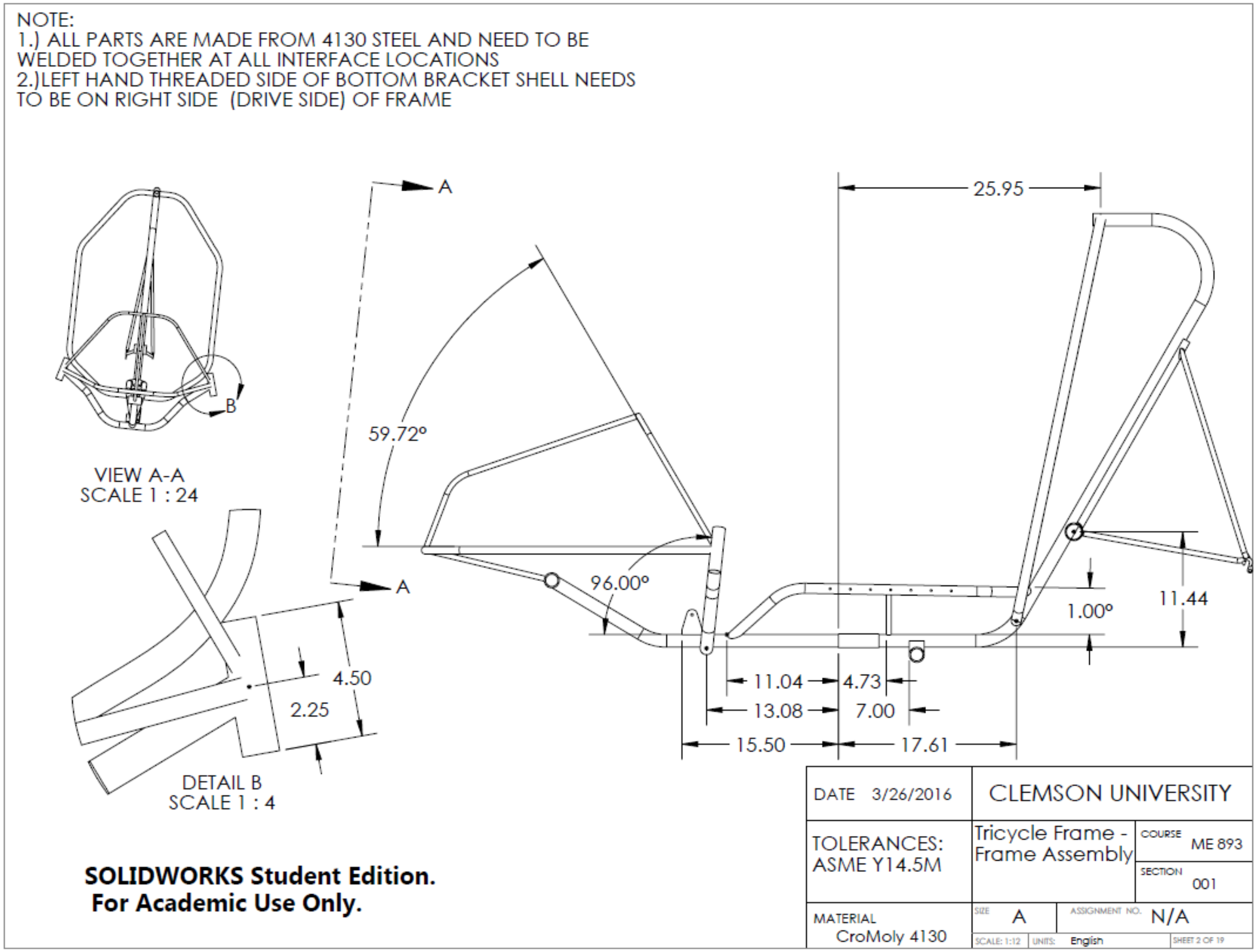


Figure 5.2 Frame assembly drawing (dimensioning)

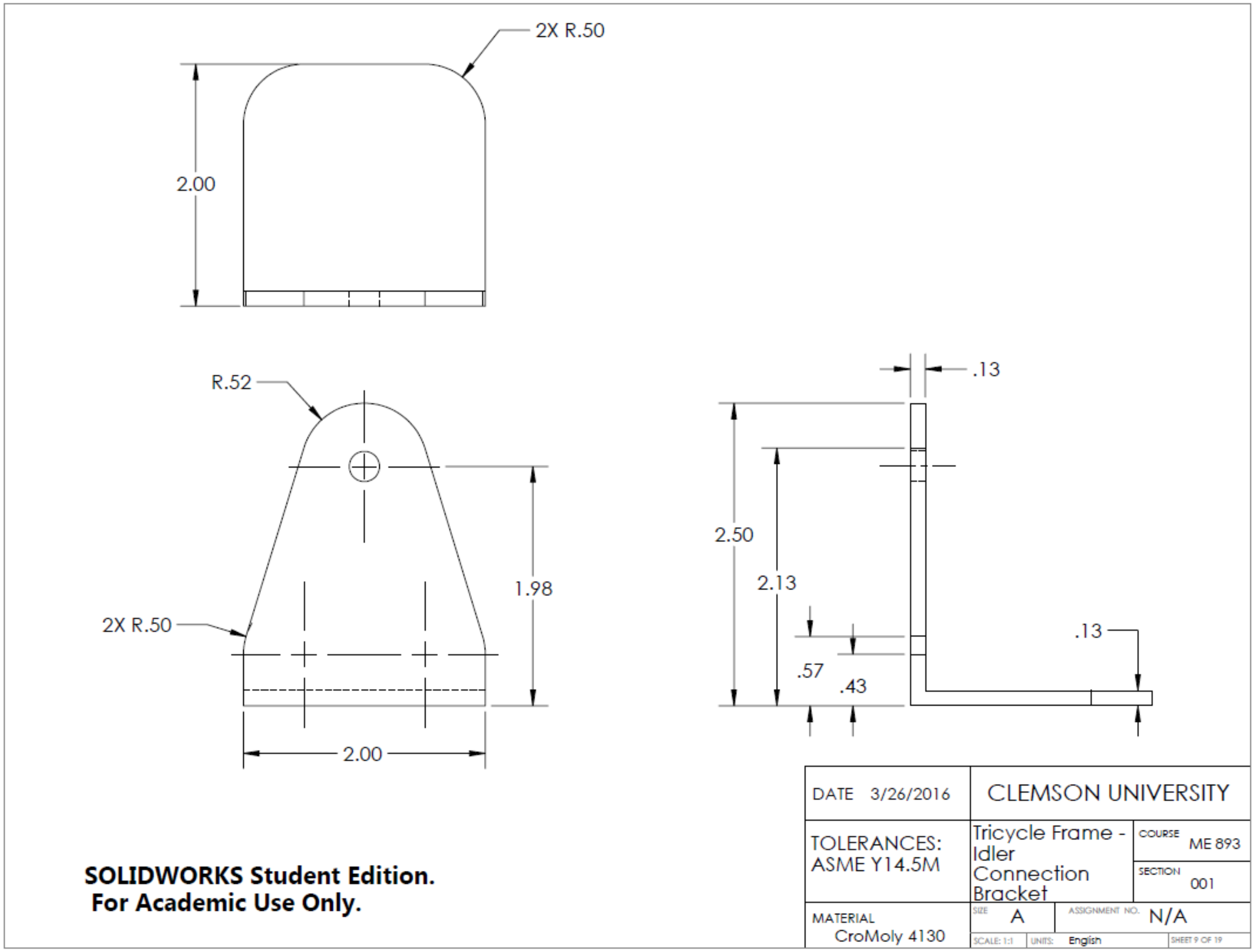


Figure 5.3 Idler connection bracket drawing

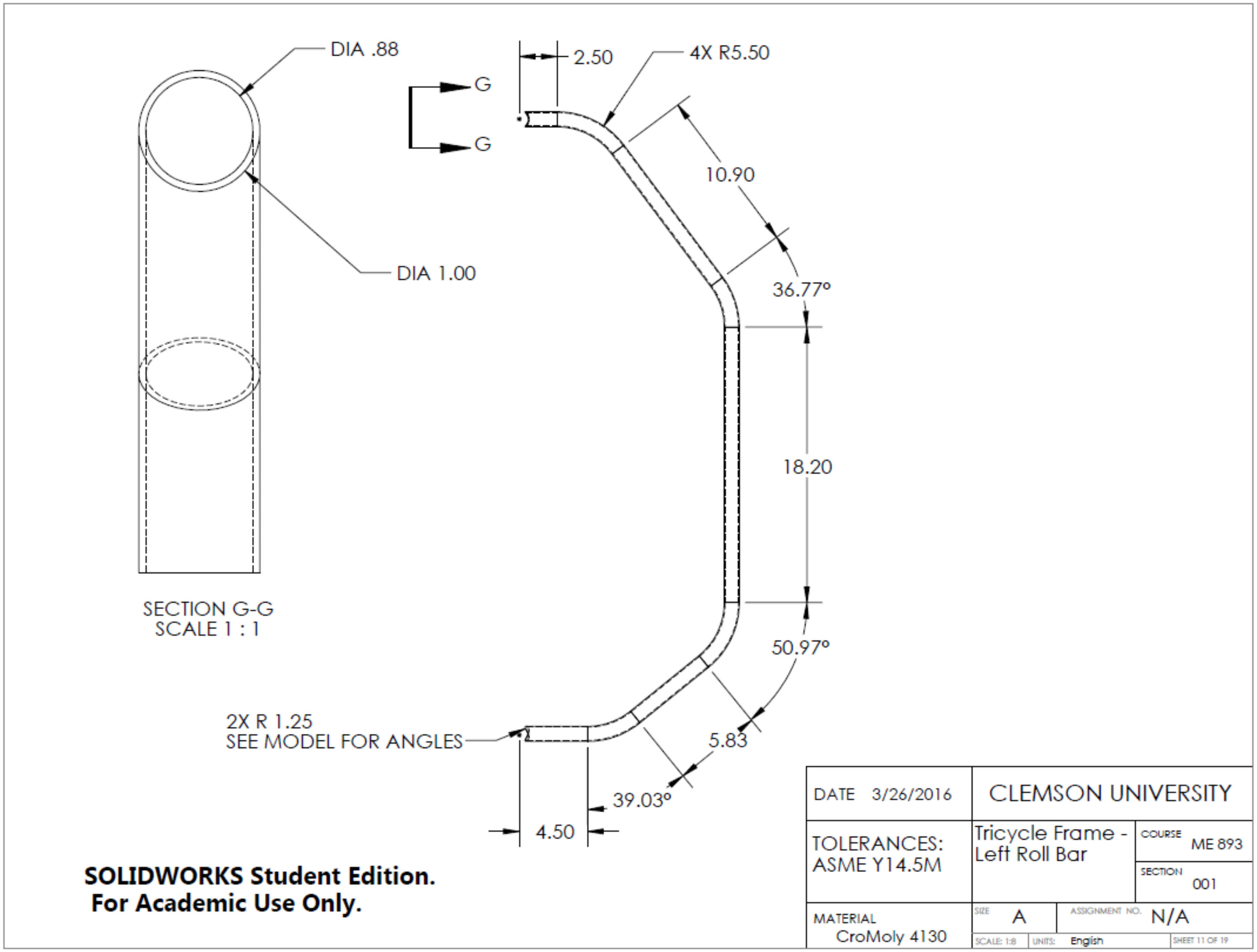


Figure 5.4 Left roll bar drawing

Assembly drawings are useful for creating the bill of materials (BOM), calling outs parts of the assembly and where they occur, and adding dimensions that are otherwise unknown. If parts are designed with specific interface features the number of needed assembly dimensions can be greatly reduced, because the interface connections between components can be adequate enough for determining part locations in the assembly. If not enough information is given in assembly drawings common assumptions may be made by the manufacturer, such as the neutral lines of tubing should intersect when tubes are welded together. Assembly can be further expanded on with installation drawings. Common furniture installation books are prime examples of installation drawings.

Part drawings are needed to detail the dimensions and requirements of individual components. Notes on the part drawings are needed to make the manufacturer aware of the part requirements. In industry drawings with large assemblies it is not uncommon to have upwards of fifteen notes on a single part drawing. These notes detail aspects about manufacturing requirements, tolerances, material properties, interface requirements, and so on. To ensure the parts are made to the proper dimensions within reason, tolerances are given. Tolerances establish the margin of error in which manufacturing dimensions can be different from the model dimensions. Tighter tolerances are associated with greater precision to ensure a better product. That being said tolerances may be tighter than necessary and result in more parts to be scraped, as well as increased manufacturing costs. Tolerances range from dimensional precision to angularity differences between parallel walls to surface finish requirements. Geometric dimensioning and tolerancing (GD&T) is the practice associated with determining how accurate parts need to be made. A widely accepted standard for GD&T is ASME Y14.5M [42].

For modeling simplicity, originally the frame outlined in Appendix J was made using one part. After the initial model was established individual models were created for each part and assembled back together. The purpose of doing this extra work was to create the individual part drawings and the assembly drawings to better document the manufacturing needs, required tolerances, give a better idea of assembly, and to help determine fixtures. To allow for a similar process, designers can create a set of global sketches that defining the system as a whole. From there, individual parts are based on the global sketch. Thus updates to the design can be made to the global sketches and the individual parts will update accordingly.

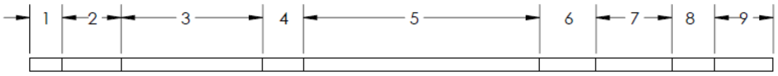
Manufacturers have more experience than student design teams. As a result, students may need more manufacturing planning than just drawings. For student teams, the students are the designers and manufacturers, whereas in industry there are separate departments for the different aspects of production. This could be in the form of documenting manufacturing protocol. This is completed in industry as well for more complex parts, tighter tolerance, more complicated manufacturing that require more planning i.e casting, forming processes, mold overlays, etc. To begin planning for manufacturing methods, the designers need to first fully understand the methods they are using. This also gives an idea of the required machinery, needed tooling, and one-use manufacturing materials (Items that are required for the production of the part that cannot be reused for multiple productions of the same part). Understanding the methods gives the designers an idea of lead times. Once the method is fully understood they can create a manufacturing procedure. To give an example of manufacturing methods, examples of bending a tube, creating an axle, and assembling components of an upper steering tube will be given.

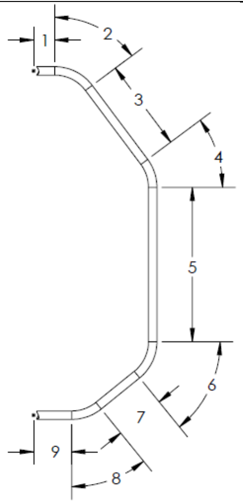
To bend tubes first a tube bending and matching dies are needed. When selecting the bender and dies, limits to the materials and geometries are given. For example, the model 3 tube bender by JD squared is a manual tube bender that would have difficultly bending a 1.25” OD solid steel tubes thicker than .120” and thinner than .058”, based on the die and bender [43,44]. Thus, bent 1.25” OD tubes in the design must fit those required in order to use the specified bender. Thinner tubes will likely crimp and larger tubes may cause damage to the dies. Before using the bender, laying out where the bends need to occur is very useful. For the 1.00” OD tube the model 3 bender is able to bend solid tubes and has a minimum wall thickness of .058”.

Consider figure 5.4 as an example for tube bending and ignore the miters at the end. To layout where the bends occur, designers could create a spreadsheet and diagram as depicted in table 5.1.

Table 5.1 Bending layout preparations for figure 5.4

Tube OD – 1.00”
Thickness - .058”
Die Radius – 5.50”
Bender offset – (-.5”)





Section	Angle	Length (in)	Total Length (in)	Start of bending mark (in)
1	0°	2.50	2.50	N/A
2	53.2°	4.53	7.03	6.53
3	0°	10.90	17.93	N/A
4	36.8°	3.13	21.06	20.56
5	0°	18.20	39.26	N/A
6	51.0°	4.34	43.60	43.10
7	0°	5.83	49.43	N/A
8	39.0°	3.32	52.75	52.25
9	0°	4.50	57.25	N/A

To determine the length of the angle section the neutral axis was used. The neutral axis radius was the outside diameter (Die radius) minus half the diameter of the tube. From there the (neutral) radius and angle was used to determine the arc length using equation (2). To finalize preparation the tubes can be marked where the bend will occur. Next the tube is mounted and secured into the bender. For the case of the model 3 bender this means aligning the correct tube mounts with the proper guide holes designed for the tubing diameter. When bending the tube it must first be bent to the indicated angle then unstressed from the bender to determine springback. Finally the tube will be bent with the initial angle plus the measured springback, so when it is unstressed from the bender it will have the intended angle. For more details about tube bending specialized guides can be used [45]. If a student was creating documentation based on the described bending process it might look something like table 5.2

$$\text{Arc length} = \frac{2\pi}{360}(\text{Radius})(\text{Angle}) \tag{2}$$

Table 5.2 Example student documentation for manufacturing tube bends

Left Roll Bar Manufacturing Plan		
Step	Description	Responsible Team Member
1	Create Part Drawing	John Sample
2	Create Preparation drawings	John Sample
3	Mark tubes for bending	Henry Sample
4	Bend tubes	Henry Sample
4a	Mount tube in bend	Henry Sample
4b	Locate bending mark and align tube accordingly	Henry Sample
4c	Bend section to desired angle	Henry Sample
4d	Release tube and measure springback	Henry Sample
4e	Bring tube section to the original angle plus the springback	Henry Sample
4f	Repeat step 4b through 4e until are bends are completed*	Henry Sample
5	Unmount tube and remove from bender	Henry Sample

*Note-When aligning multiple sections make sure bends are in the same plane unless otherwise stated. If otherwise stated ensure bend planes are properly related to each other.

To give another preparation example consider the axle adapter in figure 5.5. The axle adapter had three main functions for the Clemson 2016 design; to connect the axle to the steering tube, to space the wheel a specified distance from the steering tube, and to allow for the proper camber of the wheel. From these functional requirements the dimensions of the model can be determined. Additionally, the larger diameter tube is dimensioned to fit over a fork on the side under the crown race support if the fork end were ground off. The outside diameter of the axle needs to fit to the hub of the wheel and inside diameter had to be a standard bolt size so the wheel could be tightened to the steering tube. To manufacture this axle adapter part, given the requirements three separate tubes were selected; a hardened steel tube used for linear actuators with an OD of 20mm and ID of 12mm, a mild steel tube with an OD of 1” and an ID of .75”, and a CroMoly steel tube with an OD of 1.25” and an ID of 1.125”. Due to the axle being hardened steel, machining it would require less precision or more expensive tooling. As a result, the manufacturing plan is outlined in table 5.3, where machining to the axle is being limited.

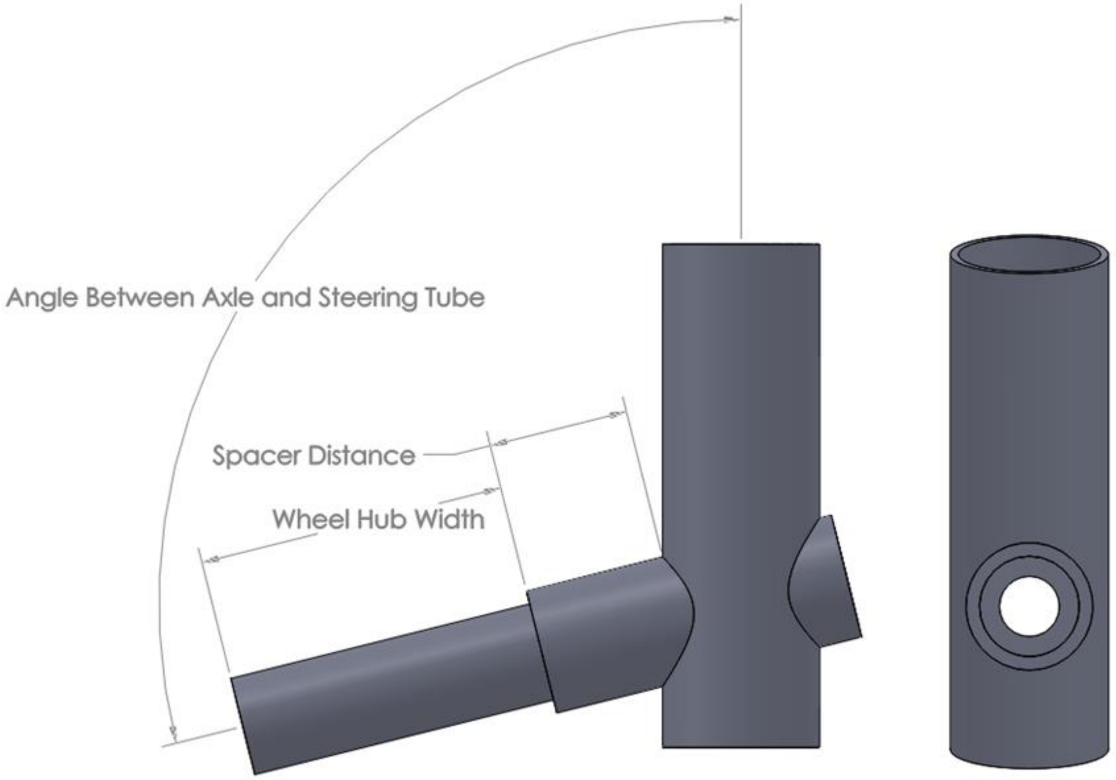


Figure 5.5 Axle adapter for steering tube to axle connection

Table 5.3 Example student documentation for manufacturing axle adaptor

Axle adapter Plan		
Step	Description	Responsible Team Member
1	Create Part Drawing	John Sample
2	Cut axle to length using chop saw	Henry Sample
3	Cut spacer to length using chop saw	Henry Sample
4	Cut steering tube extension to length	Henry Sample
5	Ream the inside of the space to 20mm (Use a milling machine and reaming chuck	Henry Sample
6	Fit axle inside spacer and weld piece together	Henry Sample
8	Miter 1” hole in steering tube extension (Attach 1” hole saw to milling machine chuck. Fix tube to proper orientation for angle)	Henry Sample
9	Fit axle and spacer combination inside steering tube (Align to the proper distance) and weld piece together	Henry Sample

To give one last example of manufacturing plans consider a steering tube from a bicycle fork. To be able to use the steering tube in the system a crown race needs to be installed, it has to be cut to length, and a star nut needs to be installed. The initial items are a stock steering tube, a crown race, a headset assembly, spacers, a stem, and a head tube. First the crown race can be installed using a race setting tool [46]. Then the headset assembly can be installed in combination with the head tube and steering tube, see figure 4.20 for reference [47]. Spacers can then be added along with the stem to determine the correct length and mark the steering tube [48]. Using a cutting guide and hacksaw the steering tubed can be cut to the correct length [48]. To finalize the steering tube the fangled star nut can be installed using a TNS-4 installation tool [49]. This example is given to demonstrate the possible need for tooling and to consider the associated tooling costs. It also shows the use of standard practices. In this case, it also emphasizes standard bicycle maintenance and installation.

Other manufacturing planning may lead to other requirements. For example, jiggings and fixtures are often needed for welding purposes and occasionally for machining purposes. Figure 5.6 gives an example of how the head tubes were jigged to the steering tube in the manufacturing process. Having the steering mitered beforehand greatly lowered the required jigging. To drill uniform holes in seat rails (figure J.12) the fixture in figure 5.7 was created. To miter an offset hole in the frame for the steering arm, wood was used in combination with a hole saw, as shown in figure 5.8. All of these examples required extra manufacturing consideration, because of manufacturing challenges such as positioning and precision. As result it was necessary to document preparation beforehand and establish a manufacturing method. Lastly it is important to plan for safety in manufacturing. This means the necessary protective wear is worn, proper equipment is used, and machinist have the required operating skills.

Figure 5.6 Jigging for steering arm and head tube connections

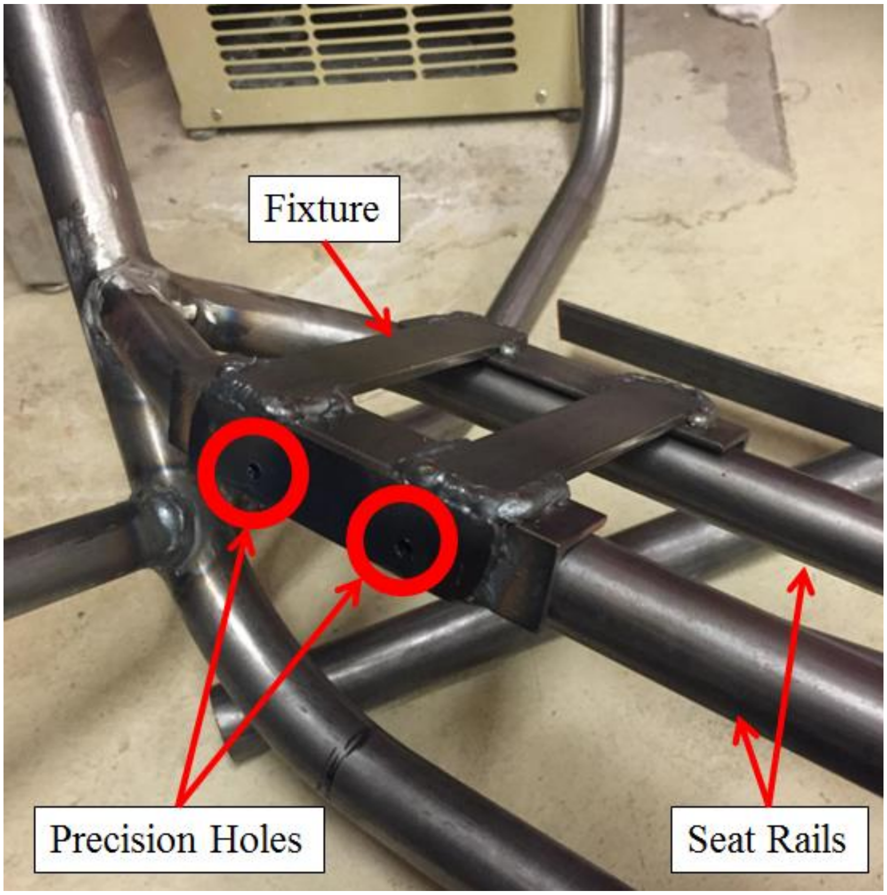


Figure 5.7 Fixture created for precision holes

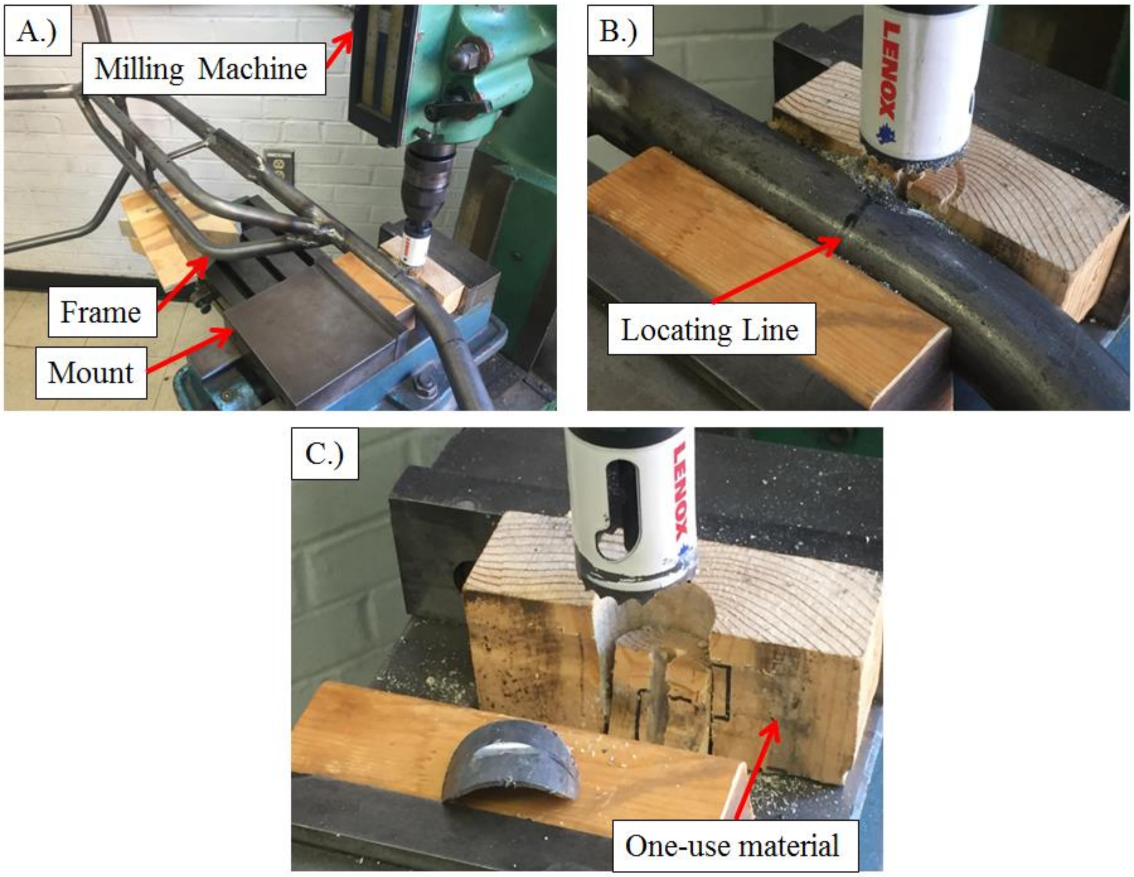


Figure 5.8 Mitering an offset hole A.) Frame mounted to milling machine B.) Setup of Miter before fabrication C.) Setup after fabrication

5.2 Material Selection

Material selection should be started earlier so it is best suited to the design application, but it will be discussed here, because this is the point where the final selection takes place and the material is decided. Selecting materials is done by determining the important material properties that correspond to the design functionality. Material selection is completed by choosing an objective function, determining the constraints, and using those to create performance relations, which will later be used to create material indices [50]. As an example consider selecting the material for a frame. As an assumption treat the frame as if it would behave like a beam, in terms of loading conditions. An objective for the frame is for it to be light. Constraints would be the frame needs to be stiff and strong. First consider the light (objective) stiff (constraint) beam (Frame/function). Assuming the cross section is circular with a thickness [t], radius [R], and length [L], the mass [m] of the beam could be determined using equation (3), where ρ is the density of the material and A is the Area of the cross section defined by equation . As minimizing mass was the objective equation (3) becomes the objective function.

$$\mathrm{m} = \rho * \mathrm{L} * \mathrm{A} \tag{3}$$

$$\mathrm{A} = \pi(\mathrm{R}^2 - (\mathrm{R} - \mathrm{t})^2) \tag{4}$$

Since the frame is being treated like a beam the stiffness of the beam can be found using equation (5), where S is the stiffness, S* is the minimum stiffness, C_2 is a constant that changes with loading conditions and geometry, E is the young's modulus of the material, and I is the moment of inertia of the cross section. The moment of inertia can be defined using equation (6). To simply the problem assume t is a function of R and is equal to the constant A times R, where $(0 < A \leq 1)$. A value of A=0 would indicate zero thickness and a value of 1 would mean a solid cross section. After that assumption combining equations (5) and (6) and rearranging gives equation (7). Keeping the assumption of the thickness the object function in equation (3) can be combined with the constraint equation (7) to create the performance relation in equation (8).

$$\mathrm{S} = \frac{\mathrm{C}_2\mathrm{EI}}{\mathrm{L}^3} \geq \mathrm{S}^* \tag{5}$$

$$\mathrm{I} = \frac{\pi}{4}(\mathrm{R}^4 - (\mathrm{R} - \mathrm{t})^4) \tag{6}$$

$$\mathrm{R} \geq \sqrt[4]{\frac{\mathrm{S}^*\mathrm{L}^3}{\frac{\pi}{4}\mathrm{C}_2\mathrm{E}[1 - (1 - \mathrm{A})^4]}} \tag{7}$$

$$\mathrm{m} = \left(\frac{4\pi\mathrm{S}^*(1 - (1 - \mathrm{A})^2)^2}{\mathrm{C}_2(1 - (1 - \mathrm{A})^4)}\right)^{1/2} (L)^{5/2} \left(\frac{\rho}{E^{1/2}}\right) \tag{8}$$

Equation (8) is broken down into three parts; the functional requirements and constants, geometric relations, and material properties respectively. If the length was fixed the only other free variable in equation (8) would be the material properties. They can be used to create a material index of $M_1=\frac{E^{1/2}}{\rho}$ and as M_1 increases the mass of the frame decreases. Moving forward this material index can be used with a material chart to map out groups of materials best suited for the design as shown in figure 5.9. In the material selection chart a log-log plot is used to plot the material properties of different materials. The material index is then used to create a guideline. The slope of the guideline is determined by the index and the y-incept of the guideline is free to change. The intercept of the guideline should be positioned such that most material choices are "eliminated" in the selection process. Based on reducing weight and maintaining stiffness the guideline in figure 5.9 shows that carbon fiber reinforced polymers (CFRP), some woods, and some Al alloys are good choices. Steel is a mediocre choice in comparison to the material index.

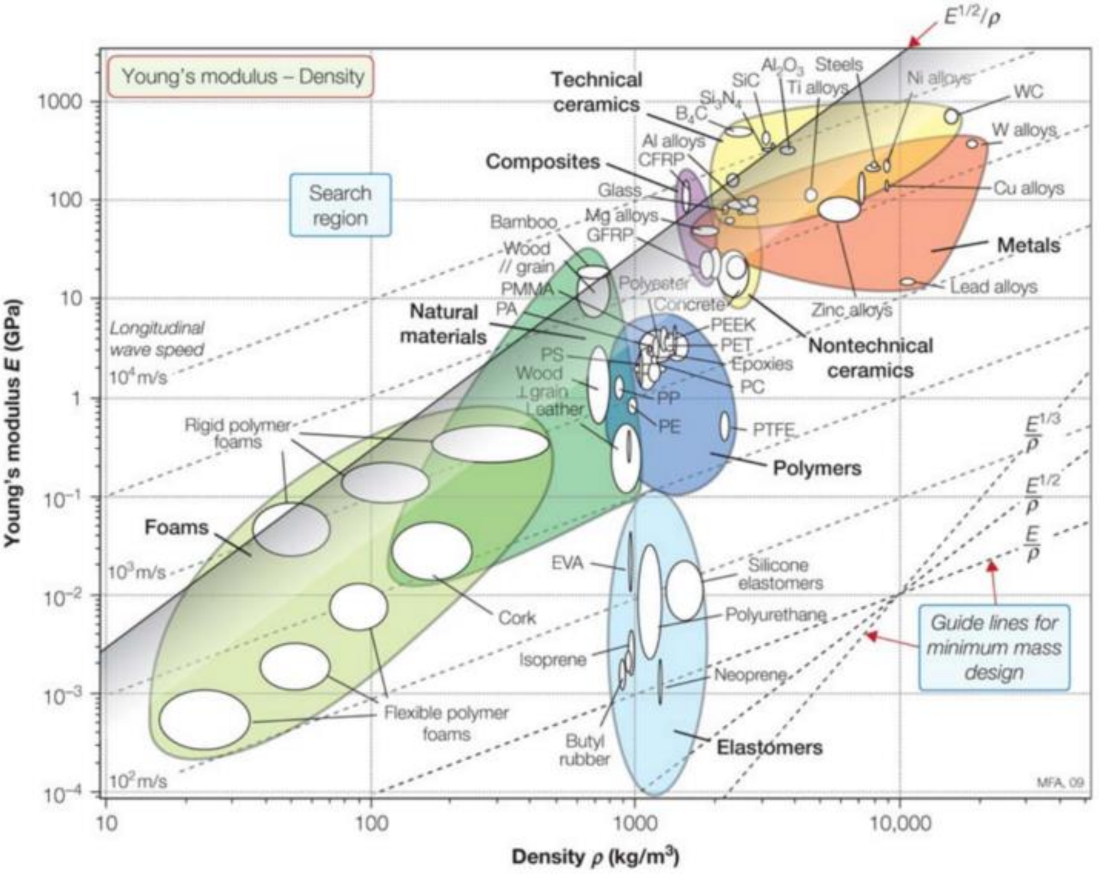


Figure 5.9 Material selection chart for light stiff frame [50]

To repeat the process for a light (objective) strong (constraint) beam (Frame/function) the objective function can remain the same. For the material to remain strong, it must not yield under stress. From this and considering a simple loading case equation (9) can state the constraining relation, where σ is the stress seen, M is the moment acting on the material, and σ_y is the yield stress of the material. By combing equations (6) and (9), rearranging and maintaining the assumption of the thickness equation (10) becomes the new constraint. The performing relation, defined by equation (11), then becomes a combination of equations (3) and (10). From here the material index would be $M_2 = \frac{\sigma_y{}^{2/3}\rho}{\rho}$. Figure 5.10 can then be used to determine the materials best suited for a light strong frame. Note, the guideline in the selection chart would have a slope of 2/3 not a slope of one as pictured. The picture chart was taken from a different case study, which is why the guidelines are different. That being said, for the selection of a light strong frame the best candidate would be CFRP, followed by woods, Al alloys, and steels.

$$\sigma = \frac{MR}{I} \geq \sigma_y \tag{9}$$

$$R \leq \sqrt[3]{\frac{M}{\frac{\pi}{4}\sigma_y\left(1-(1-A)^4\right)}} \tag{10}$$

$$m = \left(\frac{4M\left(1-(1-A)^2\right)^{3/2}}{\pi^{1/2}\left(1-(1-A)^4\right)}\right)^{2/3} (L) \left(\frac{\rho}{\sigma_y{}^{2/3}}\right) \tag{11}$$

Overall, CFRP is best choice for frame material, but it is more expensive. This is an indication of why most higher end bicycles are made of composite materials. While the Al alloys and steel are similar in strength, the better stiffness in Al alloys is a likely reason why Al frame dominated over steel frames in the market for cheaper bicycles. Lastly, it is interesting to examine how wooden and bamboo frames have gained support, when comparing materials.

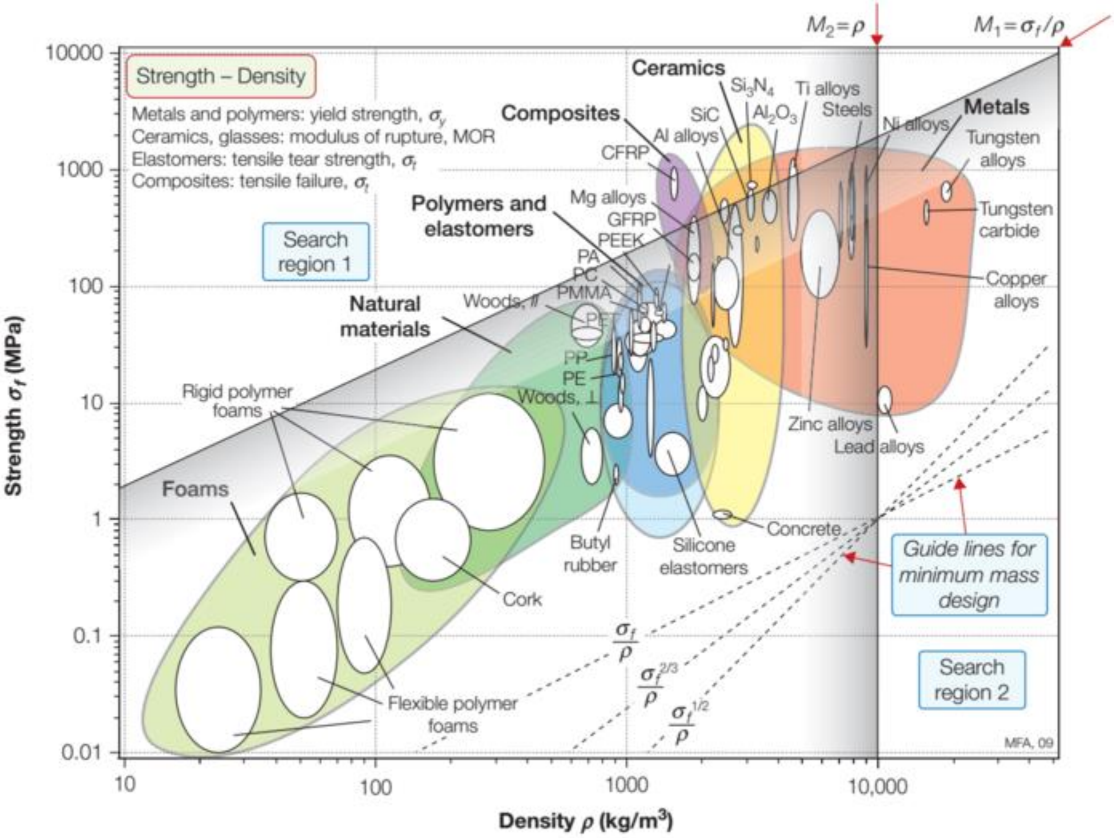


Figure 5.10 Material selection chart for light strong frame [50]

Once the top material classes for the design are selected further selection is required to define one final material choice to be used. Within a specific class of materials, such as Al alloys there are subclass, members, coating, etc. to choose from. This is where the designer's knowledge and material availability come into play. In addition, other material considerations are necessary. Possible considerations are shapes, sizes, machinability, weldability, and availability. Additionally, part of the material selection should be conducted earlier in the design process, because some of these considerations might not be needed. For example, welding a frame might not be necessary. Thus, carbon fiber reinforced 3D printed lugs could be considered for the interface connections instead. This would mean that CFRP would still be a viable option and wouldn't be thrown out on the technicality of not being able to be welded. Everything being considered the final material choice is up to the designer and should be properly documented.

In addition, hybrid materials are examples of how materials can be manipulated to show an even greater performance then raw materials. Shape manipulation is an example of how the shape can be adapted to increase properties. For example metamaterial optimization helps to establish microstructures that perform as well or close raw materials at a reduced mass, such as honeycomb structures. These microstructures can then be combined with general shapes to form hybrid materials. Figure 5.11 shows a frame tube made from a hybrid polymer with a honeycomb microstructure. The hybrid material was noted to have an increased stiffness per weight, than typical frame materials [51]. It was noted the hybrid did a better job of damping vibrations as well.

Figure 5.11 Example hybrid material for HPV frames [51]

Lastly in material selection it is important to consider the manufacturing method and type of raw stock being used. Differences in standards may become an issue for other parts of the design. If the stock is designed for a different purpose it may not perform optimally or as expected. For example, tubing and piping standards and manufacturing methods are different because the stock materials are created for different purposes. Pipes are designed for flow, whereas tubing is designed for structural purposes. Thus, for a frame tubing should be used and not piping, because a frame is needed structurally.

5.3 Design Analysis

After materials for the different features in the system have been established, more in-depth analysis can be conducted. The analysis will help to validate the model of the design. If it does not validate the design the analysis will indicate where improvements need to be made. Prior to testing computational analysis is heavily relied on, because it is easy to compete, effective, works on difficult problems, and is repeatable. Finite element analysis (FEA) and computational fluid dynamics (CFD) are some of the most common computational tools. Additionally there are continual developments in the field to make implementation easier, faster and more accurate. Computational analysis is based on numerical methods and thus is always an approximation. Finer mesh sizes and optimized mesh locations are items that can make the approximations more accurate.

By estimating loads, FEA can predict the maximum von misses stress and locations for a component or system. It will display stress distributions that will help indicate stress concentrations and stress heavy areas. This is turn either validates structural considerations for the design, or details specific features that need to be redesigned. For example the wall thickness of a specific tube might need to increase to meet structural requirements. CFD, shown in figures 4.23-4.25, can quantify aerodynamic performance, based on the pressure distribution of a moving fluid. Other applications include heat transfer and flow analysis.

For non-computational analyses there are many different aspects to be considered as well. Fatigue life analysis can be used to determine if the hubs/axles of wheels might fail. To performance the fatigue analysis designers must consider the weight of the vehicle and the rider, the weight distribution on the wheels, how the wheels are supported, and environmental stress enhancements, such as road bumps.

After having the material selected and model dimension, a weight assessment can be used to determine the center of gravity, overall weight, and weight distribution. This should be determined with and without a rider. The weight assessment can be used to estimate the vehicle dynamic performance. As mentioned in section 4.3.1, designs with a lower center of gravity have better handling. In terms of weight distribution, 70% of the weight on the front wheels and 30% on the rear wheel is recommended for tadpole trikes for a more optimal design. Additionally, previous back of the envelope calculations can be better defined with a more accurate weight estimate. Based on the center of gravity and wheel layout the designer could assess the probability of rollover in high speed turns, using centrifugal force equations coupled with moments acting on the system about the center of gravity as outlined by Portland state in figure 5.12 and equations (12)–(14) [13]. Equation (12) is the sum of the moments about the center of gravity, equation (13) is the radial acceleration, and equation (14) is the combination of the previous two equations. Here $F_r=ma_r$, where Fr is the radial force, m is the mass of the vehicle, a_r is the radial acceleration, y_{cg} and r_t are the dimension shown in figure 5.12, g in the gravitational constant, and r the radius of the corner (turn)

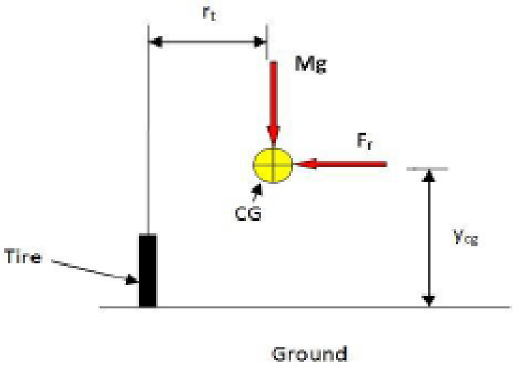


Figure 5.12 Free body diagram for rollover analysis [13]

$$F_r y_{cg} = m*g*r_t \quad (12)[13]$$

$$a_r = \frac{v^2}{r_{corner}} \quad (13)\ [13]$$

$$v_{roll}(r) = \sqrt{\frac{g * r_{corner} * r_t}{y_{cg}}} \qquad (14)\ [13]$$

Braking forces can be assessed using the minimum acceleration to zero time, and weight of the vehicle, using the simple F=ma calculation. The braking force is then translated to how well brake pads grip a stopping mechanism in the case of rim and disc brakes, by calculating the frictional forces and corresponding normal forces. The braking analysis could be furthered by estimating wear, heat dissipation, cable tension abilities, and grip strength required to pull brake levers. Weights could also be used to determine the power requirements of the rider for different speeds, grades, and gearing. This could be extended further by including CFD results for aerodynamic drag predictions at different speeds. This would result in an overall practicality assessment of the vehicle speed and distance ranges, based on rider power and fatigue.

Other analyses could include steering sensitivity, energy recovery, and system interfaces. For steering sensitivity, if a non-direct steering method is used, such as a four bar mechanism, the linkage system would undergo dynamic calculations to determine the sensitivity. In other words, the linkage system could be treated as a four bar mechanism to predict how much the wheels will turn and the rate at which they do (sensitivity), based on the rider's input. Another way steering sensitivity could be defined is the ratio the wheels turn compared to the how much the handles turn. This could also be calculated using a four bar mechanism approximation. For energy analysis the system's ability to store energy could be found using predetermined calculations, such as with equation (1) describing the energy storage of a flywheel. System interfaces could be analyzed in the model to assess the probability of part collisions from the movement of dynamic parts. For example, turning limits might have to be placed on the front wheels of a tadpole trike so they don't intersect with other components such as the frame. Otherwise the limits would be dependent on how well the rider can drive the vehicle.

For the design itself a retrospective analysis can be conducted to evaluate the goodness of the design and areas or features that can be improved on. The retrospective analysis can be focused on specific areas. This type of analysis is known as design for X (DFX), where X is a specific area such as assembly or manufacturing. DFX will be discussed in more detail in section 5.4. In all of the analysis completed on the proposed solution, redesigns and design tradeoffs will have to be made. The designers are responsible for the decision of which tradeoffs to move forward with and their choices will impact how the design progresses. Additionally analysis on the design's environmental impact is recommended by the HPVC rules [6]. This can be completed by determining the carbon footprint of the vehicle throughout the life of the design (production, logistics, consumer use, end of life, and product after life).

The purpose of analysis is to validate the design meets the requirements developed. When the design is not validated by the analysis future testing is required. By outlining areas where the design is not validated, areas of future testing needs are highlighted as well. Thus, planning for that testing could be completed in the analysis of the design. In addition, testing of the prior analysis should be conducted as well to verify the analysis validation is accurate.

With a definitive model backed by analysis and records of planning for future testing, a comprehensive budget can be developed. To begin determining the associated costs of production the BOM details all of the components needed, such as raw material stock and standard off the shelf items. Further examination of those components will help estimate the related manufacturing expenses. In the manufacturing expenses time costs can be estimated based on lead times, shipping estimates, and labor. Other manufacturing expenses include wasted materials, machinery, required tooling, safety training, and tools/equipment. The manufacturing costs can be correlated to lead times, and manufacturing complexing. Thus to reduce costs, lead times could be expanded and fabrication complexity of the design can be reduced. Expanded lead times lower over time labor and can reduce the amount of required skill labor needed at a time ("Time is money"). Planning for product testing gives an idea of possible additional costs. For example, destructive testing, would require additional fabrication. Specific to the HPVC, students need to plan for travel costs for going to the competition, including transportation, lodging, and team/school attire. Lastly, for the production of large scale industries shipping, packing, advertising, and similar expenses need to be considered.

5.4 Design for X

Design for X or DFX is evaluating a design with respect to aspect X. After evaluation updates and redesign should be made. As previously stated, these redesigns may require assessing design tradeoffs. Examples of DFX include; design for maintenance assembly, ergonomics, maintenance and repair, performance, safety, off the shelf, life cycle, and design for transportation. Table 5.4 was created to provide guidelines for considerations in each of the DFX areas mentioned. Like most of the paper, some of the considerations are more specific to HPVs than designs in general.

Table 5.4 Considerations for Design for X

Design for:	Guidelines/Considerations
Manufacturing [1]	• Aim for uniform wall thickness • Arrange for easier machining • Avoid small tooth profiles for gears • Avoid unnecessary machining by break up large sections • Combine machining processes • Avoid sloped machining and holes at unique angles • Choose simple shapes • Avoid shape edges and angles • Avoid rounded edges and sharp angles • Avoid tangential transitions • Allow for tooling • Reduce the number of steps required for production • Avoid complex bends • Allow for minimum bending radii • Provide stiffness at the end of sheet metals • Allow for simpler tool shapes • Provide adequate clamping support • Avoid waste by careful layout of cut parts • Avoid tight tolerances • Avoid narrow spacing between holes

Table 5.4 (Cont.)

Design for:	Guidelines/Considerations
Manufacturing Cont. [1]	• Aim for easily weldable seams • Avoid buildup material and interesting weld stems • Aim for good accessibility • Use appropriate standards where applicable
Assembly	• Parts are easily identifiable [1] • Interfaces are simplified [1] • Avoid near symmetry where possible, either make the features symmetric or have obvious asymmetry [1] • Avoid identical interface for interlocking elements [1] • Aim for symmetry [1] • Position handling surfaces based on center of gravity [1] • Aim for interface elements with a stable geometry [1] • Using assembly standards that are common practice in the area of design to give simplicity of understanding • Reduce the number of components • Use interfaces that are compatible with standard tooling for installation ○ Pedals, cassettes, brakes can all use hex keys ○ Chains and bottom brackets have specialized standard bicycle tools
Ergonomics [1]	• Consider specific body movements and postures • Use anthropometric data for dimensioning • Consider stress, loads, and fatigue on the body • Account for the preferred thermal temperatures of the body • Consider visibility ○ Intensity of light ○ Quantity of sight • Reasonable intensity of noise • Simple to understand and use • Reduces annoyance • Precise response to human inputs • Limits all physical dangers • Dampening vibrational (road) effects • Is appealing (in color, style, and finish)
Maintenance and Repair	• Prevent damage and increase reliability [1] • Avoid possible errors during disassembly, reassembly, and start-up [1] • Simple service procedures [1] • Prefer self-balancing and self-adjusting solutions [1] • Aim for simplicity and fewer parts [1] • Use Standard components [1] • Allow easy access [1] • Apply modular principles [1,24] • Use few and similar service and inspection tools [1] • Consider ergonomic requirements in maintenance and repair [1]

Table 5.4 (Cont.)

Design for:	Guidelines/Considerations
Maintenance and Repair (Cont.)	• Function processes and supporting measures should be clear [1] • Exchange of components should be easy (Replacing outdated features should be easy) [1] • Design with wear parts to reduce replacement costs (brake pads, cassette, chain) • Consider lubrication in design (Grease in bearing, installation of pedals, installing fork) • Distinguish features not be disassembled by using coupled versus decoupled interfaces [24]
Performance (HPV specific)	• Minimize vehicle weight • Minimize weight of dynamic parts • Aim for quality components • Aim for quality and efficient bearings • Improve aerodynamics • Aim for high efficiency components • Maximize handling ability • Minimize risk [1]
Safety	• Avoid sharp edges and angles • Design for collision prevention (RPS, Bumpers) • Account for collision impact damage • Allow for quick vehicle exits • Secure rider when necessary (harness is needed) • Remove tripping hazards • Provide adequate cooling so the rider does not overheat • Allow for visibility of the road • Ensure vehicle and rider can be seen by other road users • Incorporate methods for the rider to indicate intentions • Create secondary fail safes for dangerous part failures
Off the Shelf (Standard components)	• Encourage designer to use existing standard solutions [1] • Document state of the art technologies [1] • Only be used if economical and useful [1] • Should only be altered for technical and not purely formal reasons [1] • Support a simple, clear, and safe solution [1] • Used to reduce manufacturing requirements • Used to reduce amount of design required

Table 5.4 (Cont.)

Design for:	Guidelines/Considerations
Life Cycle	Production • See design for manufacturing In service • See design for performance • Reduce probability of system failure • Design with fail safe measures • Allow for reworking or replacement of failed parts End of Life • Design for recyclability [1] o Minimize corrosion o Make from recyclable material o Consider carbon footprint o Allow for reconditioning ▪ Complete disassembly (damage free, number of connection features, number of required tools) ▪ Cleaning ▪ Testing ▪ Reuse of worthwhile parts, repair of worn parts, reworking of parts to be adapted, replacement of unusable parts with new ones ▪ Reassembly (use existing tooling) ▪ Final testing • Design for disassembly • Consideration for waste disposal requirements • Create decommissioning plans
Storage and Transportation	• Create maximum size requirements • Consider folding mechanisms (folding bike, folding trike) • Minimize weight for carrying • Although for quick disassembly of larger parts • Consider transportation standards (bike rack and rooftop racks on automotive vehicle • Allow for easy building access (fit though doorway) • Allow for vehicle to lock to standard bike racks • Use theft deterring mechanisms

5.5 Detailed Design Summary

Detailed design allows the preliminary layout to become well defined through documentation, production planning, material selection, analysis, and retrospective evaluation, resulting in a definitive layout. By verifying the design through analysis, demonstration, inspection, and testing it becomes ready for further testing [2]. Testing and testing procedure will be further discussed in chapter six. To summarize the detailed design elements discussed in this chapter, table 5.5 summarizes different detailed considerations.

Table 5.5 Detailed design summary

Detail design aspects	**Aspect specifics**	**Aspect specific considerations**
Production	Documentation	• Part and assembly drawings
	Planning	• Rough to detailed outlines for required machines, tooling, time, methods, and procedure
Analysis	Computational	• CFD • FEA
	Hand calculations	• Fatigue life analysis • Weight distribution (Rollover probability, braking analysis) • Drivetrain analysis (Range, speeds, practicality) • Energy recovery • Steering (sensitivity, turning limits)
	Future testing	• Creating preliminary testing documentation • Outline required testing
	Demonstration / Inspection	• Use models or prototype to prove functionality aspects • Validate procedures used • Visual inspection to examine defects • Inspection of design requirements
	Other	• Budget analysis • Interface analysis • Failure mode and effect analysis (FMEA) • Design tradeoff assessment
Material selection	General approach	• Material selection approach [50]
	Final selection	• Available materials • Designer experience
Design for X	N/A	• Manufacturing • Assembly • Ergonomics • Maintenance and repair • Performance • Safety • Off the shelf • Life cycle • Storage and transportation

CHAPTER SIX: PROTOTYPING, TESTING, AND FINAL PRODUCTION

After the definitive layout is complete the design can move forward with fabrication, prototyping, testing, final analysis, redesign, and final production. Prototyping and testing is key before final production because it helps with the discovery of otherwise unnoticed problems in the design. These problems are then correlated to requirement redesigns in the model. After the redesigns are accepted and validated, the design is completed with the final production.

6.1 Prototyping

Prototyping, as briefly mentioned in embodiment design, is establishing models to verify design aspects meet defined criteria. The purpose of prototyping is to communicate, test, and validate the design solution. Additionally, prototypes help visualize form, fit, and functional understandings. In this stage of the design physical testing is the remainder of validation needed. Therefore physical prototyping is required. Most, if not all, custom fabricated components should be prototyped and tested in some form. Standard off the shelf components may not require testing, because testing has already been completed by the manufacturer. That being said, the designer needs to consider the limits set by the manufacturer and their reliability.

For the HPVC, students make a one-off vehicle product specifically for the competition. This is common in student design with a limited budget and time constraints. In this case the prototype of the system is often the same product as the final solution. As for the HPVC, the design report requires estimates of the vehicle in mass production. Here design recommendations could be made that would not happen to the prototype raced at the competition and the associated costs could be approximated.

For HPVs there are three main types of prototyping and corresponding testing that can occur. The first stage of prototyping is along the lines of inspecting all fabrication components for errors, strength issues, stiffness, problems, and overall functionality. To give an example of why this is important, consider the seat on a tadpole trike. In Clemson’s 2016 design the students decide to explore making the seat from fiberglass sheets (This was also to examine how easy or difficult it would be to create a fairing out of the same material). After what was thought to be a sufficient amount of layers the seat was taken out of the mold. When inspecting the part, it was overly malleable and the shape could be deformed with a minimally applied force from a person’s hand. Therefore, redesigns were needed to fix the problem, before the seat was combined with the overall system.

In the second phase of prototyping the parts can be assembled into the system (HPV). By doing this the interface, fit, and connectivity between parts can be inspected and tested. For student projects the fabrication of parts does not always meet the desired tolerances (somewhat due to the differentiation between CAD models, raw materials used, manufacturing experience, and available machinery/tooling) and interface problems occur as a result. In Clemson’s 2015 design inspection of the system indicted problems of rigidity and overall misalignment of the steering geometry (in relation to the details outline in section 4.3.2). The last phase of prototyping and testing is to evaluate the performance, strength, and requirements of the system a whole. Different system level testing for HPVs will be described in the next section.

6.2 Testing

As mentioned several times, testing is for validating the design and previous analysis. Also variations of different tests need to be applied and testing documentation should be created. The remaining testing examples will occur at the system level, but testing can (and should) occur at the component level to ensure each component is adequate enough for the overall system.

6.2.1 Different Tests Specific to HPVs

The following tests are examples of how prototypes can be measured in terms of performance and design evaluation. More specifically the tests are an outline of some aspects to quantify the effectiveness of a HPV for the HPVC. The first set of testing involves verifying requirements. A great example of design verification testing is outlined in Cal Poly's 2010 design report [52]. Here examples of weight measurements, identifying the turning radius, calculating acceleration times, and assessing braking requirements are outlined. Measuring the weight of the vehicle could be considered difficult depending on the tools available. Figure 6.1 shows how the weight of the Clemson 2015 vehicle was measured using two scales. After measuring the combined weight, the weight of the vehicle could be measured by subtracting the weight of the people from the combined weight. Multiple scales could also be used to determine the weight distribution, with and without a rider.

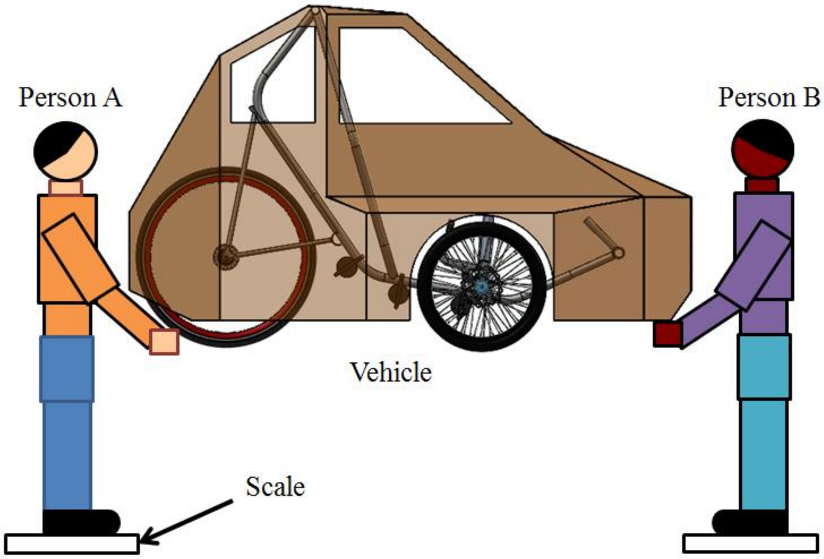


Figure 6.1 Vehicle weight test example

To find the turning radius of the vehicle, the vehicle can turn in the tightest circle possible. Then the diameter of the circle can be measured. From that the turning radius could be found. For the acceleration time, riders could pedal from zero velocity to x velocity in a time t. The time could be measured by a simple stopwatch. The average acceleration would be the difference in the velocity divided by the time. This could be completed multiple times using different riders to give a more accurate acceleration approximation of the vehicle, including a mean and statistical distribution. The braking requirements could be examined in a similar method. As defined in table 1.3, the vehicle must be able to stop in a distance of 6.0m from a speed of 25km/hr. To test this, two lines can be marked on the road six meters apart. Measuring speed and getting to the first line test the vehicle's ability to get to that speed. Then after reaching the first line at the required speed, stopping at or before the second indicates if the vehicle would meet the braking requirements.

System integration testing should be conducted to ensure all the interfaces come together and interact as expected. This is partially fulfilled by prototype development followed by inspection, but it can be further examined through system level testing. An example of this is testing the vehicle dynamics to ensure individual components do not have any negative effects on the overall system. System integration testing could include aspects such as inspecting rigidity, vibrational damping correlated to discomfort, and how the vehicle responds to different road conditions (gravel, sand, pavement, etc.).

Some of the performance testing could be completed by simulating events that occur during the HPVC event. For example, testing for the quick turn obstacle of the endurance race would help evaluate how well the vehicle responds to rapid changes in direction. In the quick turn riders are funneled into a single 3m wide lane [6]. Then riders are signaled to make a turn once entering a 3.5m long section as shown in figure 6.2. If the rider hits a cone they fail the obstacle. To access how well the vehicle responds to the quick turn obstacles, multiple riders can approach the obstacle with different speed ranges. From here a probability of success estimate could be created based on different speed ranges.

Another obstacle that could be used to test the performance of the vehicle is the slalom section, depicted in figure 6.3. Here the cone distance from the center could be varied, along with riders, and speed to determine maximum slalom performance, based on speed ranges. Different riders and speed ranges help create a statistical probability of success, maximum cone distance, and obstacle times.

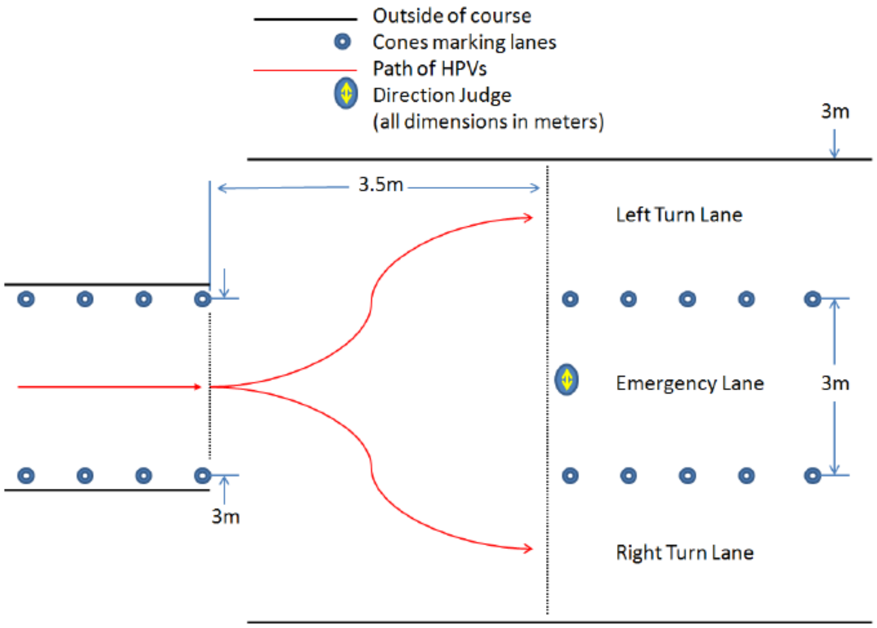


Figure 6.2 Quick turn obstacle [6]

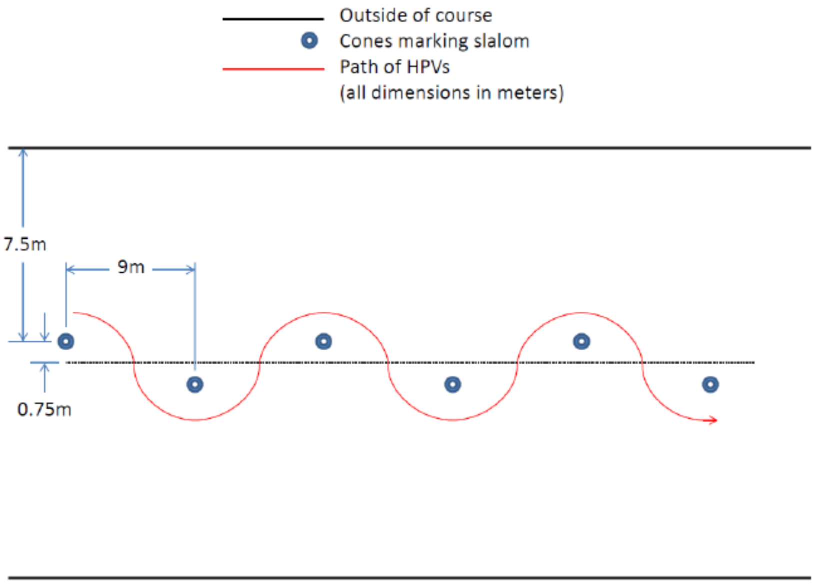


Figure 6.3 Slalom section obstacle [6]

Another HPVC is the speed bump. To test the strength of the HPV system, riders could hit the speed bumps at varying degrees of intensity to assess for any possible damage or dynamic repercussions (flying into the speed at higher speeds). Since this is a form of destructive testing and HPV prototypes are often the final solution, testing should only be performed to an acceptable level of possible damage. This means the speed bump should first be approached at low intensities (slow speeds). Then the intensity of collision (measure by a factor of vehicle speed) could be increased by slow steps until “maximum” intensity is achieved. To obtain more robust testing analysis different sized and shaped speed bumps can be used.

To evaluate pit times and the accessibility of the vehicle different riders can enter and exit the vehicle. In the process, any tripping hazards or potentially dangerous features should be noted. The riders can practice different exiting and entering speeds, such as rushed, normal, and relaxed. Rushed speeds will approximate pit change times and emergency exits. To take this a step further, the vehicle can be placed in difficult positions, such as on its side or upside down to inspect exiting safety in the event of a crash.

To test the speed of the vehicle a set route can be predetermined. The the time it takes different riders to complete the route can be used to indicate average speeds. To make the testing more accurate power sensors should be used to measure the rider input. Therefore, a correlation between speed and input power can be estimated. Through multiple trials, the correlation becomes a more accurate assessment. If this is compared to the gearing analysis previously discussed, a power transfer efficiency can be determined. Depending on the route and environment the speed test could also indicate how well the vehicle responds to changes in elevation and wind directions.

A specific application of the speed test includes coast down testing. Here the vehicle is driven preferably in a straight line on a flat road. The vehicle increases speed until it reaches critical speed. Then the vehicle is ridden at that speed until it reaches a predetermined start point. Once reaching the start point, the rider stops supplying power and the vehicle begins coasting. Once the vehicle stops or reaches a predetermined speed, the distance between the start and the end is measured. This is completed over multiple trials for different configurations of the vehicle (such as with and without a fairing). Configurations that coast farther may have better performance, which is indicate by their ability to coast (decreased resistance i.e drag). Statistical comparisons between the different configurations will outline the methods, such as a fairing with better aerodynamics, that are advantageous. If a flat road is used then the weight of the vehicle only affects the rolling resistance of the wheels, which should be comparable in the different configurations. Thus, the coast down testing is a measure to describe the aerodynamic performance of the vehicle.

For safety considerations, harnesses, RPS, visibility, ventilation/cooling, and crash testing may be needed. First, the harness needs to be able to secure the rider. To test this, the vehicle can slam on the brakes, take quick sharp turns, and be flipped over (stationary), with the rider harnessed into the vehicle. If the harness fails to secure the rider at all then more improvement are necessary. To test the RPS, ASME has indicated that the requirements in figure 6.4 must be followed. To test these, first the RPS must be measured. Second, the system needs to be fixed. Lastly, the given forces can be applied using a method of the designer's choice.

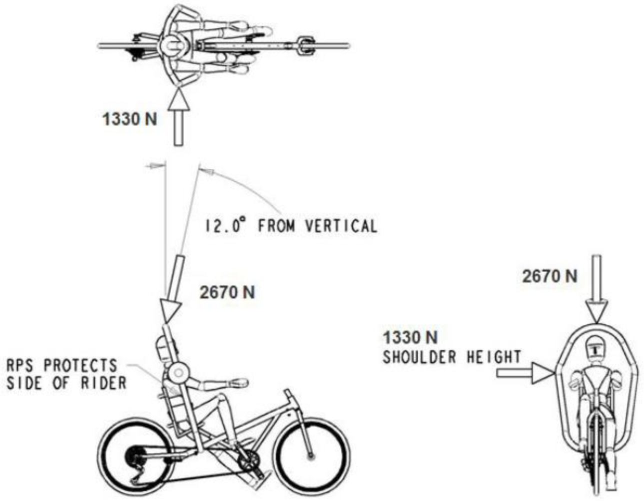


Figure 6.4 RPS load requirements [6]

For the visibility testing the vehicle can remain stationary with a rider sitting in the HPV. Another person can place an object at different heights from the ground and at different locations.

The rider then indicates when they can or cannot see the object. A diagram, such as figure 6.5, can be used to summarize the rider's visibility inside the vehicle. Additional testing could examine how the visibility changes with grade. Ventilation testing could be taken by measuring the airflow and temperature distribution with the HPV at different speeds, in comparison to the ambient properties. Doing so gives an indication of the effects of heat transfer to cool the rider. Completing the tests in a natural environment will yield more accurate results than a wind tunnel or similar testing method, because of considerations such as solar radiation, convective heat transfer from wind, and humidity. Finally, crash testing can describe the vehicle's ability to absorb energy and protect the rider. Students fabricating a single model should avoid this, because the destructive testing can ruin their project, but FEA using estimated impact loads is a valid approach to the same problem.

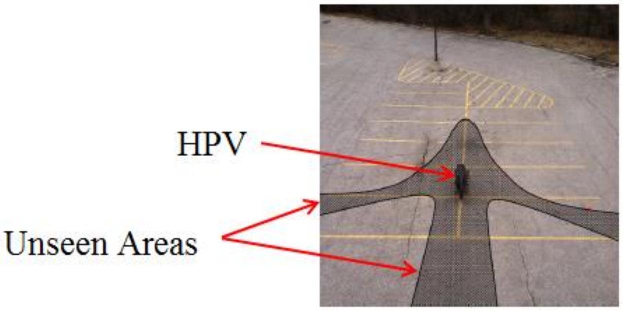


Figure 6.5 Field of vision testing results [26]

Other miscellaneous testing includes energy recovery, storage, and ergonomics. Energy recovery systems should be tested for reliability, likelihood of failure, and efficiency. Storage includes testing for cargo space, accessibility, and usefulness. Lastly, ergonomic testing can be conducted to examine how well the vehicle fits differently sized riders. It can be completed and rated on a subjective level per person. Some ergonomic considerations include comfort, spatial dimensions, understanding, and adaptability.

6.2.2 Testing Documentation

The purpose of testing documentation is to ensure required information is recorded, appropriate preparation is conducted, all testing accessories are acquired, and meaningful results are obtained. Testing documentation involves a list of testing procedures, needed considerations, and required measuring devices before the test occurs. During the test, testing documentation deals with recording all necessary information. After the test is completed, the designers need to analyze and review the results. To give an example of testing documentation and its usefulness table 6.1 provides documentation for visibility testing, and table 6.2 details how coast down testing could be conducted.

Table 6.1 Visibility testing documentation example

<table>
<tr><th colspan="3">Testing Documentation: Visibility Testing Procedure</th></tr>
<tr><td>Rider Name</td><td>Time of Day/Date</td><td rowspan="2">Trial 1 of 20</td></tr>
<tr><td>Henry Sample</td><td>2:00pm 3/16/2016</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Cloud cover</td><td>Road Grade (parallel to vehicle, forward of vehicle is positive)</td><td>Road Grade (perpendicular to vehicle, left of vehicle is positive)</td></tr>
<tr><td>0%</td><td>0%</td><td>.5%</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td colspan="3">**Objective:** To measure the rider’s visibility in the vehicle</td></tr>
<tr><td colspan="3">**Measurement devices:** Eyesight, Marker Height</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td rowspan="2">**Variables**</td><td>Rider (anthropometric dimensions)</td><td>10pmh</td></tr>
<tr><td>Marker Height</td><td>2 feet</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td colspan="3">**Testing procedure:** Have rider position themselves in vehicle. Equally space cones around the vehicle in circle a set distance away. Move the cones inwards and outwards to identify visibility ranges.</td></tr>
<tr><td colspan="3">Step 1: Have rider enter vehicle and change adjustable features to fit them</td></tr>
<tr><td colspan="3">Step 2: Take 30 cones and space them around the vehicle in a circle</td></tr>
<tr><td colspan="3">Step 3: Place an object on the ground and move until it is not visible to the rider</td></tr>
<tr><td colspan="3">Step 4: Repeat steps 2 and 3 with a new set of cones and use an object that is the marker height from the ground</td></tr>
<tr><td colspan="3">Step 5: Record the position of the cones</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td colspan="3">Analysis Procedure</td></tr>
<tr><td colspan="3">Step 1: Based on ground locations create a model similar to figure 6.5</td></tr>
<tr><td colspan="3">Step 2: Based on marker height locations create a model similar to figure 6.5</td></tr>
</table>

Table 6.2 Coast down testing documentation example

Testing Documentation: Coast Down Testing Procedure		
Rider Name	Time of Day/Date	Trial 7 of 20
Henry Sample	1:00pm 3/15/2016	
Wind Speed [mph]	Wind direction	Path direction
5mph	East	North
Objective: To measure the distance the rider is able to able to coast		
Measurement devices: Garmin 510		
Variables	Required initial coasting speed	10pmh
	Accepted initial coasting speed error	3mph
	Finishing speed	3mph
Testing procedure: Rider must start at location A and pedal until point B located in 10m from A in a directly straight path. Once the rider reaches point B they stop pedaling and the vehicle continues to coast forward until it comes to a predetermined speed.		
Step 1: Rider must enter vehicle with required safety equipment		
Step 2: Brakes must be checked for case of emergency usage		
Step 3: Garmin 510 is turned on and checked to ensure GPS fix.		
Step 4: Course time is started on Garmin 510		
Step 5: When initiated the rider pedals from A to point B		
Step 6: Once rider reaches point B they stop pedaling		
Step 7: Once the vehicle reaches the finishing speed it is stopped		
Step 8: If the rider does not reach required initial coasting speed or exceeds the required initial coasting speed, plus the accepted initial coasting speed error go to step 1 and repeat the process		
Step 9: Crop the recorded data so that the beginning is located after point B and shows a start speed equal to the required initial coasting speed and the end is equal to the finishing speed.		
Analysis Procedure		
Step 1: The distance between point B to finish is found use recorded data		
Step 2: Using recorded data of the speed distribution, find the drag estimate assuming elevation change, rolling resistance and wind speed is negligible.		
Step 3 (Optional) : Estimate drag assuming elevation changes, rolling resistance, and wind speed are not negligible. Wind speed and direction should be recorded on this form. Elevation can be found in recorded data. Rolling resistance can be estimated from HPV components.		

6.3 Success in Failures, Redesigns, and Final Production

After validating the design through prototype testing, some aspects of the design may require improvement. In fact some aspects of the testing may have been direct failures. That being said, failures in design are not always bad, because the designers can learn from them. In other words, there can be success in failures, through redesigns and better understanding. To show how failures or bad design elements can lead to improvement some examples of past Clemson's problem will be illustrated.

The most memorable HPV Clemson design failure involved a front wheel axle breaking within days of going to the competition, after several test rides. Originally the axle was a standard meant to be used with the wheel. Upon inspection the axle was made of pot metal (cheap, low strength). To replace the axle a hardened steel axle was created from a linear actuator. The result was a dependable axle that didn't fail during the competition. If the original axle wasn't properly tested the Clemson team would have been removed from the competition. Ultimately the early failure in testing was very advantageous. This also goes to show how putting complete trust in standards without some testing could be a fatal error.

The next failed design aspect involved the drivetrain in 2015. Originally the drivetrain was comprised of a crankset, three idler gears, and a rear wheel with an IGH and chain tensioner. The idler gears were connected using clamps that were customized and standard to the purchased idler gears. The clamps were sized for 1.5" tubing (discovered after they were ordered) and the tube they were being attached to was 1.25" tubing. The proposed and implanted solution was to use cut wooden fillers attached to the tubing and clamps with compressible adhesive strips. After system integration testing, it was revealed pedaling at higher resistances caused increased tension on the chain, based on the drivetrain configuration. This increased tension was great enough to produce a moment on the idler gear capable of overcoming the friction force by the clamp causing the clamp to rotate about the tubing. In turn, the chain path was rotated to the point where the chain stopped working. Thus, the drivetrain configuration failed to function adequately. The redesign was to weld brackets to the frame to replace the previous clamps. The brackets had a through hole with a nut welded on one side. The end result was an idler gear mount capable of withstanding the moments and forces produced by the chain tension. In summary, the better solution of welded brackets was only established after the failure system of clamping was tested.

Other examples include flexing issues of the system, lack of precise jigging for welds, and stiffness issues with a seat design. First, the flexing issues occurred because the steering arm connected to the wheels was not rigid enough based on a single connection point to the frame. As a result, when ridden the stability of the HPV was lowered. The problem was fixed by adding supports that acted as stiffeners connecting the head tubes to the RPS. Each test rider noted a subjectively noticeable improvement in performance after this addition. That being said, the stiffeners did create more problems along the lines of entering and exiting the vehicle. In terms of welding, the lack of jiggings used for Clemson’s 2015 design caused the steering arm to be attached at incorrect angles and distances. This resulted in negative effects on the steering. As a result, Clemson’s 2016 design used precise miters and specialized jigs, for the steering attachment in particular. Complete testing is yet to be completed, but a noticeable improvement in performance is expected.

In Clemson’s 2016 design it was decided the seat should be made from fiberglass to reduce weight and assess the difficulty of creating a fairing from the same process. Initially the seat was made from ten layers of fiberglass sheets and removed from the mold. Upon inspection the seat was much too weak and flexible. An individual could deform the shape of the seat by pushing on it. In retrospect, that same seat needed to support an entire person’s body weight so it was obvious changes were needed. One problem was the layers of the fiberglass were all in the same orientation, meaning the benefits of using the composite material were negative because of lack of proper implementation. Another problem was there were no stiffeners or ribs in the current product. Foam stiffeners were going to be added originally, but based on the allowable deformation they were not deemed strong enough. The solution shown in figure 6.6, was prosed instead. Here, steel flat stock would be added inside the fiber glass layers to act as a stiffener and provide more strength. The geometry or amount of material could be optimized if desired. After fabrication of the new seat is finished if it is still not stiff enough other considerations may be needed. First foams sections could be added to the support the back of the seat. Additionally, a telescoping member connecting the (adjustable) seat to the frame would provide more than enough support. The seat design itself could also be changed to carbon fiber with reinforced Kevlar (a stronger, stiffer combination) or it could include thick sections of Nomex between certain layers of the composite.

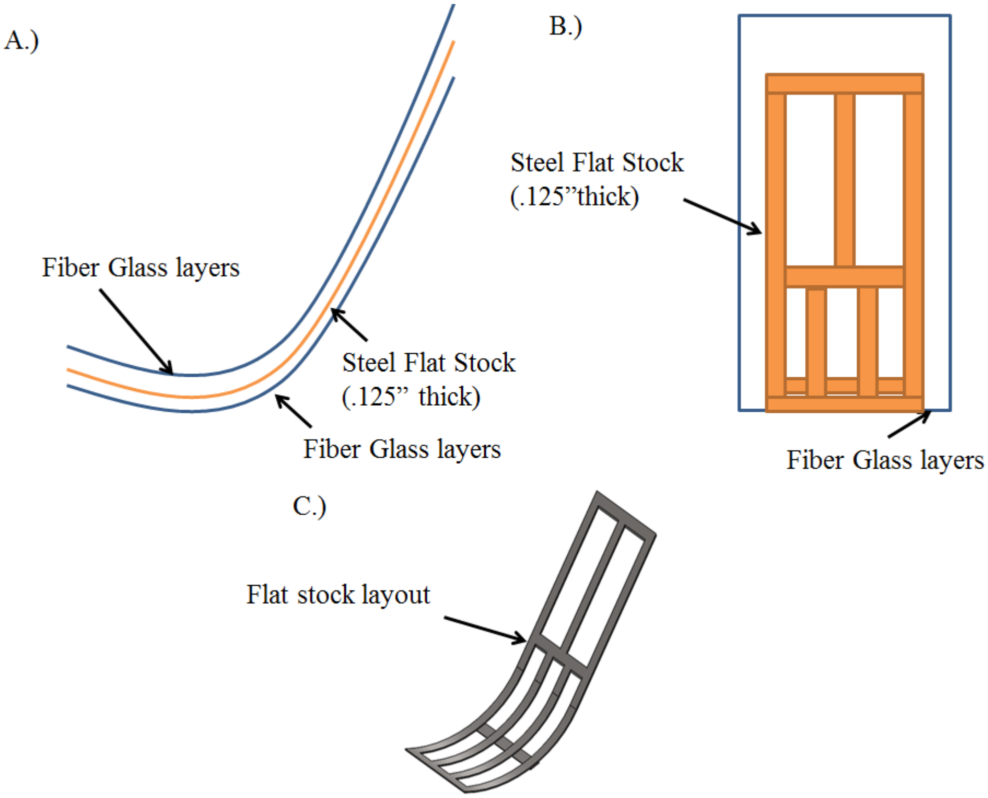


Figure 6.6 Possible seat stiffness solution for composite materials A.) Layers of fiber glass and steel flat stock B.) Front view of steel layout C.) Isometric view of steel layout

To finalize some examples of redesigns, consider the differences between Clemson's 2015 and 2016 initial frame models, shown in figure 6.7. More notable difference between the designs include the rear triangle location, lack of front shifter support on the newer design, change in shape of the RPS, stiffener additions on the main member of the frame, addition of a front bumper section on the frame. The change in the rear triangle was done to create a lower center of gravity, so the vehicle would ultimately have better handling. The shifter support was removed, because it was considered a safety hazard for the team. Instead a jackshaft was added under the seat along with a shifting mechanism. The change in shape of the RPS was completed because the original RPS was too narrow at the bottom and uncomfortable for arm movements. The addition of stiffeners to the main member was to combat some of the effects of frame flexing. Lastly, the front bumper was added to absorb energy in the case of collisions and provide a stopping support in the event of forward lean from hard braking. Later, the wheel base was also increased to assist with hard braking in the 2016 model.

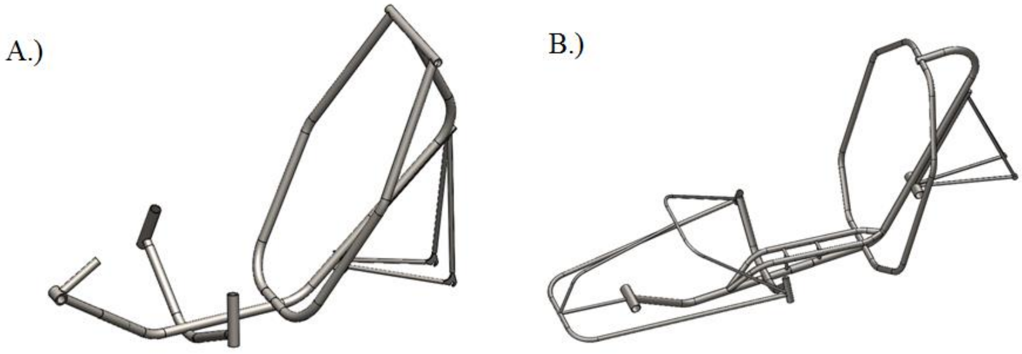


Figure 6.7 Clemson's initial HPV frame A.) 2015 design B.) 2016 design

After completing necessary testing and evaluating possible redesign, the product can move forward to final production. For student design projects prototypes are often the final design. Design considerations may be discovered and mentioned for the large production, but depending on the degree of difficulties to implement said changes to the prototype reflects the likelihood of redesigns occurring to the final student production model. Lastly the final design involves documenting everything into a final report and giving a full description of the design and all details involved [2]. For HPVC the details will be narrowed to focus content on specifics outline in the grading rubric and competition rules [6,7].

6.4 Prototyping, Testing, and Final Production Summary

After completing analysis of the design prototyping and testing it is necessary to perform a final validation of the design. Initial prototyping and testing involves inspecting the individual features and product assembly. Further testing involves different system level aspects. After testing is complete examining failures and weak spots of the design will highlight aspects that need to be improved. Once redesigns are established and validated the design can be finalized and final production of the design can begin. To summarize the remaining contents of this chapter table 6.3 is provided.

Table 6.3 Prototyping, testing, redesigns, and final production summary

Prototyping and Testing	Stage 1 –Individual Components	
	Stage 2 – Assembled	
	Stage 3 System level testing	
System Level Testing	Different Tests	• Design verification testing (weight, turning radius, acceleration, braking, etc.) • System integration testing (inspecting rigidity, road condition effects, vibrational damping) • Testing events (Quick turn, slalom, speed bumps, vehicle accessibility) • Performance (Speed, coast down testing) • Safety (Harness, RPS, visibility, ventilation/cooling, crash testing)
	Create testing documentation	
Redesigns	Examine failures and weak design aspects Incorporate and recommend design changes Test changes for improvement verification	
Final Production	Finalize documentation of design Create design report include all necessary information	

CHAPTER SEVEN: DESIGN PROCESS EVALUATION

The aforementioned design process and corresponding appendices is a relatively exhaustive document that includes elements from the traditional design process, the systems engineering design process, and aspects specific to HPVs. The process is given to help mentor students in systems engineering design, traditional design, and HPV specific design information. That being said the process needs some form of evaluation to prove its usefulness. Unfortunately, the best measure of usefulness would be completing a large case study involving many different teams, but that is outside the scope of this paper.

To create a form of preliminary evaluation a survey was conducted involve different schools participating in the 2016 HPVC East event. The complete survey and results is included in Appendix K, but a summarized version will be described here. To begin the survey was sent to the leaders of different schools participating in the East competition. Of the twenty four invitations, four partook in the survey. Thus there is clear evidence of volunteer basis in the results. Additionally, three students from Clemson took the survey from an initial group of 12. Of the schools that did complete the survey there was a large range of (school) experience, including a first year team, a team with one year of experience (Clemson), two schools with four to five years of experience, and a school with about ten years of experience. That being said the students taking the survey did not have the same amount of experience as the school, for the most part.

From the survey results many questions were asked, but it was evident there was some difference in how different teams approached the design. For example, one team said they didn’t use a design process and many teams are weak or strong on different areas of the design process. There was a general census that most teams have difficultly fabricating the vehicle before the competition, and the amount of testing before competition is generally not adequate. Often a project plan is completed and then not followed very well. Most teams feel like they have a decent understanding of the HPV systems, but required many redesigns at the later stage of the design process. The perceived usefulness of the guidebook is shown is figures 7.1-7.3. Figure 7.1 shows how much the teams thought the guidebook would benefit them. Figure 7.2 shows what design aspects the different teams are interested in. Figure 7.3 gives an estimate of how likely team would be to use the guidelines.

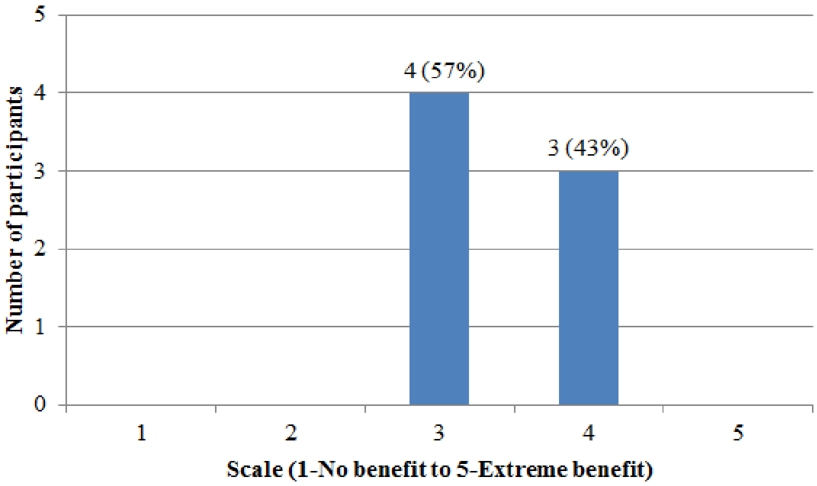


Figure 7.1 Survey results: Subjective benefit of guidebook

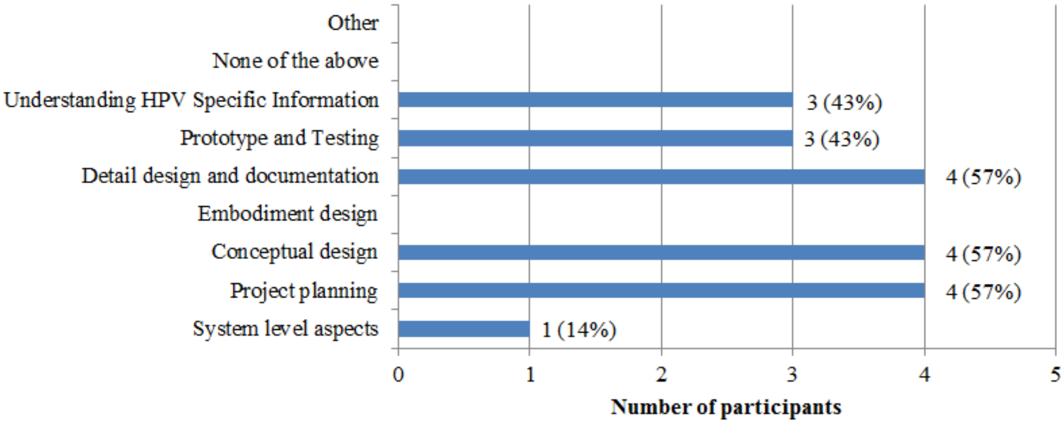


Figure 7.2 Survey results: Specific design areas of interest

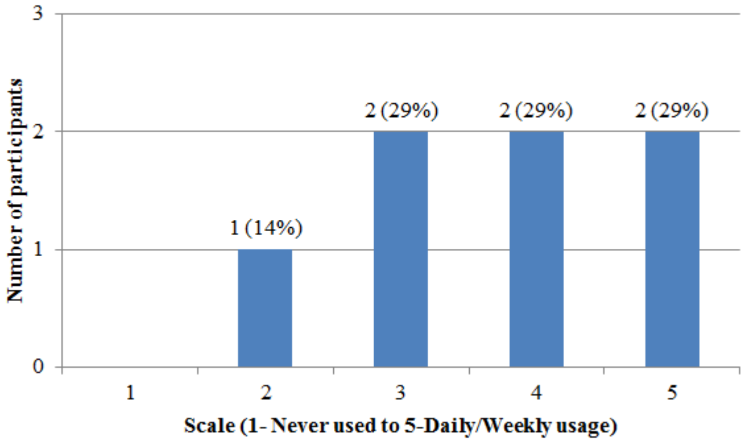


Figure 7.3 Survey results: Subjective likelihood of guidebook use

Overall, the results show different teams would make use of different areas of the guidebook. In terms of the desired areas of coverage from figure 7.2, ample information is given on each of the topics. Also, all teams stated there would be some benefit to having the guidebook, and most would likely use it if they had a copy. Looking into more detail from the individual responses, it appears the overall teams with less experience would be more likely to use the guidebook. This makes sense as well, because they have less experience. Additionally, helping newer teams, by using the guidebook, would be a form of mentoring, which is the main goal of this paper.

To evaluate the guidebook use further, future work would include testing new teams and examining the HPV designs and performance with and without the guidebook. The control group would be teams not given the book and the experimental group is therefore teams that have the guidebook. The selection of the teams would be randomized by schools, students involved, and etc. to avoid possible biasing. To evaluate how well designs are accomplished and the overall understanding of design direct and indirect measures can be used. Indirect methods are more commonly used to evaluate the students understanding of design. For HPV design these methods could include comparing the vehicle performance and design reports, obtaining customer surveys of the products, and comparing HPVC results. A direct method to evaluate the teams understanding of design could include testing the students for certifications about design process elements, such as examining if different design aspects are understood (requirements, concept evaluation, etc.) as well as the different stages of design. Additionally case studies could be used to examine student's learning throughout the entire design process.

Using the 2015 and 2016 Clemson vehicle as an indirect comparison, using elements of the guidelines in 2016 design has allowed for a more maintained project schedule, higher quality manufactured parts, and expected better vehicle performance and HPVC rankings. Full comparisons cannot be made about performance and rankings, because the projected time of completion of the 2016 design occur after this paper will have been submitted. Additionally, the improvements may be attributed to experience rather than the guidebook. Overall, based on the preliminary survey and Clemson's improvement it does appear there is merit in the described design process, but future work is still required to make accurate assessments of the design process.

In terms of rating the design and progress of Clemson's 2015 and 2016 designs, Appendix L provides Clemson's 2015 and 2016 innovation and design report submissions and the respective scoring criteria. While the 2016 reports still need to be evaluated by competition judges it can be easily seen the 2016 reports would rank higher based on the scoring criteria. As stated the difference between the submissions is the attributed to better project management, a greater understand and use of design processes, and more experience in HPV design. With the exception of more experience, all of these elements were enhanced by the use of these guidelines in the 2016 design. In the end this does provide some merit in terms of guideline usefulness and impact on student design education.

CHAPTER EIGHT: CONCLUSION AND FUTURE WORK

As outlined in table 1.1 the goal of this paper was to provide guidelines for HPV design, using system engineering design and the traditional design method, in order to help mentor students. In addition to the goal, four objectives were defined; to give an understanding of design method, provide discussions and examples for the various design stages, outline useful design tools and methods for students, and to discuss an evaluation system for the given design process.

The first objective was completed in the first chapter where overviews of different design processes were given. Additionally, the remaining text and appendices discussed each of the design stages outlined in more detail. To help detail the different design stages many methods, tools, and examples were given to develop understanding, fulfilling objectives two and three. In the project initiation section planning tools, communication methods, group formation methods, and problem development examples are given to illustrate how the project started. An entire project plan and requirements set is detailed in the appendices. For the conceptual design, several concepting tools are explained and evaluation methods are discussed in detail. Examples of concepting and evaluation tool usage are provided in the appendices as well. For the embodiment chapter a general explanation of modeling, preliminary analysis and system level aspects are discussed and coupled with HPV specific considerations. Manufacturing planning and considerations, material selection, specific design analysis calculations, and DFX factors are included to describe the detailed design phase. Finally, chapter six outlines prototyping example, useful testing procedures and documentation, and illustrates different redesign examples. Ways to measure design effectiveness and student understanding were described in chapter seven, which fulfils the fourth objective. A preliminary survey indicated that current HPVC team thought the guidebook would be useful and they would be likely to use it. Additionally, all areas of design in which student requested more information are covered in detail.

The overall goal itself is mostly completed through having the detailed guidebook, but more evaluation is needed to test its ability to mentor students. Measuring its ability to mentor will be future work for this paper. In terms of future work multiple student teams need to be divided into two groups; a control group which will not get the book, and an experimental group that will. All teams will then be asked to design, fabricate, and race HPVs, with case studies being used to analyze the progress of all the students. After students have completed the design, manufactured the product, and competed indirect and direct methods can be used to test the students' understanding of the design process. If the guidebook can statistically provide enhanced indirect and direct measures of understanding, it can be considered capable of mentoring students in HPV design. Additionally in order to provide more effective guidelines the given work in this thesis needs to be condense into clear and concise text outline the design features to be used. In other words a simplified cookie cutter outline needs to be created to efficiently describe what design aspects need to be used and to what quality. This would give a more specific framework of HPV design (non-specific to HPVC) that would help mentor students without design experience. The framework would be a baseline of general details such as main requirements for subsystems, initial milestones in project management and so on, combined with specific design tools to use and details of what items need to be generated.

Lastly, some of the future work includes outlining how to create a design report and finalize the results of the design process. Appendix L has been provided to outline examples of what design reports look like and how they can be structured, but more through details and descriptions are needed to give students an understanding of the design report's usefulness, organization, aspects, and formatting. Overall, the design report is critical in communicating the purpose of the design features, analysis behind the design, and progression to reach the final solution. Without being able to effectively communicate the final design in the design report the ultimately will appear less valid to others examining it.

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APPENDICES

APPENDIX A: LITERATURE REVIEW OF ERGONOMICS IN HPV DESIGN

A.1 Abstract

Human powered vehicles, HPVs, use human energy to allow for more efficient transportation. The design of an HPV should be completed using an ergonomics analysis to ensure a suitable vehicle is created for human use. Designing with ergonomics allows the vehicle to comfort the user from various aspects, thus creating a more preferred design. Tradeoffs between ergonomic features create different styles of HPVs design. Some of the key ergonomics factors to consider are power, performance, comfort, dynamics, safety, environmental concerns, and anthropometric relations.

A.2 Introduction

The purpose of this paper is to complete an extensive review of how different aspects of ergonomics are addressed in human powered vehicle design. Human powered vehicles, HPVs, were limited to the design of two, three, and four wheeled land based transportation designs. Of those, two and three wheeled vehicles were more extensively explored. From various literatures and experimentation with human powered vehicle design there have been several ergonomic aspects of vehicle design. In addition, there are select methods that can be used to incorporate the ergonomic aspects into the vehicle design. To examine these ergonomic factors, case studies and market available products are used to explore design features of HPVs. These examples are also used to extract features that can be used to benefit ergonomics. It is important to note this review covers the ergonomic aspects geared mostly towards people without disabilities or injuries, as there is also large research specifically in that field of study.

To address the ergonomic factors some designers recommend the use of CAD software [53]. Anthropometric data can also be useful for dimensioning aspects of the vehicle. This aspect will be explored briefly using literature examples and personal research of anthropometric tables

[29,30]. To further the discussion the most noteworthy factors are outlined in the following list. The list also serves as an outline to the remainder of the appendix.

1.) Power production and performance factors
2.) Human configurations, comfort, and applications
3.) Weight influence on vehicle dynamics
4.) Static and dynamic stabilization
5.) Safety of the rider regarding collisions
6.) Visibility of the rider and vehicle
7.) Maneuverability and the ease of entering and exiting
8.) Environmental considerations and thermal comfort
9.) Maintenance and Repair
10.) Storage capabilities and Energy recovery
11.) Anthropometric and Vehicle Relations

A.3 Power Production and Performance Factors

Power generation from the riders can be attributed to many aspects ranging from the oxygen level of the environment to the personalized crank length of the pedals. Additionally, power generation can be examined from various forms, such as endurance using fatigue models, and sprints using peak analysis models. Performance factors, such as aerodynamic fairings and recumbent positions, can reduce the efforts required by the rider, by lowering drag forces. Lastly, different methods of power production can be examined.

To begin there are several means that can be used to measure power input. Chavarren *et al* discuss measuring power using anaerobic methods and direct measurements from instrumentation [54]. Their measurements came in the form of power (watts), from torque and cadence measurements, heart rate (bpm), and oxygen consumption ($\dot{V}O_2$). They have also shown that correlations between pedaling rate and power intensity can be made. In short, several plots were developed relating different pedaling speeds to power intensity levels using time intervals of two to four minutes.

McCartney *et al* examined peak performance power outputs [55]. In their experiment thirteen students were tested for power output data. Oxygen intake was measured for maximum bouts of cycling at a constant crank velocity ranging from 60 rpm to 160 rpm. This was completed for duration times of ten and thirty seconds. From their results they found the peak torque to be inversely related to crank velocity. McCartney *et al* noticed the power decreased over time, which is reasonable and has been researched under the study of fatigue. Using the decrease of power output over time, they created a fatigue index in the form of Eq. (15) . To support their notion of fatigue the original power inputs of the students ranged from 700-1000W, with a final output power of 450-600W, using crank velocities of 60 rpm, 100 rpm, and 140 rpm. From their research peak power generation occurred around 140rpm. Lastly, their data supports the conclusion that greater power generation causes greater fatigue, using Eq. (15). This is understandable considering that without nutrition humans have a net energy supply and depleting that energy supply quicker, results in lower levels of energy faster. The energy supply comes in different forms and affects different aspects of fatigue.

$$\text{Fatigue index score} = \frac{\mathrm{Power}_{\mathrm{initial}} - \mathrm{Power}_{\mathrm{final}}}{\mathrm{Power}_{\mathrm{initial}}} \text{ x } 100\% \qquad (15)$$

Abbiss *et al* outline a detailed discussion about fatigue, based on the examination of elite athletes [56]. Neuromuscular, muscle trauma, biomechanical, thermoregulatory, psychological, central governor, energy storage and cardiovascular depletion, and complex system models are created to discuss endurance cycling performance. In the discussion of cardiovascular fatigue the main discussion points are oxygen consumption, oxygen usage, and metabolite accumulation, which relate to red blood masses, plasma volume, and lactate concentrations. High lactate thresholds (>90% of $\dot{V}O_{2\ max}$) allow for the maximal aerobic power (>500W). The neuromuscular fatigue model is based around the ability of the cardiovascular system being able to provide, nutrients, and oxygen to the working muscles. The biomedical model suggests that fatigue is related to the motion of patterns during cycling. Thermoregulatory models discuss the environmental temperature impacts on cycling exercise, such as causing hypothermia or overheating. Psychological models explain that lack of motivation and enthusiasm can create fatigue. Overall the models of fatigue created explain the power production of a person based on their athletic ability.

Morton *et al* examine the critical power for cyclists based on duration [57]. The critical power is the theoretical power production that can be produced regardless of previous energy usage, while assuming proper nutrition can be sustained. From there data gathering an asymptotic relationship was developed as shown in figure A.1. From this a critical power was found to be approximately 260W. The participants used were six endurance trained athletes, thus results for average users can be much. Estimates of 40% of the elite athletes power can be used to determine average power, with professional athletes having critical powers of 300W [58,59].

Too *et al* discuss how various body configurations can affect power production [60–62]. In the first study, sixteen males were placed in five different body configurations. [61] Toe clips were used for three minutes increments with pre-defined loads until the subject was exhausted. The configurations were determined by placing the seat tubes at angles of 0°, 25°, 50°, 75°, and 100°. By varying the seat tube angles the effective hip, knee, and ankle angles changed for the subjects. The corresponding mean hip angles, knee angles, and the mean corresponding ankles angles were recorded and are tabulated in table A.1 with the seat tube angle configurations. After converting the power measurements, the corresponding average power outputs were added to table A.1. Using these results Too found the optimal hip angle to 77°, with an average hip range of 41° for power production. The data gathered showed a systemic decrease in hip angle, increase in knee angles, and decrease in ankle angles as the seat tube angle increases. The corresponding knee and ankle information can be used to help determine placement of the pedals, when used in combination with anthropometric data.

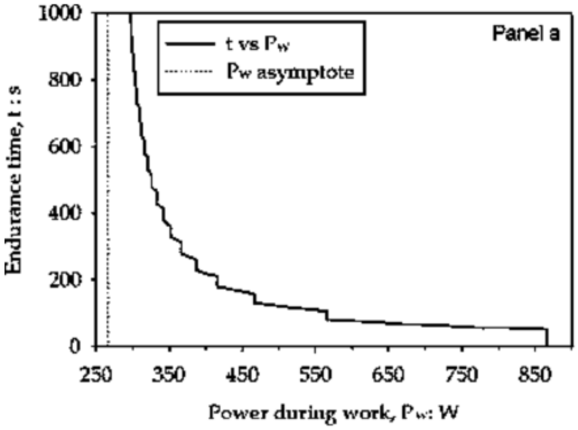


Figure A.1 Plotting the relation between power and endurance [57]

Table A.1 Average body configurations and Power outputs

Seat Tube Angle	0°	0°	50°	75°	100°
Mean Hip Angle	130.9°	13.4°	100°	76.8°	99.9°
Mean Knee Angle	95.5°	7.9°	103.3°	103.6°	103.8º
Mean Ankle Angle	113.4°	5.3°	93.6°	96.0°	91.8º
Average Power Output	126W	45W	166.7W	172.8W	160.5W

Too validated his results with a second study where fourteen subjects had similar mean angles and ranges [60]. He concluded that seat configurations around the 75° angle resulted in the largest performance values, similar to before. The performance values of hip angles gradually changed with a person’s height. Too explained due to aerodynamic drag the study used cannot specify the actual affect the seating adjustments will have on cycling performance. Lastly, Too *et al* examined different biomechanics and the resulting power outputs [62]. They examined the seat-to-pedal distance, joint angles, muscle length, and crank arm length. The main results were changes in the crank arm length affect the force production by the hips, changes the joint angles, changes the muscle length, and it affects the torque applied to the crank. Shorter crank arm produce lower ranges of joint motion, but also resulted in reduced applied torques.

Examining non-traditional methods of power production Jansen explored power generation of hand cranks, using eight male subjects [63]. Preferred crank speeds were determined for the different crank lengths of various products and it was found the preferred speed were 123 rpm with a standard deviation of 27.3 rpm. Additionally the required torques were determined for the different crank lengths. Ultimately, the power production of hand cranks was established. In the analysis of the hand crank an average critical power of 54W was found with a 31W critical power at the 95th percentile of people.

Various performance factors can lower the required power production to travel at similar speeds. Elite athletes and time trial cyclists try and do this using various methods as explained by Atkinson *et al* [64]. To begin they discuss the power production distribution over the course of a time trial race. In doing so they discuss how it varies throughout the race because of environmental factors, such and pacing behind racers, hilly terrain, and winds. Hence more aerodynamic position and pacing allow for increases in performance, due to reduced drag forces. In addition, Atkinson *et al* provide a discussion on pacing strategies and the corresponding fatigue data, by accounting for heat generation, physiological effects, and anticipation. Overall, an outline optimal pacing strategy is defined to maximum the power produced, while accounting for endurance aspects.

The largest performance factor in cycling can be attributed to aerodynamics and the reduction of drag forces. Íñiguez *et al* outline the aerodynamic of cycling on power for various vehicle designs with different conditions [65]. Some of their discussions points include recreational bicycles, triathlon bicycles, recumbent tricycles, and human powered flight. They create mathematical models for wind loading of various speeds and directions in terms of power requirements. Aspects of team cycling such as drafting are analyzed for aerodynamic benefits. Íñiguez *et al* take into account specific cycling equipment and the use the fairings by justifying them with quantifiable drag reductions. In parallel with this work, Gross *et al* outline the drag coefficients of various styles of HPVs and fairings [66]. The comparative drag analysis is shown in figure A.2 and table A.2. Lukes *et al* discuss how aspects of the vehicle design can be changed to increase aerodynamic performance [67]. In addition to drafting, wind effects, and rider position, they discuss how the vehicle design, wheels, clothing, and use of helmets can affect general aerodynamics.

Another performance factor that is often discussed is the use of clipless pedals and their benefits to power production. As stated by Davis *et al* the power difference between clipless and flat pedals is not well discussed [68]. To account for this discrepancy, Ostler *et al* conducted a study, using eleven males to examine the effects of clipless pedals [69]. Original claims stated the use of clipless pedals compared to flat pedals would result in oxygen consumption reduction of 8% to 18%. Recalling from the previous discussion, the oxygen consumption levels are directly related to measuring aerobic power production [54]. From the results of Ostler et al, the subjects consumed 2.1% more oxygen, on average, when using the clipless pedals. From this, claims of the power production benefits from clipless pedals can be disproven with 99% confidence.

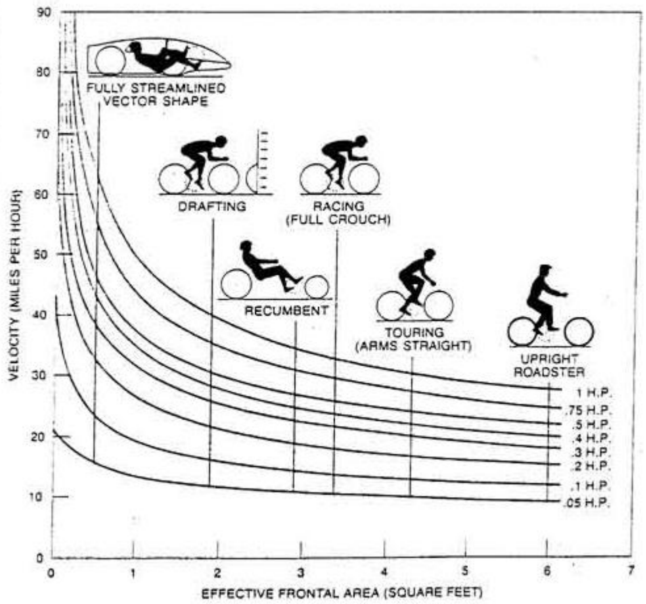
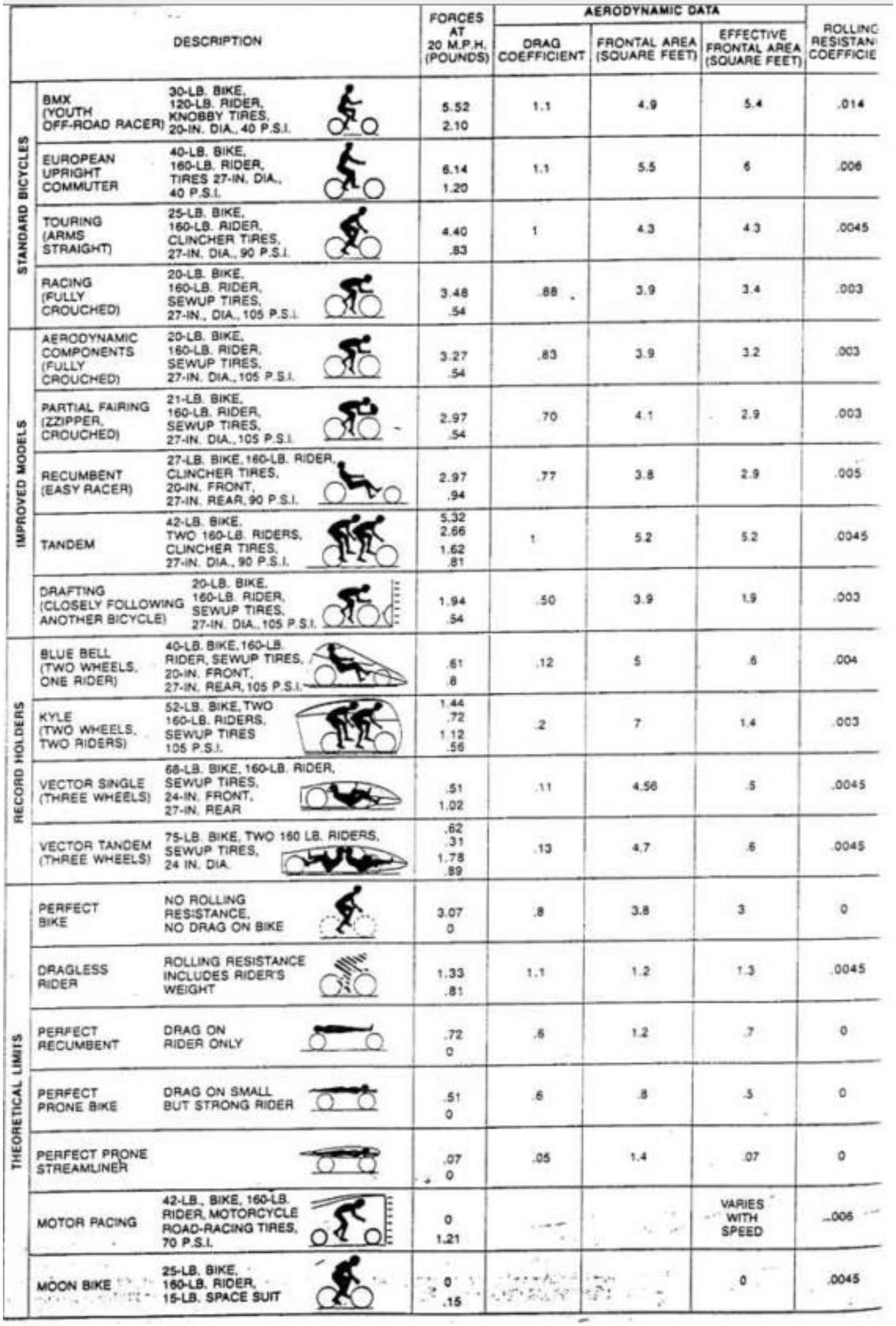


Figure A.2 General cycling configurations and associated abilities [66]

Table A.2 Vehicle configurations and associated drag [66]



	DESCRIPTION		FORCES AT 20 M.P.H. (POUNDS)	AERODYNAMIC DATA			ROLLING RESISTAN COEFFICIE
				DRAG COEFFICIENT	FRONTAL AREA (SQUARE FEET)	EFFECTIVE FRONTAL AREA (SQUARE FEET)	
STANDARD BICYCLES	BMX (YOUTH OFF-ROAD RACER)	30-LB. BIKE, 120-LB. RIDER, KNOBBY TIRES, 20-IN. DIA., 40 P.S.I.	5.52 2.10	1.1	4.9	5.4	.014
	EUROPEAN UPRIGHT COMMUTER	40-LB. BIKE, 160-LB. RIDER, TIRES 27-IN. DIA., 40 P.S.I.	6.14 1.20	1.1	5.5	6	.006
	TOURING (ARMS STRAIGHT)	25-LB. BIKE, 160-LB. RIDER, CLINCHER TIRES, 27-IN. DIA., 90 P.S.I.	4.40 .83	1	4.3	4.3	.0045
	RACING (FULLY CROUCHED)	20-LB. BIKE, 160-LB. RIDER, SEWUP TIRES, 27-IN., DIA., 105 P.S.I.	3.48 .54	.88	3.9	3.4	.003
IMPROVED MODELS	AERODYNAMIC COMPONENTS (FULLY CROUCHED)	20-LB. BIKE, 160-LB. RIDER, SEWUP TIRES, 27-IN. DIA., 105 P.S.I.	3.27 .54	.83	3.9	3.2	.003
	PARTIAL FAIRING (ZZIPPER, CROUCHED)	21-LB. BIKE, 160-LB. RIDER, SEWUP TIRES, 27-IN. DIA., 105 P.S.I.	2.97 .54	.70	4.1	2.9	.003
	RECUMBENT (EASY RACER)	27-LB. BIKE, 160-LB. RIDER, CLINCHER TIRES, 20-IN. FRONT, 27-IN. REAR, 90 P.S.I.	2.97 .94	.77	3.8	2.9	.005
	TANDEM	42-LB. BIKE, TWO 160-LB. RIDERS, CLINCHER TIRES, 27-IN. DIA., 90 P.S.I.	5.32 2.66 1.62 .81	1	5.2	5.2	.0045
	DRAFTING (CLOSELY FOLLOWING ANOTHER BICYCLE)	20-LB. BIKE, 160-LB. RIDER, SEWUP TIRES, 27-IN. DIA., 105 P.S.I.	1.94 .54	.50	3.9	1.9	.003
RECORD HOLDERS	BLUE BELL (TWO WHEELS, ONE RIDER)	40-LB. BIKE, 160-LB. RIDER, SEWUP TIRES, 20-IN. FRONT, 27-IN. REAR, 105 P.S.I.	.61 .8	.12	5	.6	.004
	KYLE (TWO WHEELS, TWO RIDERS)	52-LB. BIKE, TWO 160-LB. RIDERS, SEWUP TIRES 105 P.S.I.	1.44 .72 1.12 .56	.2	7	1.4	.003
	VECTOR SINGLE (THREE WHEELS)	68-LB. BIKE, 160-LB. RIDER, SEWUP TIRES, 24-IN. FRONT, 27-IN. REAR	.51 1.02	.11	4.56	.5	.0045
	VECTOR TANDEM (THREE WHEELS)	75-LB. BIKE, TWO 160 LB. RIDERS, SEWUP TIRES, 24 IN. DIA.	.62 .31 1.78 .89	.13	4.7	.6	.0045
THEORETICAL LIMITS	PERFECT BIKE	NO ROLLING RESISTANCE, NO DRAG ON BIKE	3.07 0	.8	3.8	3	0
	DRAGLESS RIDER	ROLLING RESISTANCE INCLUDES RIDER'S WEIGHT	1.33 .81	1.1	1.2	1.3	.0045
	PERFECT RECUMBENT	DRAG ON RIDER ONLY	.72 0	.6	1.2	.7	0
	PERFECT PRONE BIKE	DRAG ON SMALL BUT STRONG RIDER	.51 0	.6	.8	.5	0
	PERFECT PRONE STREAMLINER		.07 0	.05	1.4	.07	0
	MOTOR PACING	42-LB., BIKE, 160-LB. RIDER, MOTORCYCLE ROAD-RACING TIRES, 70 P.S.I.	0 1.21	—		VARIES WITH SPEED	.006
	MOON BIKE	25-LB. BIKE, 160-LB. RIDER, 15-LB. SPACE SUIT	0 .15			0	.0045

A.4 Human Configurations, Comfort, and How it Applies to HPV Designs

Different configurations of vehicle design can affect aspects of power availability, but they can also affect the comfort of the rider. In the studies by Too mean hip, knee, and ankle angles and ranges were discussed in terms of power generation [61]. In terms of comfort, the mean values help determine general positions the body will adjust to given a seating arrangement. The ranges provide details about range of motion for a given seat tube configuration. As a result, they may be good indicators of comfort when coupled with the general body configurations. For example lower ranges of motion might be considered more comfortable, because it requires less movement from the user. The ranges were derived from minimum and maximum values for each different configuration (hip, knees, and ankles). Considering these are the extremes of the body configurations that might be considered the most uncomfortable position, which could relate to a measure of comfort for the overall seating configuration. Lastly, standard deviations for every measurement are provided. These, in combination with the other measurements, can be used to help determine comfort for the general population using probabilistic statistics. Table A.3 is provided to outline the range values specified and is an extension of figure A.1.

Table A.3 Ranges of motion for various seating configurations

Seat Tube Angle	0°	20°	50°	75°	100°
Hip Angle Range	37.4°	38.8°	38.1°	40.6°	44.6°
Knee Angle Range	65.6°	73.9°	77.0°	75.2°	72.6º
Ankle Angle Range	43.6°	15.8°	13.2°	14.5°	16.1º

A gap in research includes conducting a comfort study and relating the measures described in table A.3 to a comfort index. Lanzotti *et al* have shown how to create a regular seating comfort index [70]. Combining this with the motions of cycling to create a new index, would be beneficial to find a more robust seating selection that incorporates comfort and power production. Additionally, models relating knee and ankle angles to the hip angles could provide insight to comfort and seating designs as well. Preliminary work on this has been completed by Too when he discusses various muscle fatigues based on the hip positions [60]. Here muscle fatigue could be considered one aspect of comfort. In addition to the 75° seat tube configuration having the most power production, it also disturbed the most the loads over the most muscle groups. The 100° seating position had muscle fatigue localized in the gluteal area. In the 25° configuration the quadriceps received most of the muscle fatigue. Overall, Too did state the results are limited if trying to provide an optimal seating position. This again encourages that a seating comfort index for cycling would be helpful in providing a more accurate optimal seating configuration.

Jansen considered creating a comfort model using outputs and external stimuli; such as visuals, smells, history and states, temperatures, pressures, touch, posture, and movement [63]. They also note how discomfort is automatically added when adopting human energy. They determined a hand crank was generally perceived to be uncomfortable. To investigate this further the work of Goswami examines a hand tricycle [71]. Goswami says for the hand crank to be comfortable it should be centered in front of the person. Additionally, the comfort of the hand crank is dependent on the seating configuration as well as arm movement. Using the 95th percentile of anthropometric data a popliteal height was decided. It was also determined the popliteal height should be 2cm to 5 cm lower to avoid discomfort and allow proper circulation. The seat width was found using hip breath measurements. Goswami notes the back rest should be rigid and gently rounded for more comfort. The preferred seat angles and back rest angles were 25° to 26° and 105° to 108º respectively. To have a comfortable seat depth, clearance for the back of the person calves are needed. Here between 9cm and 19cm was recommended. Overall, the details of the seating position such as preferred seat angle and back rest are helpful in creating characteristic of seating comfort, but models of arm movement for comfort, have been neglected.

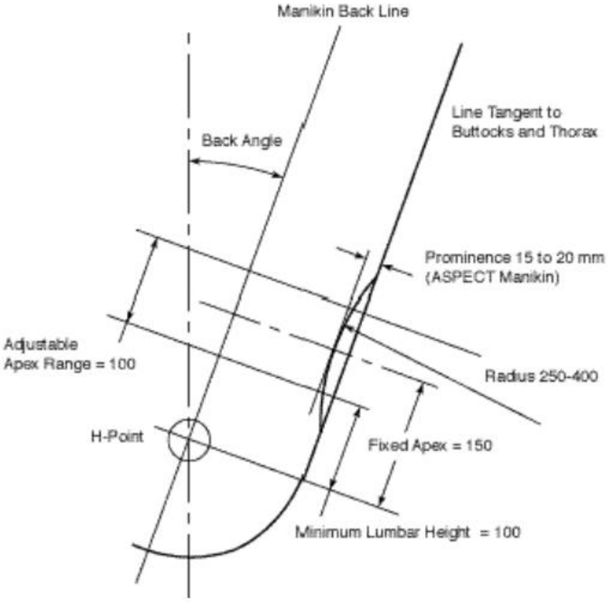


Figure A.3 Lumbar support recommendations (in mm) [72]

Reed conducted a study to examine the comfort of seating in automobiles [72]. Some of the factors he considered could transfer to HPV design. Specifically, recumbent style designs share the same features such as cushion width and length, backrest height and width, seat adjustments, and lumbar support. To assess a comfort model, Reed created feel and fit parameters. Unlike similar studies full body scans were taken to capture the fit of a person in the seating position. Reed also addressed the idea of different body shapes, such as larger mid sections. Figure A.3 demonstrates reeds recommendations regarding lumbar support.

Arm movements are a factor of human comfort and are generally neglected within the context of human powered vehicles. This likely means that within certain ranges of motion all arm movements might considered reasonable. That being said, there have been several features that assist arm comfort, such as pads for aerobars and different grip sizes for handle bar tape. Adding to this puncher at el have shown that handlebars affect the comfort of the rider [73]. Specifically, for non-traditional steering such as under bar steering and direct knuckle systems for recumbent tricycles [4], thorough research has not been conducted in the context of arm movement comfort.

Carpes *et al* measured the comfort of seating on a a normal bicycle saddle using pressure distributions [74]. They adapted insole instrumentation to cover the surface of the saddle. It was hypothesized the pressure could be influenced by the saddle design, but ultimately there was little change between normal and holed saddle. They found the saddle pressure decreased as the trunk position shifted forward in men due to the change in weight distribution. The saddle pressure was unaffected by trunk position for women. It was observed that lowering the weight distribution on the gluteal area will make the rider have less localized pressure there and thus more comfort. Expanding this idea to recumbent seating, where the back and trunk are supported together, the gluteal pressure will be lowered and thus the position might be considered more comfortable.

In terms of comfort adaptations for specific vehicle configurations typical bicycles have specific sizing and adjustments to account for various riders. Christians *et al* developed a bicycle simulator to create and examine the adjustments and sizes for optimal individual comfort [75]. They note the main factors that change to add more comfortability are the frame height, frame length, saddle to pedal distance, and crank length. Additionally, they tried to relate these parameters to anthropometric data to create relations for easier implementation. Garnet developed mathematical models to represent human configurations for recumbent style vehicles [76]. They also analyzed the effects of hand torques for steering. Beach *et al* designed a partially collapsing vehicle to give the option of recumbent style configurations and upright features based on the rider's preference and the environment [12].

Clipless pedals were previously discussed in the context of power production and seen as not being advantageous. Davis *et al* concluded this as well, but they also examined the possibility of added comfort from the pedals [68]. In their findings plantar pressures were found to be higher in clipless pedals, but they were spread across more of the foot's surface. The pedals reduced twisting in the knees and helped with alignment issues of the lower back. Lack of floatation in the pedals was found to cause knee pain. Overall, these conclusions show that clipless pedals might provide more comfort and stability when moving. Additionally the pedals allow riders to pull up on the pedal, which allows them to use different muscle groups based on their levels of fatigue. On the other hand, using clipless pedals riders are more prone to falling when stationary. How the pedals could affect injuries in the case of collisions was not discussed.

A.5 <u>Weight Distribution and Stability</u>

Vehicle dynamics are an important area of HPV design. Unlike automotive dynamics, the rider has a large influence on the dynamics of the vehicle, because of their weight in comparison to the vehicle. To account for this the rider must be considered as a weight source in HPV design. The weight distribution of the person gradually changes through the use of the vehicle and when assessing the controls of the vehicle this must also be considered. Astrom *et al* thoroughly discuss determining the stability of a bicycle using mathematical models and controls theory [77]. They consider stabilization during movement, self-stabilization, gyroscopic effects, and rear steering effects. They discuss how the manual control from the rider changes the input controls of steering and self-stabilizations. As a result they recommend a lighter grip on the hand bars. Astrom *et al* also model the effects of leaning. Lastly, they suggest more complex non-linear models to better capture the mass distribution and vehicle stability.

For recumbent bicycles, Garnet outlines mathematical models to assess the steering and controls [76]. When creating models they considered counter balances of masses, lean induced torque, and determining the trail of the bicycle. They also considered turning the wheel and leaning torques for stationary balances. Adding to the concept of balancing on a bicycle Hung *et al* considered gyroscopic stabilization of a bicycle [78]. By applying the principles of gyroscopic effects they were able to successfully balance an unmanned bicycle. In their detailed analysis behind controls they create system models for bicycle balancing. That being said, balancing a stationary bicycle, upright or recumbent is difficult and dependent on the rider. Being stationary is often required for riders because of societal standards such as lights, stop signs, and parking. Thus, more reliable sources are often needed. Market available solutions can be used such as kickstands or three or more wheels to remain stationary [3,12]. For more solutions of dynamic stabilization, Tracy *et al* examine aspects such as cornering, lean steering, and suspension for non-traditional HPVs, such as recumbent tricycles [3].

In a case study design of a hybrid all terrain tricycle, Dutta *et al* note the vehicle weight distribution played an important role in the overall balance [79]. A ratio of 65:35 in favor of the front of the vehicle was determined to improve overall cornering. They also discussed how overloading the front wheels may eliminate the effects of the rear wheels on hard cornering and braking. The backrest angle and seat position were changed to account for the weight distribution of a person. A backrest angle between 30° and 40° was used to preserve a lower center of gravity and more stability. The wheel base and track width were 58 inches and 45 inches respectively to add stability and prevent roll overs.

A.6 Safety Considerations

The safety of HPVs is a large aspect of the design. It allows riders to perform better and adds protection in the case of vehicle failures, accidents, and accident prevention. The main categories of HPV safety include protective features, visibility, and ease of maneuverability, such as entering and exiting a vehicle. Protective features can include wearable products, such as helmets, or built in safety features. Such as harnesses and roll protection systems. Protective measures typically do not include features used for accident prevention. One of the most common protective features is the use of helmets, because of their ability to prevent head injuries. Rivara *et al* have shown from several case studies that helmets can reduce head injuries form 63% to 88% [80]. Pucher *et al* mention that helmets have become lighter, more comfortable, cheaper, and more stylized to appear more to consumers, while maintaining safety [73].

Dutta *et al* included a roll protection system to protect the rider [79]. In addition, they included a three point harness in the design. Additionally, they added a front bumper to absorb energy from impact collisions. Due to being a hybrid vehicle electronics were included. To prevent possible injuries covers and kill switches were added. Lastly, a headrest was included for comfort which brings up the issue of helmets usefulness when combined with roll protection systems. Wearing a helmet with a head rest creates discomfort, thus it could be inferred that riders of their vehicles might not wear helmets for safety, due to having a roll protection system. Assessing the safety combination, or lack of, between helmets and roll protection systems is something that is that not clearly discussed in literature and needs more review. Roll protection systems and bumpers are examples of protective safety features and have been included in several designs. Dutta *et al* developed another design that included these features as well [81].

A preventative safety measure for vehicle design could include the use of duplicate brakes, as pointed out by Pucher *et al* [73]. Other preventative safety measures include the visibility aspects of seeing and being seen. In order to negotiate traffic, riders of HPVs must be able to see well as well as be seen. This includes during night time and times of increment weather. Pucher *et al* outline several products that account for this aspect of safety. Bright powered lights and mirrors can be added to help riders see well. Lights, reflectors, flags, horns, and reflective paint can help with visibility and awareness. Due to advances in retroflective materials these features have improved recently. The HPV can also be designed to maximize unobstructed vision to improve visibility [81]. The last aspect of visibility includes being aware of the vehicle’s performance and the rider’s wellness for safety aspects, such as speeding and human fatigue. For this cyclometers, can track the speed, cadence, power, etc. to monitor the energy output, or human fatigue, and vehicle performance. Global positioning or instrumentation added to the HPV can make the measurements more accurate.

In terms of maneuverability the vehicle should be designed to allow the rider to quickly, safely, and easily enter and exit the vehicle. Dutta *et al* suggest that narrowing the width of the vehicles makes getting in and out easier [81]. Tripping hazards can be prevented by designing a path for the rider, minimizing items that need to be stepped over, and/or reducing the that chance that a stepped over item will cause the rider to fall. Pucher *et al* suggest enclosed drivetrain systems, step over frames, and chain guards for this [73]. Tracy *et al* provide a literature coverage of the various types of HPVs [3]. Within the review they note that some vehicles designs have more maneuverability than others. For instance, velomobiles are difficult to enter and exit and streamlined vehicles cannot be started without assistance. Upon further investigation, some velomobiles such as the Sun Rider incorporate an opening front hood to account this [82] or vehicles such as the Elf velomobile where a large opening and small step is added for easy access.

A.7 Environmental Considerations, Thermal Comfort, Maintenance, and Repair

Different environmental factors affect the ergonomics of HPV design. The main considerations are temperatures, weather conditions, and terrain. To keep the rider clean and comfortable various features can be added to account for non-preferred road conditions such as mudguards over the wheels [79] and faired bottom surfaces [82]. For weather protection windshields or roofs could be added [81,82]. In addition, fully faired vehicles or partially enclosed recumbents provide practical wind shield and precipitation protection [73]. Beach *et al* examine the weather pattern for the area the vehicle was designed for [12]. As a result of designing for a mostly precipitous area, the material selection and vehicle design was modified for easy maintenance. This was achieved through corrosion resistant materials and easy-to-lubricate areas. The environment was also full of bikes, racks, etc. due to living in a strongly supported cycling community. This was considered in the design as well. Another environmental consideration often overlooked is the possibility of theft [73]. In addition to typical locks, Pucher *et al* recommend removable components, such as saddles, lights, wheels, GPS units, etc. On the other hand, minimizing detachability lowers the number separate features that need to be locked.

Environmental factors can cause maintenance and repairs, such as continuous inclement weather and muddy roads. Other factors, such as accidents and prolonged use can cause maintenance issues as well. Designing for maintenance allows users to quickly and easily repair their vehicles. This includes designing for accessibility to parts requiring maintenance, lowering deconstruction difficulty, and reducing the maintenance occurrences. Aside from guides on how to repair bicycles and provide maintenance to already given products, the researched literature does not provide guidelines of how to design for maintenance, while making it more ergonomically efficient. That being said Downs presents a detailed manual of how to provide repairs and maintenance to most aspects of mountain and road bikes [83].

Environmental factors have a great influence on the temperature surrounding the rider. Colder temperatures can be accounted for by heat production and wearing warmer apparel. The act of cycling creates heat and raises body temperatures, which is beneficial for colder climates as well. Warmer temperatures require cooling, which is more difficult to supply. The main source of cooling comes from ventilation or the effects of accelerated convection. Schreur discuss how a person only operates within a narrow range of temperatures efficiently [41]. Most cycling occurs during warmer climates and in addition to high temperatures, humans generate heat while cycling, fully faired vehicles absorb solar heat, and the solar radiation raises heat indexes. Schreur states cooling is a necessity and ventilation aspects should be added to vehicle designs. To get optimal ventilation an intake and outtake should be added. Sizes and positions can be changed to create more efficient cooling. For more direct cooling, the air flow should be directed towards the head and shoulders as they are prime areas for heat exchange. Lastly, intakes can negatively affect the aerodynamic of faired vehicles. A submerged intake is a prime example of an intake that tries to negate these negative effects, while also providing proper ventilation.

For non-faired vehicles direct ventilation is already applied, but riders often wear helmets that stop cooling to the head. To account for this helmets often have geometry that allows for ventilation [84]. Alam *et al* provided an analysis of thermal comfort in the context of helmets and discusses possible aerodynamic enhancements that can be provided from wearing helmets.

A.8 Storage and Energy Recovery

While riding an HPV, users often need to carry cargo with them. This can be cargo that does not need to be assessable for the trip or items, such as water bottles, that would be preferred to be used while riding. Pucher *et al* mention aftermarket products such as backpacks, baskets, panniers, saddle bags, trailers, and attachable holders can be used for assessable and non-assessable storage [73]. They also outline multi-person vehicles that can be used to carry cargo such as cargo bikes and pedicabs. Lastly, they mention that four wheeled vehicles are better suited for multiple riders. Yao considers various aspects of changing a frame to allow for more non-assessable storage [85]. He considered adding a rack on the rear wheel, extending the frame with storage between the rider and the wheel, and storage areas in front of the handle bars. Overall, their results were lacking and had many problems, but the ideas presented illustrate ways to change a frame to allow for more storage. Avila goes through the process of designing a chassis that can be coupled to the rear of a bicycle [86]. They considered a design that was further back from the rider to stop problems of kicking the cargo during use. They also tried to minimize the weight to reduce the power required from the rider. Additionally, their design was changed to fix chain length problems. Having two rear wheels created better stabilization, but the weight caused the wheels to fail and bend under stress. Lastly, depending on the amount of stored cargo its influence on dynamics may have to be considered.

In some environments, such as cities, frequent stops and impedances are required [73]. To assist the rider’s comfort energy recovery systems can be added to store energy that would be otherwise lost from the continuous starting and stopping. Mil considered adding solar panels to bicycles and tricycles allowing for easier transportation, including disabled passengers [87]. Adding the solar panels as a roof also helped to prevent from weather elements. Other possible systems include regenerative braking, the use of flywheels, or the combination of both [88,89]. Energy can be stored by mechanical means such as a flywheel or spring and electrically means such as a battery or motor. Some HPVs included pre-charged electrically elements as well human energy and are classified as a hybrid design, because they only use part of the human power as the overall power source [79,81].

A.9 Anthropometric Analysis

One of the key aspects to ergonomic design of HPVs is creating a vehicle that is proportionate to the person riding it. When the vehicles have dimensions more tailored to the rider they are typically more comfortable. For this reason bicycle manufactures offer different sizes, crank lengths vary, and seats are adjustable. Bicycle dimensioning is widely studied and relatively down to a science [75,90–93]. On the other hand, tricycle designs and roll protection systems are not as often used. As a result there is little literature covered on the subject, in regards to anthropometric dimensioning. It has been done, but general guidelines are outlined. Examples at attempts to creating guidelines included the works by Goswami using data for the popliteal height and Reed using anthropometric analysis for automotive seat designs [71,72]. Figure A.4, figure A.5 , and table A.4 offer general guidelines to add some anthropometric dimensioning aspects to roll protection systems and recumbent tricycle designs [29,30]. This is similar to Reeds work shown in . Additionally, using similar methods dimensioning aspects of various HPV styles can be outlined. After creating the anthropometric geometry the other ergonomic factors of a design should be assed as well. For example, the knee angles, crank length, hip angles, etc. of could be examined for comfortability similar to Too’s experiments [60,61]. Similarly, aspects of ventilation, power production, comfort, environmental considerations, etc. should be reinvestigated for specific designs and anthropometric guidelines.

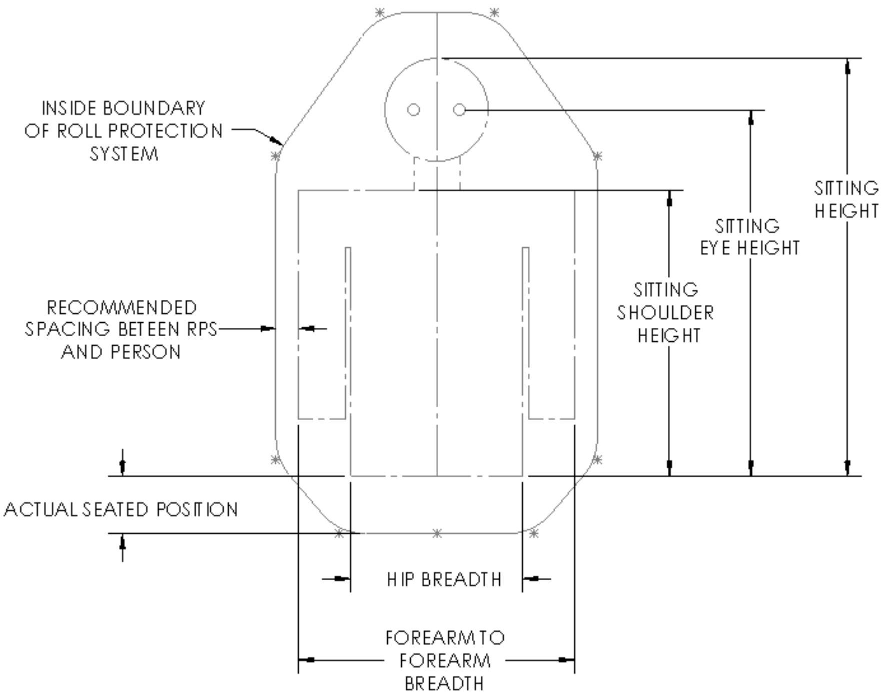


Figure A.4 Example Roll Protection System in Relation to Anthropometric Dimensions

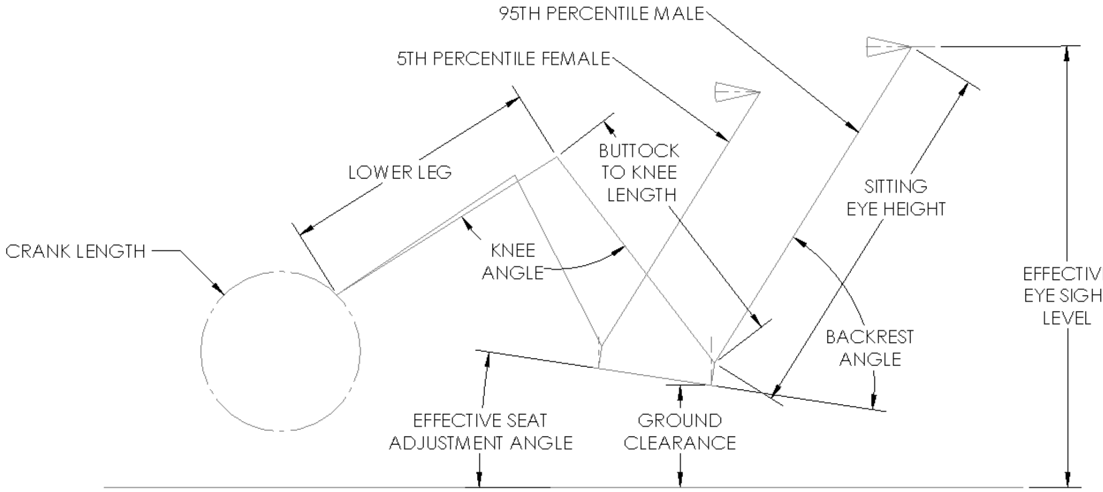


Figure A.5 Example Sitting Configuration in Relation to Anthropometric Dimensions

Table A.4 Summarized Anthropometric Dimensions [29,30]

Dimension	Female (Percentiles in inches)				Males (Percentiles in inches)			
	1st	5th	95th	99th	1st	5th	95th	99th
Buttock to Knee Length	20.54	21.34	25.19	25.99	21.68	22.40	26.28	27.04
Forearm to Forearm Breadth	15.52	16.33	20.80	22.03	17.76	18.80	24.43	25.70
Hip Breadth	11.65	12.12	15.05	15.75	11.67	12.19	14.82	15.48
Lower Leg	15.73	16.40	19.78	20.58	17.44	18.15	21.72	22.37
Sitting Eye Height	26.14	26.95	31.27	32.23	28.02	28.94	32.92	34.23
Sitting Height	30.50	31.31	35.84	36.74	32.59	33.67	38.26	39.03
Sitting Shoulder Height	19.38	20.04	23.76	24.54	20.68	21.59	25.44	26.16

A.10 Conclusion

At first glance the ergonomics of human powered vehicles seems like a simple subject, but there are many aspects of it. The limits and energy outputs of the human body control the power production available to drive HPVs. Performance factors added to HPVs help use the the power production more resourcefully. Adding comfort to vehicles makes use more enjoyable. Comfort can be added by using appropriate body configurations and elements suited to the rider, such as crank length. The person's weight influences the vehicle dynamics and stabilization, which is a necessary factor that must be included in the static and dynamic analysis. Various safety features can be used to prevent accidents, reduce damage and injuries, such as roll protection systems, increase visibility, and provide easier maneuverability.

Environmental considerations for ergonomics allow vehicle designs to be practical in different areas. Additionally, environmental factors affect the thermal comfort of riders and the cooling system of vehicle designs. Vehicle use and longevity should be considered in the design aspect to allow for for quick and easy maintenance and repairs. Storage aspects allow riders to carry needed cargo. Energy recovery systems can be used to store otherwise wasted energy, in the forms of motors, flywheels, regenerative braking, and electrical devices. Hybrid bicycles employ this concept to use human energy in combination with stored and/or recovered energy. HPVs are human oriented, thus anthropometric and vehicle relations should be established. Lastly, there are different types of human powered vehicles available; hand-crank vehicle, bicycle, recumbent styled vehicles, tricycle, cargo bicycle, and etc. [3]. Each type of vehicle is suitable based on the application and user.

When trying to capture a holistic view of human powered vehicle ergonomics some topics were ill represented or not explored. The ergonomic aspect of vehicle storage and travel was not examined. This includes the ease of fittings through doorways, difficultly to carry, the ability to fit in automotive vehicles, and the difficult to travel commercially with. Topical coverage of travel and vehicle storage would be useful, because it includes additional design considerations that effect the requirements of HPV development. A more in depth analysis of energy recovery systems would be beneficial in highlighting standard approaches, efficiencies, complexity, and practicality of the various systems. Examining heat generation aspects of vehicles would be useful for designing HPVs for colder environments, making vehicle usage more practical for annual use. Creating a comfort index would be beneficial for comparing changes to different features to address the level of comfort the changes create. Additionally, it would make assessing tradeoffs between comfort and performance or other ergonomic aspects more justifiable. A comfort index could also be used to assess levels of pain, such as joint pain, overextension, and back pains associated with various configurations. Overall, more analysis on comfort would be useful for judging the quality of different HPV styles and solutions. This might be possible by creating and using anthropometric guidelines more efficiency. Different body shapes should also be considered in the models for comfort and anthropometric guidelines. Due to being a human oriented design, there should be more research on dimensioning vehicles using anthropometric results and the effects it has on other ergonomic factors, like comfort.

Lastly, there needs to be more research in regards to assessing tradeoffs between ergonomic factors. Additionally, these factors could be related to the development of various styles and types of HPVs. For example, a beach cruiser is designed for comfort, while a triathlon bicycle is driven by performance. Establishing a means to compare tradeoffs for HPV ergonomics has various implications, which could determine the basis for HPV design and requirement generation. It could also assist the conceptual development of vehicle design and provide justifications for the decision making process.

APPENDIX B: REVIEW OF EXISTING HUMAN POWERED VEHICLES

Table B.1 Examples of existing bicycles (Adapted from [3])

Bicycle Type	Image	(Unique) Properties
Single Speed	 [94]	1.) No gear shifter 2.) Convectional road frame 3.) Flat handle bar 4.) With or w/o fixed gear 5.) Most popular type 6.) Price \$800 - \$1600
Used “vintage” road bikes	 [95]	1.) 10 Speeds and up 2.) Steel Frame 3.) Very popular 4.) Price \$250 - \$400
Cruiser bikes	 [96]	1.) Designed for style 2.) Upright seat position 3.) Larger diameter tires 4.) Heavy frame 5.) Price \$500-\$700

Table B.1 (Cont.)

Bicycle Type	Image	(Unique) Properties
Mountain bikes	 [97]	1.) Likely to have suspension 2.) Made for off road terrain 3.) Variety of wider wheels and taller for more traction and easy of going over obstacles 4.) Heavier more durable frames 5.) Common types are suspension, hardtail, and 29ers 6.) Variety of frames to account for suspension type and wheel sizes 7.) Prices $250 -$2,000 and up
Road Bikes	 [98]	1.) Typically has integrated shifters and brakes 2.) Typically Aluminum and carbon frames 3.) Made for Racing and commuting 4.) Skinny Wheels 5.) Dropouts for more hand positions 6.) Prices $500- $3,000 and up
Hybrid Bikes	 [99]	1.) A combination of mountain and road bike styles 2.) Wheel width slightly larger than road bikes to allow for basic off-roading 3.) Flat handlebars 4.) Prices ~$250 - $1,000

Table B.1 (Cont.)

Bicycle Type	Image	(Unique) Properties
Triathlon Bikes	 [100]	1.) Made for performance and aerodynamic 2.) Frames have more of a teardrop shape for better drag 3.) Additional handlebars for streamlined comfortable riding 4.) Add on features, such as water containers to improve drag and hydration 5.) Price \$1,000 - \$10,000 and up
Electric bikes	 [101]	1.) Electric motor 2.) Battery 3.) Power Controller 4.) Top Speeds of 25mph 5.) 30M in china 6.) Prices ~\$500 - \$1,000
Folding Bikes	 [102]	1.) Folds into smaller version 2.) Great for Storage and can be easily carried 3.) Suitable for office spaces and quick commuting 3.) Price \$300-\$1,800

Additionally, there are more types of bicycles as well. Aside from the alternatives shown in table B.2 , endurance, cyclocross, and track bikes are extensions and variation of the bikes mentioned in table B.1.

Table B.2 Examples of existing alternatives to bicycles (Adapted from [3])

Alternative type	Images	Key Properties
Tradition Recumbent	 [103]	1.) Long Chain for drivetrain 2.) Efficient power delivery 3.) Difficult to start 4.) Price $1,000
Covered "Streamlined"	 [104]	1.) Speed record (81mph) 2.) Straight flat roads only 3.) Can't start without helpers 4.) Price $2,000
Two Front Wheels ("Tadpole" Trike)	 [105]	1.) Stable in slippery conditions 2.) Easy to stop from stop 3.) Price $1,600

Table B.2 (Cont.)

Alternative type	Images	Key Properties
Two Rear Wheels (Delta Trike)	 [106]	1.) Can tip while break in turns 2.) Bulky 3.) Price $350
Velomobiles (car-cycles)	 [107]	1.) Covered 3 wheeler 2.) 2 front wheels 3.) Higher speed than open version 4.) Difficult to enter-exit 5.) Price $4,000-$10,000

Table B.3 Examples of existing HPVs with tilting or three of more wheels (Adapted from [3])

Tilting Bike Name	Image	Key Properties
Tripendo HPV	 [108]	1.) Hand lever tilting 2.) Hand lever steering 3.) Carbon monocoque body 4.) 4 bar suspension linage w/ tilting mechanism 5.) Full sized wheels 6.) Price $3,000 and up

Table B.3 (Cont.)

Munzo TT	 [109]	1.) Rear swing arm tilting 2.) Single suspension shock 3.) Composite rear wheels 4.) Width no wider than rider 5.) Detachable front section 6.) Price ~$2,000
Apex Hydraulic	 [110]	1.) Extraordinarily smooth 2.) Heavy/complex hydraulics 3.) Narrow width 4.) Price $3,000
Black Max	 [111]	1.) Very fast cornering 2.) Like Munzo TT but with parallelogram linkage 3.) No suspension 4.) Price ~$1,000
Jet Trike	 [112]	1.) Integrated tilting and leaning 2.) No suspension 3.) Open-source design 4.) Price ~$1,000

Table B.4 Examples of existing rowing bicycles (Adapted from [3])

Rowing Bike Name	Image	Key Properties
Thys Rowing Bike	 [113]	1.) Stationary center of gravity 2.) Lines don't rust and last longer 3.) Unique spiral pulley gearing system 4.) Steering & rowing combined in handlebar 5.) Price $4,400
Rowbike	 [114]	1.) Lines don't rust and last longer 2.) Sliding seat, large rider movement 3.) Chain based drivetrain 4.) Foot steering Price $1,200
Scull Trek	 [115]	1.) Single Speed, Pulley and drive 2.) Sliding seat and mass 3.) Hand Steering 4.) Price $1,800
VogaBike	 [116]	1.) Cable-chain hybrid 2.) Stationary rider mass 3.) Complex pulley and linkage power delivery 4.) Price $2,000

Table B.5 Examples of existing powered designs (Adapted from [3])

Powered Design	Images	Key Properties
CarCycle	 [117]	1.) Integrated carbon fiber suspension 2.) Indicator fin 3.) Large cooling vent 4.) Power assist 5.) Non-tilting trike 6.) Price ~$4,000
RunAbout Cycles	 [118]	1.) Large electric power system 2.) Heavy wheels designed for downhill MTN bike racing 3.) Heavy 2.5" heavy-duty tires 4.) Robust steel frame 5.) Non-tilting trike 6.) Price $6,000
Tripendo w/motor kit	 [3]	1.) Tilting tadpole design 2.) Independent suspension 3.) 3x 26" Wheels 4.) Lever tilt & Steering control 5.) Price $6,000
Raht Racer	 [119,120]	1.) Used pedal assist from the rider and a 20kWh unique flywheel generator 2.) Has a 50 mile range on full charge 3.) Capable of reaching speeds up to 100mph 4.) Maintainable speed of 30mpn 5.) Price ~$35,000 to $45,000

Table B.6 Examples of HPV for multiple users

Vehicle type	Image
Tandem Bicycle [121]	
Tandem Bicycle (aerodynamic) [122]	
Tandem Recumbent Bicycle [123]	
Tandem Tadpole Trike (The Viking) [124]	 AtomicZombie.com

Table B.6 (Cont.)

Tandem Rowing Bicycle (Thys Carbon Tandem) [125]	
Tandem Velomobile [126,127]	
Triplet [128]	
Quad [128]	

Table B.6 (Cont.)

Quint [128]	
Hex (Sextuplet) [128]	
Conference Bike [129]	
Trolley Pub [130]	

The multiple person HPVs (greater than two) are designed more for family and business. The four to six person tandems can also be classified under the category of family tandem for this reason.

The list is given as an introduction to HPV systems. This is by no means an exhaustive list. There are many variants under each of the system designs listed. In addition there are many designs that do not go large scale production. Also, some types for HPVs may have not been mentioned and ideas are continual being developed. There are also more categories for human powered vehicles such as, water HPV, track HPV, and air HPV. Land HPV is the focus of this paper. For more information on other type students can begin by looking into the world human powered vehicle association (WHPVA) [131].

APPENDIX C: EVALUATION METHODS

C.1 Decision Matrices

Decision matrices are design tools used to organize a designer's thoughts. The structure of a design matrix includes rows and columns composed of ideas to be evaluated and criteria for evaluation. It does not matter if the rows are composed of the ideas or if they contain the evaluation criteria, but the columns must have the elements that are not contained in the rows. In order words if the criteria were in the rows of the matrix, the ideas would be in the columns and vice versa. For the purposes of this discussion the columns will contain the evaluation criteria. To better explain how decision matrices work table C.1 gives an example from Bamford et al.

Table C.1 High level decision matrix example [13]

	Rule Compliance	Weight	Reliability	Looks	Top Speed	Corning	Comfort	Safety	Ease of Use	Cost	Manufacturability	Maintenance	Simplicity	Total
Importance	5	3	4	2	3	5	2	5	4	2	3	1	3	
2 Wheels	3	5	5	3	5	3	4	3	2	5	3	5	5	156
3 Wheels Rigid	3	4	4	4	4	4	3	4	3	4	3	4	4	154
3 Wheel Indep. Steer	3	3	4	5	4	5	5	5	4	4	3	3	4	170
3 Wheel Integrated	3	3	3	5	4	5	5	5	5	4	3	3	3	167
Regenerative Assist	-1	-1	-	1	1	-	1	-	2	-1	-1	-1	-1	-2
Hub Center Wheel	-	1	-	1	-	1	-	-	-	1	-1	-	-1	6
Front Wheel Drive	-	-2	-1	1	-1	-1	-	-	-	1	-1	-2	-2	-27
Suspension	-	-1	-	1	-	-	2	1	1	1	-1	-1	-1	3
Fairing	1	-1	-1	1	2	-	1	1	-1	2	-1	1	-1	7

Table C.1 shows the high level ideas and evaluation criteria used for a human powered vehicle design. To evaluate the ideas arbitrary numbers are given for the criteria. The numbers are supposed to signify how well the idea fits the criteria. For this there is a scale. Common scales involve a weak, medium, or strong evaluation or a very weak, weak, medium, strong, or very strong evaluation. Recommendations for scales are discussed by Olewnik *et al* [16]. In their findings they noticed little changes in the results based on type of scales. Their evaluations include testing the differences between the following scales (1-2-3), (2-5-8), (1-3-9), and (1-50-100). Table C.2 gives examples of recommended scales.

Table C.2 Recommended Scales for design evaluation tools

Scale Type	Example scales
Weak-Medium-Strong	-1,0,1
	1,2,3
	1,3,9
	2,5,8
Very Weak-Weak-Medium-Strong-Very Strong	1,2,3,4,5
	-2,-1,0,1,2
	1,4,5,6,9

Looking at table C.1 it is hard to determine one defined scale that was used. This problem with inconsistency is something that should be avoided. It is likely in the later part of the decision matrix that scale was changed to allow an evaluation to decide where an idea was good on its own rather that comparatively.

Choosing a scale with 5 levels of evaluation rather than three allows the designer to have more detailed comparisons between the ideas. It also means the designer is more confident in their discussions, because they are making more precise choices by using a more well-defined scale. The confidence in the designer's choice should be backed by information and experience.

The decision matrix can have weighted criteria by adding a weighted or importance row as seen in table C.1. Scaling for the importance row can be arbitrary similar to those outline in table C.2. Additionally, the scaling for the weightings can be relative. In other words, the weight for a given criteria could be a number between 1 and the total number of criteria, with each criteria getting a unique number. As an example the importance rows given in table C.1 could have been the following: 13, 6, 9, 4, 8, 11, 2, 12, 10, 3, 7, 1, 5. This would also mean none of the criteria have equal importance. Thus the range could be reduced by the total number of equally important criteria and completed again, with some cases of repeating numbers when criteria are considered equally important. Relative scaling and arbitrary scaling can be should be used at the discretion of the designers. As aforementioned the choice of scaling method is more effected my information used rather than the choice of method.

Without changing any information, except for changing the scale table C.3 was created using the information provided in table C.1. In the process the assumption was made that two different scales were used. The upper portion of the decision matrix in table C.1 was assumed to be rated on a scale of (1-2-3-4-5), while the lower portion had a scale of (-2, -1, 0, 1, 2). The change in scale was completed because the use of a singular scale provides a fairer assessment. Additionally, to correctly use the decision matrix only one category of ideas should be included in the decision matrix, such as one subsystem, type of configuration, powering method, and so on. In other words, table C.1 and table C.3 are still not true decision matrices, because they include multiple categories of ideas. Table C.4 is provided to demonstrate what a correct decision matrix should look like.

The usefulness of decision matrices is their ability to organize a designer's thoughts and highlight the ideas that show a greater likelihood of success. That being said the likelihood of success is dependent on the quantity and accuracy of the information used throughout the evaluation process. In other words in the designer uses poor judgement, false information, and opinionated decision rather than rational choices, the decision matrices will highlight poor ideas.

Table C.3 High level decision matrix example with adjusted scale

	Rule Compliance	Weight	Reliability	Looks	Top Speed	Corning	Comfort	Safety	Ease of Use	Cost	Manufacturability	Maintenance	Simplicity	Total
Importance	5	3	4	2	3	5	2	5	4	2	3	1	3	
Configuration														
2 Wheels	0	2	2	0	2	0	1	0	-1	2	0	2	2	30
3 Wheels Rigid	0	1	1	1	1	1	0	1	0	1	0	1	1	28
3 Wheel Indep. Steer	0	0	1	2	0	2	2	2	1	1	0	0	1	41
3 Wheel Integrated	0	0	0	2	1	2	2	2	2	1	0	0	0	41
Energy Storage														
Regenerative Assist	-1	-1	-	1	1	-	1	-	2	-1	-1	-1	-1	-2
Powering Method														
Hub Center Wheel	-	1	-	1	-	1	-	-	-	1	-1	-	-1	6
Front Wheel Drive	-	-2	-1	1	-1	-1	-	-	-	1	-1	-2	-2	-27
Other Features														
Suspension	-	-1	-	1	-	-	2	1	1	1	-1	-1	-1	3
Fairing	1	-1	-1	1	2	-	1	1	-1	2	-1	1	-1	7

Table C.4 Corrected high level decision matrix with single idea category

	Rule Compliance	Weight	Reliability	Looks	Top Speed	Corning	Comfort	Safety	Ease of Use	Cost	Manufacturability	Maintenance	Simplicity	Total
Importance	5	3	4	2	3	5	2	5	4	2	3	1	3	
2 Wheels	0	2	2	0	2	0	1	0	-1	2	0	2	2	30
3 Wheels Rigid	0	1	1	1	1	1	0	1	0	1	0	1	1	28
3 Wheel Indep. Steer	0	0	1	2	0	2	2	2	1	1	0	0	1	41
3 Wheel Integrated	0	0	0	2	1	2	2	2	2	1	0	0	0	41

Additionally, decision matrices are not guaranteed to highlight the best idea, because it is impossible to give precise results using an arbitrary scale. Uncertainties in the evaluation also make the outcomes less decisive. Therefore, the usefulness in the decision matrix is not to select the best the idea, but rather to select a group of best ideas and eliminate use of the bad ideas. Lastly, designers who use decision matrices should keep track of the reasoning for their evaluation. Some recommendation would be either keeping a log of all the reasoning used or creating a duplicate table and filling in the reasoning for all of the number entries. Giving the reasoning is useful for retrospective analysis, which may be extremely beneficial for later parts of the design process, outside viewers, and justifications to criticisms.

C.2 Thorough Evaluation Method

To combat some of the flaws of decision matrix students could use a more developed evaluation method, such as the model created by Mistree et al. [28]. Adapted models are provided as detailed examples in Appendix H. This section is meant to give a detailed description of how to complete the evaluation method. To begin the process of this evaluation method will reflect the outline given in table 3.3.

Step 1: Creating acronyms

First acronyms should be given to all the concepts to be used in the evaluation process. This helps to abstract the ideas and illuminate possible bias associated with names. Additionally, it helps to shorten the names of concepts which will help with formatting the evaluation matrix later.

Step 2: Outline the essential requirements

For the next step of the process a set of evaluation criteria is needed. For this the designer needs to summarize the requirements in a concise of “essential requirements”. The essential requirements reflect the most important demands given the system being designed. In the case of the frame design, the group determined the essential requirements were the structural integrity, manufacturability, performance and ergonomics, safety, and integratability. After defining the essential requirements, criteria to evaluate them are needed. The criteria can be based on the previous requirements as well. Aside from the requirements the designers can develop additional criteria that have been otherwise overlooked, but still remain valid for the evaluation process. Three to five essential requirements are useful for the evaluation process, with two to five criteria for each one. These are only recommendations and the designers can change the total number of evaluations as they see fit. If needed the designers should describe the evaluation criteria and outline aspects of what they can be evaluated on.

Step 3: Creating the evaluation matrix

To begin setting up the evaluation matrix the essential requirements are placed in the different rows of the first columns. The concepts are placed in the columns of the rows. Under each of the essential requirements the different criteria is added. Two rows are added for score and normalized score after an essential requirement. The last two columns of the matrix will include a total normalized score and a total non-weight rank. One of the concepts is also chosen for a datum. Once the datum is selected zeros are placed in that concepts column wherever there is a corresponding evaluation criterion.

Step 4: Preforming the evaluation

For each of the evaluation criterion all of the concepts are compared to the datum concept. If the concepts are better than the datum for a specific criterion a 1 is placed in the corresponding location. A -1 is placed in the location if the datum is superior and a 0 is added if the concepts are equal in regards to the criterion. Unlike the arbitrary evaluations used in decision matrices the comparisons allow for a known (with some uncertainty) a better than or worse case.

In other words, there is less uncertainty in the decisions using this method. The scores for the essential requirements are then computed by adding together all of the evaluation from the various criterion. The normalized score is there calculated using eq. (16). For the combined normalized score, the average of the normalized scores of the different essential requirements was taken. This assumes no one essential requirement was more important than another.

$$\text{Normalized Score} = \frac{\text{Score} - \text{Minimum Score}}{\text{Maximum Score} - \text{Minimum Score}} \tag{16}$$

Step 5: Record justifications

After performing the evaluation, designers should record all of the reasons for their choices. When doing this the evaluation might be adjusted, because of new thoughts. Either way once the justifications are record there is documents saying why an evaluation was performed a certain way. This is important for differing opinions as well as retrospective analysis. If designers need to look back at the evaluation data it is beneficial to have recordings of why choices were made a certain way. Based on the recordings and new evidence some changes might need to be made. At this time the justifications should be updated.

Step 6: Creating a weighted analysis

The different essential requirements were assumed to have equal importance but this may not be the case. By performing a weighted analysis the evaluation can be adjusted by the importance of the essential requirements. A recommended method for a weighted is shown in table 3.5. Here a different weighted scenario is applied to reflect one essential requirement having more importance than the others. Additionally, a perceived weighting system reflected the ideas of the perceptions of the designers. Next a case that combines the different scenarios gives results that consider the perceptions of the designer, but also smooths the weighting. This is helpful, because there is uncertainty in the designer’s perception and smoothing the designer’s weighting helps combat some of that uncertainty, without eliminating their ideas completely. Also, a case showing only their weighting system has already been completed. Running the different scenarios shows how the results can be affected by different weighting schemes, as displayed in table H.4. To find the score of the weighted analysis the normalized scores from the essential requirements are multiple by the weight given for that essential requirement and then divided by the total number of weights used.

Step 7: Repeat of multiple datums

Steps 3 through 6 are repeated for different datums. Five to Seven datums is recommended for ten to fifteen concepts and seven or eight datums for fifteen or more concepts. While repeating for the different datums it is important to remain consistent. One method to ensure consistency is to first logical propagate the next evaluation matrix (new datum) based on the information provided. Table C.5 demonstrates consistency required by logical propagation, where X shows new evaluations that will have to be determined.

Table C.5 Logical propagation for consistency A.) Previous datum B.) New datum

A.)

Criteria	Concepts		
	A	B	C
D	0	1	1
E	0	1	0
F	0	1	-1
G	0	0	1
H	0	0	0
I	0	0	-1
J	0	-1	1
K	0	-1	0
L	0	-1	-1

B.)

Criteria	Concepts		
	A	B	C
D	-1	0	X
E	-1	0	-1
F	-1	0	-1
G	0	0	1
H	0	0	0
I	0	0	-1
J	1	0	1
K	1	0	1
L	1	0	X

Step 8: Combine the results

Lastly the results are combined from the different datums. Examples are provided in Appendix H where the average was taken using the combined weighted analysis for each datum.

APPENDIX D: PROJECT PLANNING FOR HPV DESIGN

While project planning for HPV design a detailed Gantt chart was created. The Gantt chart example is provided in this appendix to provide insight to scheduling a system based project and to provide a scheduling guideline for HPV design. In addition, the scheduling includes estimated times to complete tasks, outlines specific areas that should be focused on for HPV design, and a relative completion times between tasks.

Some details were left out such as some relations between the tasks. The relations between tasks refers to the the prior tasks that must be completed before a given task can be completed and the tasks that are effected by the completion of a given task. Although basic task relations can be seen within a given subsystem by looking at the Gantt charts, tasks related to a different subsystem's task are not shown for clarity.

Further project planning could be conducted, such as allocating resources, associated costs, and other project analysis tools. Resources such as people, equipment, and materials could be linked to all of the tasks and estimated costs associated with the resources. Based on the task's time requirements and workloads, resources allocation analysis could be conducted and project cost estimates created. Resource allocation analysis would give insight to over used resources and if either the tasks time needs to be changed or additional resources need to be allocated. Other project analysis tools such as a critical path analysis would get to focus to tasks that are critical to the project management and thus have a completion priority.

Table D.1 HPV Project planning overview

Task Name	Duration	Start	Finish
1 Lead Project planning	**220 days**	**Wed 8/19/15**	**Tue 5/10/16**
1.1 Project Initiation	14 days	Wed 8/19/15	Tue 9/1/15
1.2 Structure Product Requirements	5 days	Wed 9/16/15	Sun 9/20/15
1.3 Structure Conceptual Design Selection	31 days	Mon 9/21/15	Mon 10/26/15
1.4 Structure Product Development	33 days	Mon 11/9/15	Sat 1/16/16
1.5 Final Design Details	7 days	Sun 1/17/16	Sat 1/23/16
1.6 Competition and Preparation	66 days	Tue 3/1/16	Tue 5/10/16
2 Structure (Frame) subsystem	**97 days**	**Wed 9/2/15**	**Sun 1/17/16**
2.1 Initialize	7 days	Wed 9/2/15	Tue 9/8/15
2.2 Research Background Information	7 days	Wed 9/9/15	Tue 9/15/15
2.3 Product Definition	7 days	Wed 9/9/15	Tue 9/15/15
2.4 Conceptual Design	13 days	Wed 9/16/15	Mon 9/28/15
2.5 Product Development	60 days	Tue 9/29/15	Sun 12/6/15
2.6 Final Prototype Manufacturing	31 days	Sun 11/8/15	Wed 1/13/16
2.7 Testing and Analysis of Prototype	12 days	Tue 11/24/15	Wed 12/9/15
2.8 Final Product Development	7 days	Thu 12/10/15	Sun 1/17/16
3 Controls (Steering) subsystem	**122 days**	**Wed 9/2/15**	**Thu 2/11/16**
3.1 Initialize	7 days	Wed 9/2/15	Tue 9/8/15
3.2 Research Background Information	14 days	Wed 9/9/15	Tue 9/22/15
3.3 Product Definition	7 days	Wed 9/9/15	Tue 9/15/15
3.4 Conceptual Design	13 days	Wed 9/16/15	Mon 9/28/15
3.5 Product Development	68 days	Tue 9/29/15	Fri 1/15/16
3.6 Final Prototype Manufacturing	17 days	Tue 12/1/15	Mon 1/18/16
3.7 Testing and Analysis of Prototype	7 days	Tue 1/19/16	Mon 1/25/16
3.8 Final Product Development	17 days	Tue 1/26/16	Thu 2/11/16
4 Energy Supply (Drivetrain) subsystem	**119 days**	**Wed 9/2/15**	**Mon 2/8/16**
4.1 Initialize	7 days	Wed 9/2/15	Tue 9/8/15
4.2 Research Background Information	14 days	Wed 9/9/15	Tue 9/22/15
4.3 Product Definition	7 days	Wed 9/9/15	Tue 9/15/15
4.4 Conceptual Design	13 days	Wed 9/16/15	Mon 9/28/15
4.5 Product Development	68 days	Tue 9/29/15	Fri 1/15/16
4.6 Final Prototype Manufacturing	21 days	Tue 12/1/15	Fri 1/22/16
4.7 Testing and Analysis of Prototype	7 days	Sat 1/23/16	Fri 1/29/16
4.8 Final Product Development	10 days	Sat 1/30/16	Mon 2/8/16
5 Performance and Comfort (Fairing) subsystem	**140 days**	**Wed 9/2/15**	**Mon 2/29/16**
5.1 Initialize	7 days	Wed 9/2/15	Tue 9/8/15
5.2 Research Background Information	14 days	Wed 9/9/15	Tue 9/22/15
5.3 Product Definition	7 days	Wed 9/9/15	Tue 9/15/15
5.4 Conceptual Design	28 days	Wed 9/16/15	Sun 10/18/15
5.5 Product Development	53 days	Mon 10/19/15	Fri 1/15/16
5.6 Final Prototype Manufacturing	39 days	Tue 12/1/15	Tue 2/9/16
5.7 Testing and Analysis of Prototype	10 days	Wed 2/10/16	Fri 2/19/16
5.8 Final Product Development	10 days	Sat 2/20/16	Mon 2/29/16

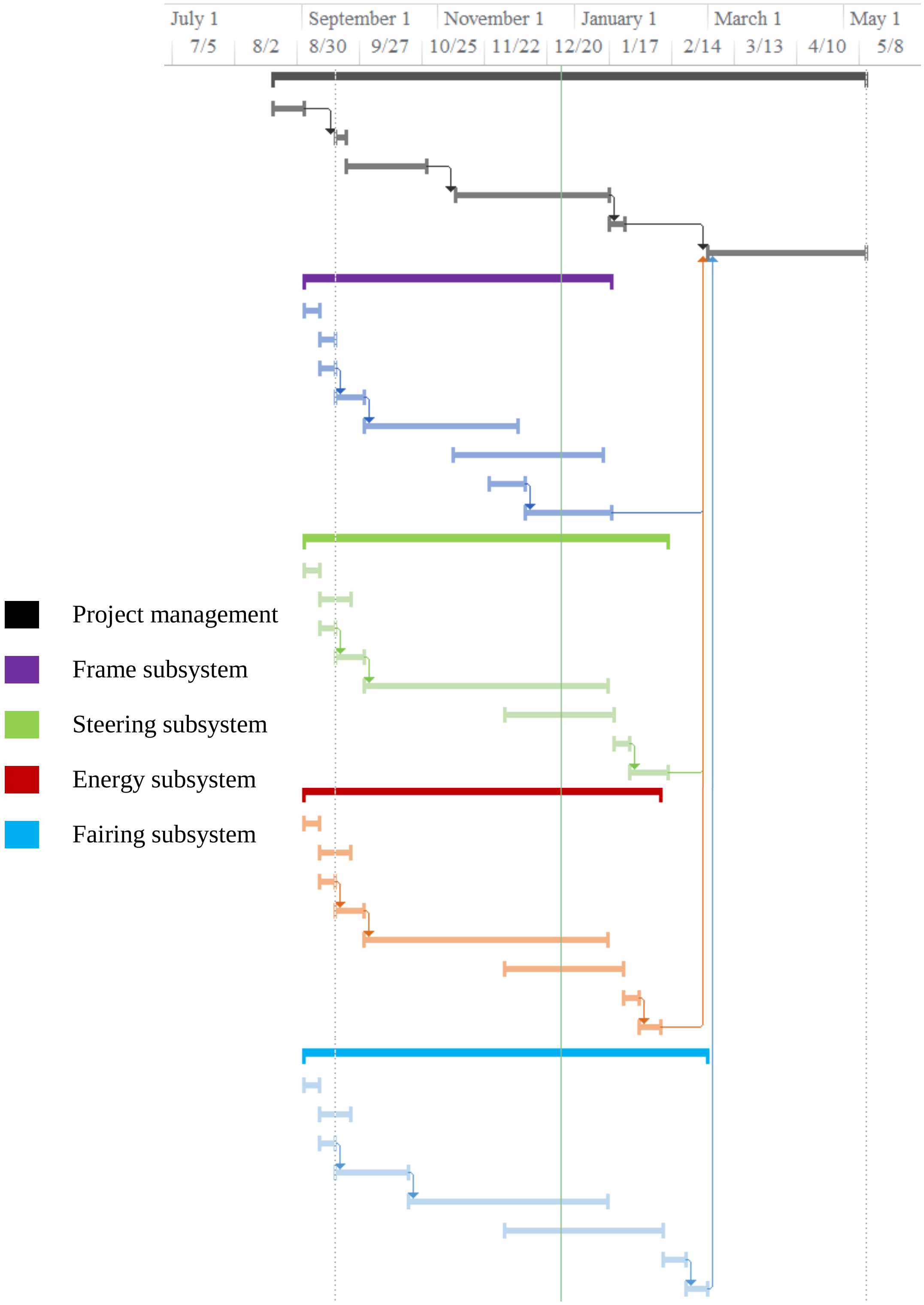


Figure D.1 Gantt chart corresponding to project planning overview

Table D.2 Detailed overview of lead project planning

Task Name	Duration	Start	Finish
1 Lead Project planning	**220 days**	**Wed 8/19/15**	**Tue 5/10/16**
1.1 Project Initiation	**14 days**	**Wed 8/19/15**	**Tue 9/1/15**
1.1.1 Define Team Roles	14 days	Wed 8/19/15	Tue 9/1/15
1.1.2 Create Means of Team Communication	14 days	Wed 8/19/15	Tue 9/1/15
1.1.3 Create Documentation Management System	7 days	Wed 8/19/15	Tue 8/25/15
1.1.4 Develop Team Schedule	14 days	Wed 8/19/15	Tue 9/1/15
1.2 Structure Product Requirements	**5 days**	**Wed 9/16/15**	**Sun 9/20/15**
1.2.1 Gather Requirements List from other groups	1 day	Wed 9/16/15	Wed 9/16/15
1.2.2 Evaluate requirements	1 day	Thu 9/17/15	Thu 9/17/15
1.2.3 Add to and adjust requirements as necessary	1 day	Thu 9/17/15	Thu 9/17/15
1.2.4 Create target values	1 day	Thu 9/17/15	Thu 9/17/15
1.2.5 Organize requirements into documentation (PDS)	3 days	Fri 9/18/15	Sun 9/20/15
1.3 Structure Conceptual Design Selection	**31 days**	**Mon 9/21/15**	**Mon 10/26/15**
1.3.1 Gather Concepts created by subsystems	1 day	Tue 10/6/15	Tue 10/6/15
1.3.2 Use criteria based on requirements to Create evaluation method	3 days	Mon 9/21/15	Wed 9/23/15
1.3.3 Give subsystems tools and directions for concept selection	**16 days**	**Mon 9/21/15**	**Tue 10/6/15**
1.3.3.1 Structure (Frame) subsystem	1 day	Mon 9/21/15	Mon 9/21/15
1.3.3.2 Controls (Steering/Braking) subsystem	1 day	Mon 9/21/15	Mon 9/21/15
1.3.3.3 Energy Supply (Drivetrain) subsystem	1 day	Mon 9/21/15	Mon 9/21/15
1.3.3.4 Performance and Comfort (Fairing) subsystem	1 day	Tue 10/6/15	Tue 10/6/15
1.3.4 Obtain top selections from each subsystem	1 day	Mon 10/19/15	Mon 10/19/15
1.3.5Ensure concept is feasible for system integration	2 days	Tue 10/20/15	Wed 10/21/15
1.3.6 Supply feedback on how to optimize system interfaces	5 days	Thu 10/22/15	Mon 10/26/15
1.3.7 Create meeting times between necessary groups to define concreate system interfaces	3 days	Thu 10/22/15	Sat 10/24/15
1.4 Structure Product Development	**33 days**	**Mon 11/9/15**	**Sat 1/16/16**
1.4.1 Obtain initial models of solution variants	1 day	Mon 11/9/15	Mon 11/9/15
1.4.2 Ensure subsystems will interface correctly	3 days	Tue 11/10/15	Thu 11/12/15
1.4.3 Obtain Bill of Materials from subsystems	7 days	Tue 12/1/15	Mon 12/7/15
1.4.4 Order necessary materials and parts	1 day	Sat 1/16/16	Sat 1/16/16
1.5 Final Design Details	**7 days**	**Sun 1/17/16**	**Sat 1/23/16**
1.5.1 Evaluate budgets	7 days	Sun 1/17/16	Sat 1/23/16
1.5.2 Add Sponsorship aspects to the vehicle	3 days	Sun 1/17/16	Tue 1/19/16
1.6 Competition and Preparation	**66 days**	**Tue 3/1/16**	**Tue 5/10/16**
1.6.1 Rider Preparation "Training"	60 days	Tue 3/1/16	Wed 5/4/16
1.6.2 Event Planning (Budget Purchases)	7 days	Thu 3/24/16	Wed 3/30/16
1.6.3 Travel	1 day	Sat 5/7/16	Sat 5/7/16
1.6.4 Competition	3 days	Sun 5/8/16	Tue 5/10/16

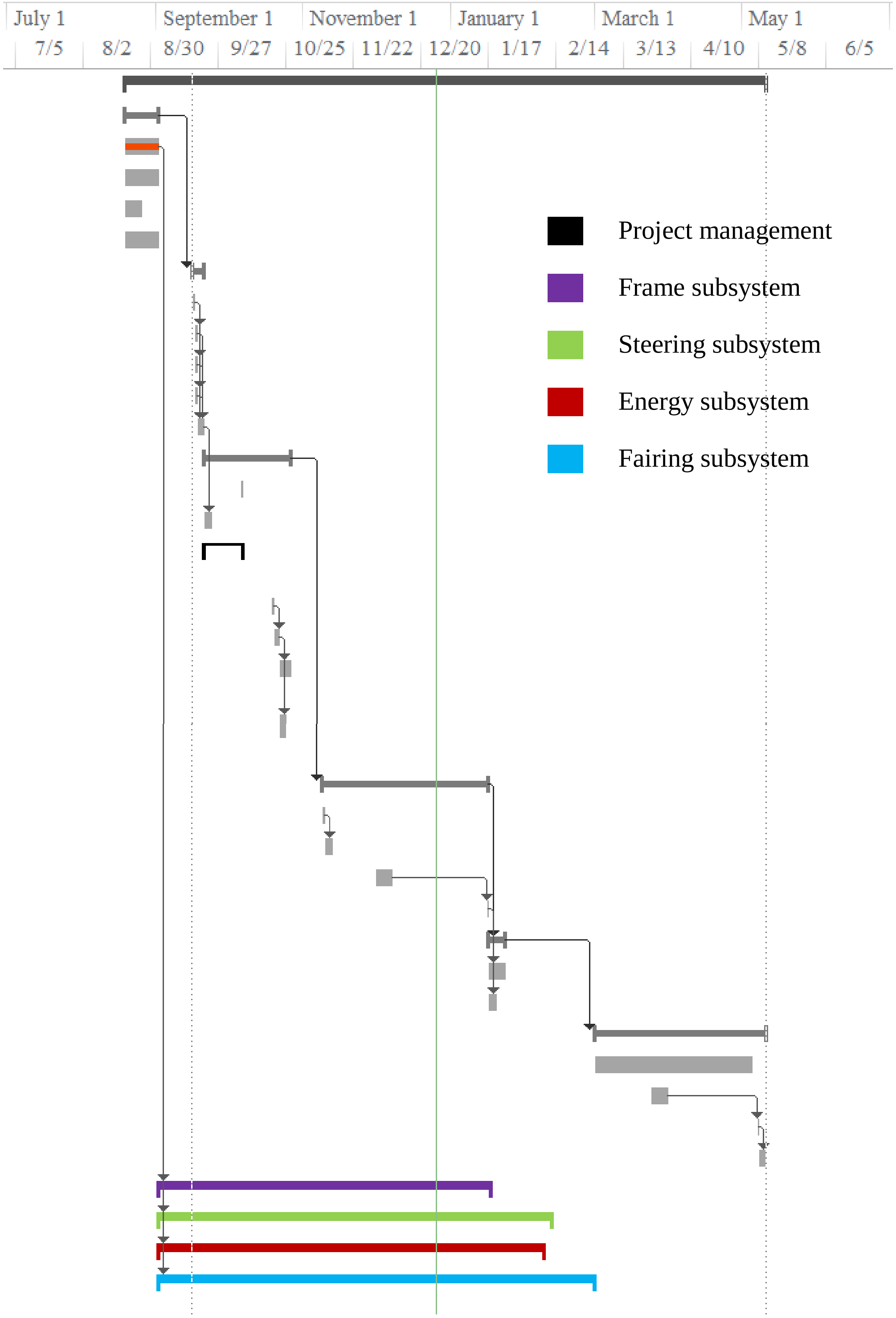


Figure D.2 Gantt chart corresponding to lead project planning

Table D.3 Detailed overview of structure (frame) subsystem planning

Task Name	Duration	Start	Finish
1 Lead Project planning	**220 days**	**Wed 8/19/15**	**Tue 5/10/16**
2 Structure (Frame) subsystem	**97 days**	**Wed 9/2/15**	**Sun 1/17/16**
2.1 Initialize	**7 days**	**Wed 9/2/15**	**Tue 9/8/15**
2.1.1 Schedule Meeting times	7 days	Wed 9/2/15	Tue 9/8/15
2.2 Research Background Information	**7 days**	**Wed 9/9/15**	**Tue 9/15/15**
2.2.1 Research different areas of frame design	**7 days**	**Wed 9/9/15**	**Tue 9/15/15**
2.2.1.1 Materials	7 days	Wed 9/9/15	Tue 9/15/15
2.2.1.2 Structures	7 days	Wed 9/9/15	Tue 9/15/15
2.2.1.3 Roll Protection Systems	7 days	Wed 9/9/15	Tue 9/15/15
2.2.1.4 Modularity	7 days	Wed 9/9/15	Tue 9/15/15
2.2.1.5 Seats	7 days	Wed 9/9/15	Tue 9/15/15
2.2.2 Compile information and summarize main points	3 days	Wed 9/9/15	Fri 9/11/15
2.3 Product Definition	**7 days**	**Wed 9/9/15**	**Tue 9/15/15**
2.3.1 Create subsystem requirements list	5 days	Wed 9/9/15	Sun 9/13/15
2.3.2 Evaluate requirements	2 days	Mon 9/14/15	Tue 9/15/15
2.4 Conceptual Design	**13 days**	**Wed 9/16/15**	**Mon 9/28/15**
2.4.1 Develop multiple concepts	3 days	Wed 9/16/15	Fri 9/18/15
2.4.2 Discuss concepts in the context of the group	1 day	Sat 9/19/15	Sat 9/19/15
2.4.3 Refine concepts to create complete frame subsystem concept	1 day	Sun 9/20/15	Sun 9/20/15
2.4.4 Evaluate concepts based on criteria	3 days	Tue 9/22/15	Thu 9/24/15
2.4.5 Refine top concepts based on based features of leading concepts	3 days	Fri 9/25/15	Sun 9/27/15
2.4.6 Analyze solution variants against criteria	1 day	Mon 9/28/15	Mon 9/28/15
2.5 Product Development	**60 days**	**Tue 9/29/15**	**Sun 12/6/15**
2.5.1 Begin Modeling top solution variants	3 days	Tue 9/29/15	Thu 10/1/15
2.5.1 Finish creating basic framework to solution variant	4 days	Fri 10/2/15	Mon 10/5/15
2.5.2 Relate design to manufacturability and refine model (Using shelf components)	3 days	Tue 10/6/15	Thu 10/8/15
2.5.3 Layout Bill of Materials and find corresponding market solutions	1 day	Wed 10/14/15	Wed 10/14/15
2.5.4 Add dimensions to solution variants	1 day	Wed 10/14/15	Wed 10/14/15
2.5.5 Analyze solution variants against criteria	**7 days**	**Thu 10/15/15**	**Wed 10/21/15**
2.5.5.1 Evaluate for ergonomics	7 days	Thu 10/15/15	Wed 10/21/15
2.5.5.2 Perform FEA or likewise methods to evaluate structure integrity	7 days	Thu 10/15/15	Wed 10/21/15
2.5.6 Compare solution variant to other subsystems	1 day	Tue 10/27/15	Tue 10/27/15
2.5.7 Refine model for system integration	**1 day**	**Wed 10/28/15**	**Wed 10/28/15**
2.5.7.1 Define set interfacing locations	1 day	Wed 10/28/15	Wed 10/28/15
2.5.8 Complete analysis again	3 days	Thu 10/29/15	Sat 10/31/15
2.5.9 Finalize detailed model	7 days	Sun 11/1/15	Sat 11/7/15
2.5.10 Create bill of materials	1 day	Wed 11/18/15	Wed 11/18/15
2.5.11 Order needed Materials and parts	**14 days**	**Thu 11/19/15**	**Sun 12/6/15**
2.5.11.1 Allow for shipping time	14 days	Thu 11/19/15	Sun 12/6/15

Table D.3 (Cont.)

Task Name	Duration	Start	Finish
2.6 Final Prototype Manufacturing	**31 days**	**Sun 11/8/15**	**Wed 1/13/16**
2.6.1 Obtain needed parts	1 day	Mon 12/7/15	Mon 12/7/15
2.6.2 Manufacturing the subsystem	**31 days**	**Sun 11/8/15**	**Wed 1/13/16**
2.6.2.1 Frame Structure	**16 days**	**Sun 11/8/15**	**Mon 11/23/15**
2.6.2.1.1 Create Jigging	**10 days**	**Sun 11/8/15**	**Tue 11/17/15**
2.6.2.1.1.1 Design Jig Assembly	3 days	Sun 11/8/15	Tue 11/10/15
2.6.2.1.1.2 Order/Buy required parts	7 days	Wed 11/11/15	Tue 11/17/15
2.6.2.1.1.3 Create Jig Assembly	3 days	Sun 11/8/15	Tue 11/10/15
2.6.2.1.2 Tubes	**7 days**	**Sun 11/8/15**	**Sat 11/14/15**
2.6.2.1.2.1 Bend tubes as required	1 day	Sun 11/8/15	Sun 11/8/15
2.6.1.2.1.2 Cut tubes to length	3 days	Mon 11/9/15	Wed 11/11/15
2.6.1.2.1.3 Miter Tubes as required	3 days	Thu 11/12/15	Sat 11/14/15
2.6.2.1.3 Assembly Frame	**9 days**	**Sun 11/15/15**	**Mon 11/23/15**
2.6.2.1.3.1 Locate tubes in jigs	2 days	Sun 11/15/15	Mon 11/16/15
2.6.2.1.3.2 Fasten Tubes as required	1 day	Sun 11/15/15	Sun 11/15/15
2.6.2.1.3.3 Weld frame together	7 days	Tue 11/17/15	Mon 11/23/15
2.6.3 Seat Assembly	21 days	Sun 11/8/15	Wed 12/2/15
2.6.4 Controls Connections	3 days	Thu 12/3/15	Sat 12/5/15
2.6.5 Fairing Connections	7 days	Sun 12/6/15	Wed 1/13/16
2.7 Testing and Analysis of Prototype	**12 days**	**Tue 11/24/15**	**Wed 12/9/15**
2.7.1 RPS Stress Testing	3 days	Tue 11/24/15	Mon 11/30/15
2.7.2 Harness Testing	7 days	Thu 12/3/15	Wed 12/9/15
2.7.3 Weight Testing	1 day	Tue 11/24/15	Tue 11/24/15
2.7.4 Rigidity Testing	1 day	Tue 11/24/15	Tue 11/24/15
2.8 Final Product Development	**7 days**	**Thu 12/10/15**	**Sun 1/17/16**
2.8.1 Optimize subsystem by makes necessary changes based on testing	7 days	Thu 12/10/15	Sun 1/17/16
2.8.2 Preform final check against requirements list to ensure vehicle makes are required specification	3 days	Thu 12/10/15	Wed 1/13/16
2.8.3 Record performance of vehicle	1 day	Thu 1/14/16	Thu 1/14/16
3 Controls (Steering) subsystem	**122 days**	**Wed 9/2/15**	**Thu 2/11/16**
4 Energy Supply (Drivetrain) subsystem	**119 days**	**Wed 9/2/15**	**Mon 2/8/16**
5 Performance and Comfort (Fairing) subsystem	**140 days**	**Wed 9/2/15**	**Mon 2/29/16**

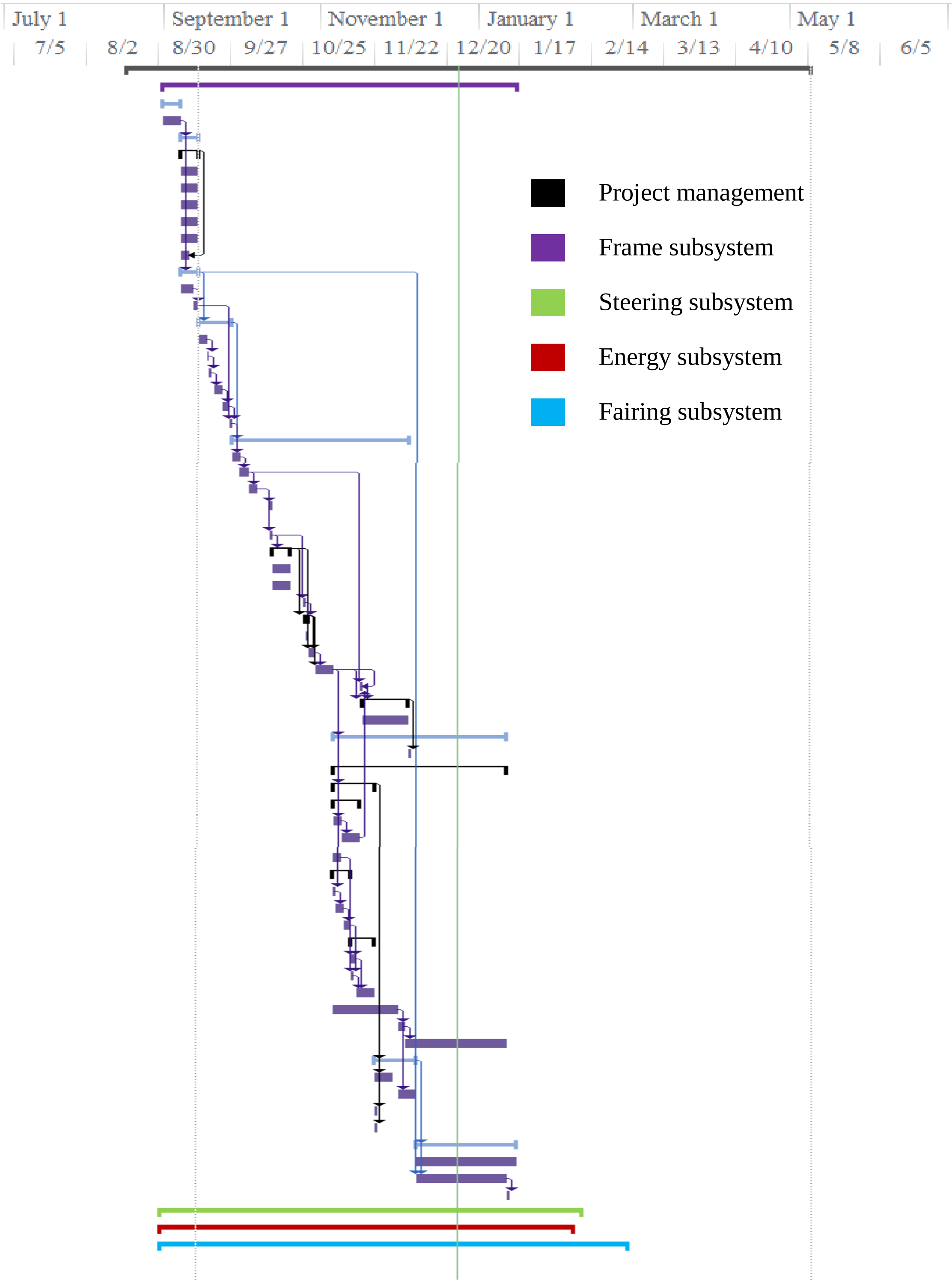


Figure D.3 Gantt chart corresponding to structure (frame) subsystem planning

Table D.4 Detailed overview of controls (steering) subsystem planning

Task Name	Duration	Start	Finish
1 Lead Project planning	**220 days**	**Wed 8/19/15**	**Tue 5/10/16**
2 Structure (Frame) subsystem	**97 days**	**Wed 9/2/15**	**Sun 1/17/16**
3 Controls (Steering) subsystem	**122 days**	**Wed 9/2/15**	**Thu 2/11/16**
3.1 Initialize	**7 days**	**Wed 9/2/15**	**Tue 9/8/15**
3.1.1 Schedule Meeting times	7 days	Wed 9/2/15	Tue 9/8/15
3.2 Research Background Information	**14 days**	**Wed 9/9/15**	**Tue 9/22/15**
3.2.1 Research different areas of frame design	**14 days**	**Wed 9/9/15**	**Tue 9/22/15**
3.2.1.1 Braking systems	14 days	Wed 9/9/15	Tue 9/22/15
3.2.1.2 Steering Linkages	14 days	Wed 9/9/15	Tue 9/22/15
3.2.1.3 Ergonomics and HPV controls	14 days	Wed 9/9/15	Tue 9/22/15
3.2.1.4 Modularity, Maintenance, and repair	14 days	Wed 9/9/15	Tue 9/22/15
3.2.2 Compile information and summarize main points	3 days	Sun 9/20/15	Tue 9/22/15
3.3 Product Definition	**7 days**	**Wed 9/9/15**	**Tue 9/15/15**
3.3.1 Create subsystem requirements list	5 days	Wed 9/9/15	Sun 9/13/15
3.3.2 Evaluate requirements	2 days	Mon 9/14/15	Tue 9/15/15
3.4 Conceptual Design	**13 days**	**Wed 9/16/15**	**Mon 9/28/15**
3.4.1 Develop multiple concepts	3 days	Wed 9/16/15	Fri 9/18/15
3.4.2 Discuss concepts in the context of the group	1 day	Sat 9/19/15	Sat 9/19/15
3.4.3 Refine concepts to create complete frame subsystem concept	1 day	Sun 9/20/15	Sun 9/20/15
3.4.4 Evaluate concepts based on criteria	3 days	Tue 9/22/15	Thu 9/24/15
3.4.5 Refine top concepts based on based features of leading concepts	3 days	Fri 9/25/15	Sun 9/27/15
3.4.6 Analyze solution variants against criteria	1 day	Mon 9/28/15	Mon 9/28/15
3.5 Product Development	**68 days**	**Tue 9/29/15**	**Fri 1/15/16**
3.5.1 Begin Modeling top solution variants	3 days	Tue 9/29/15	Thu 10/1/15
3.5.2 Finish creating basic framework to solution variant	4 days	Fri 10/2/15	Mon 10/5/15
3.5.3 Relate design to manufacturability and refine model (Using shelf components)	3 days	Tue 10/6/15	Thu 10/8/15
3.5.4 Layout Bill of Materials and find corresponding market solutions	1 day	Wed 10/14/15	Wed 10/14/15
3.5.5 Add dimensions to solution variants	1 day	Sun 11/8/15	Sun 11/8/15
3.5.6 Analyze solution variants against criteria	**7 days**	**Mon 11/9/15**	**Sun 11/15/15**
3.5.6.1 Evaluate for ergonomics	7 days	Mon 11/9/15	Sun 11/15/15
3.5.6.2 Perform simple calculations for turn radius, stability, etc.	7 days	Mon 11/9/15	Sun 11/15/15
3.5.7 Compare solution variant to other subsystems	1 day	Mon 11/9/15	Mon 11/9/15
3.5.8 Refine model for system integration	**1 day**	**Mon 11/16/15**	**Mon 11/16/15**
3.5.8.1 Define set interfacing locations	1 day	Mon 11/16/15	Mon 11/16/15
3.5.9 Complete analysis again	3 days	Tue 11/17/15	Thu 11/19/15
3.5.10 Finalize detailed model	7 days	Fri 11/20/15	Mon 11/30/15
3.5.11 Finalize method of connecting subsystem to structure	3 days	Fri 11/20/15	Sun 11/22/15
3.5.12 Create bill of materials	1 day	Mon 11/30/15	Mon 11/30/15
3.5.13 Order needed Materials and parts	**14 days**	**Tue 12/1/15**	**Fri 1/15/16**
3.5.13.1 Allow for shipping time	14 days	Tue 12/1/15	Fri 1/15/16

Table D.4 (Cont.)

Task Name	Duration	Start	Finish
3.6 Final Prototype Manufacturing	**17 days**	**Tue 12/1/15**	**Mon 1/18/16**
3.6.1 Obtain needed parts	1 day	Sat 1/16/16	Sat 1/16/16
3.6.2 Manufacturing the subsystem	**17 days**	**Tue 12/1/15**	**Mon 1/18/16**
3.6.2.1 Steering Linkages	**17 days**	**Tue 12/1/15**	**Mon 1/18/16**
3.6.2.1.1 Create Components	**14 days**	**Tue 12/1/15**	**Fri 1/15/16**
3.6.2.1.1.1 Create Tie Rod Connects to Length	3 days	Tue 12/1/15	Thu 12/3/15
3.6.2.1.1.2 Create "Axle Holder" (Connects wheels to vehicle and vehicle to steering linkage)	14 days	Tue 12/1/15	Fri 1/15/16
3.6.2.1.1.3 Create Human input connect ("handle bars")	3 days	Tue 12/1/15	Thu 12/3/15
3.6.2.1.2 Install Components	**3 days**	**Sat 1/16/16**	**Mon 1/18/16**
3.6.2.1.2.1 Linkage	3 days	Sat 1/16/16	Mon 1/18/16
3.6.2.1.2.2 "Axle Holder" and wheels	3 days	Sat 1/16/16	Mon 1/18/16
3.6.2.1.2.3 "Handlebars"	3 days	Sat 1/16/16	Mon 1/18/16
3.6.2.2 Braking systems	14 days	Tue 12/1/15	Fri 1/15/16
3.7 Testing and Analysis of Prototype	**7 days**	**Tue 1/19/16**	**Mon 1/25/16**
3.7.1 Turn Radius	1 day	Tue 1/19/16	Tue 1/19/16
3.7.2 Stability	7 days	Tue 1/19/16	Mon 1/25/16
3.7.3 Ergonomics	3 days	Tue 1/19/16	Thu 1/21/16
3.7.4 Braking ability	4 days	Tue 1/19/16	Fri 1/22/16
3.8 Final Product Development	**17 days**	**Tue 1/26/16**	**Thu 2/11/16**
3.8.1 Optimize subsystem by makes necessary changes based on testing	7 days	Tue 1/26/16	Mon 2/1/16
3.8.2 Preform final check against requirements list to ensure vehicle makes are required specification	14 days	Tue 1/26/16	Mon 2/8/16
3.8.3 Record performance of vehicle	3 days	Tue 2/9/16	Thu 2/11/16
4 Energy Supply (Drivetrain) subsystem	**119 days**	**Wed 9/2/15**	**Mon 2/8/16**
5 Performance and Comfort (Fairing) subsystem	**140 days**	**Wed 9/2/15**	**Mon 2/29/16**

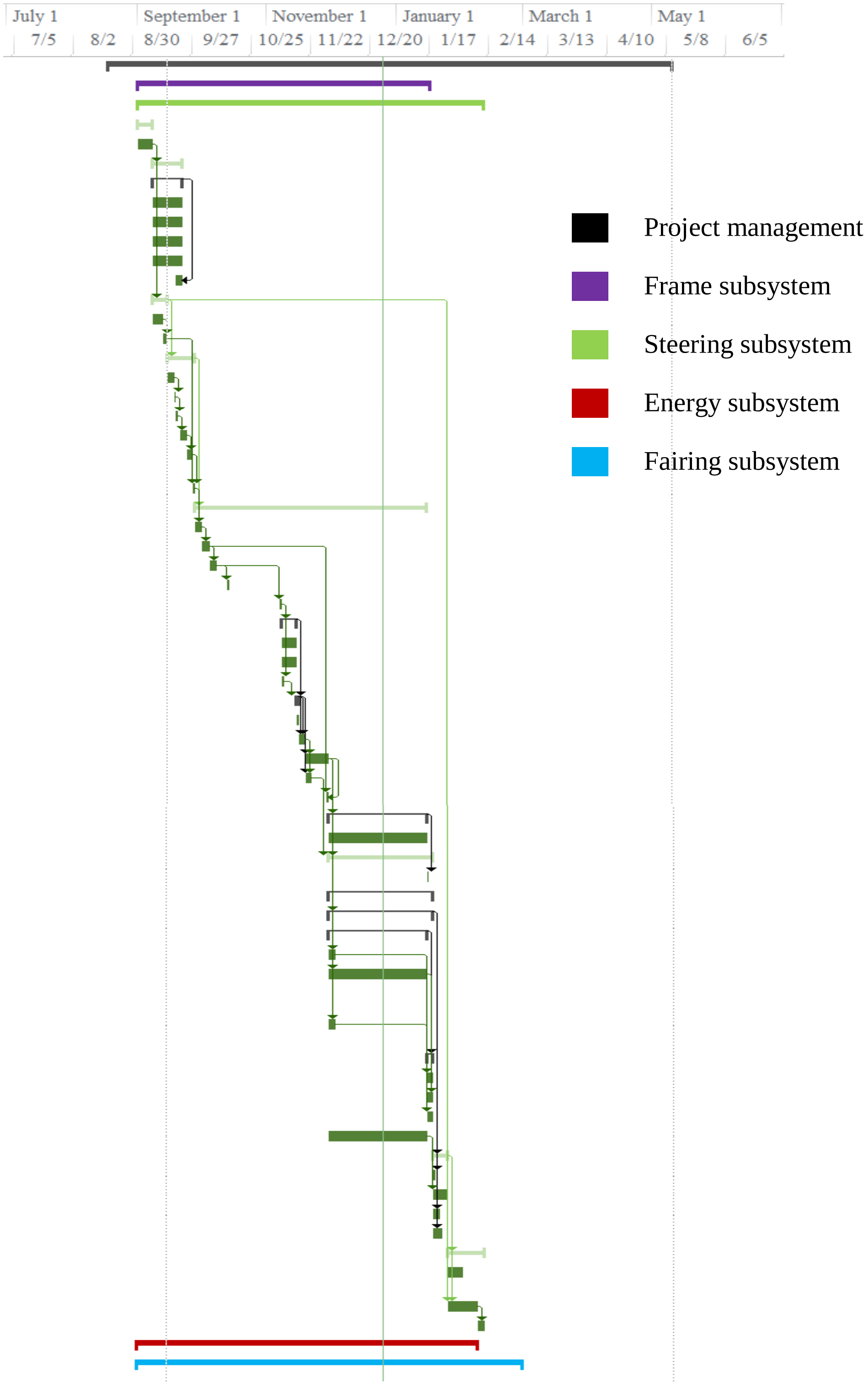


Figure D.4 Gantt chart corresponding to controls (steering) subsystem planning

Table D.5 Detailed overview of energy supply (drivetrain) subsystem planning

Task Name	Duration	Start	Finish
1 Lead Project planning	**220 days**	**Wed 8/19/15**	**Tue 5/10/16**
2 Structure (Frame) subsystem	**97 days**	**Wed 9/2/15**	**Sun 1/17/16**
3 Controls (Steering) subsystem	**122 days**	**Wed 9/2/15**	**Thu 2/11/16**
4 Energy Supply (Drivetrain) subsystem	**119 days**	**Wed 9/2/15**	**Mon 2/8/16**
4.1 Initialize	**7 days**	**Wed 9/2/15**	**Tue 9/8/15**
4.1.1 Schedule Meeting times	7 days	Wed 9/2/15	Tue 9/8/15
4.2 Research Background Information	**14 days**	**Wed 9/9/15**	**Tue 9/22/15**
4.2.1 Research different areas of frame design	**14 days**	**Wed 9/9/15**	**Tue 9/22/15**
4.2.1.1 Chain path	14 days	Wed 9/9/15	Tue 9/22/15
4.2.1.2 Energy Storage	14 days	Wed 9/9/15	Tue 9/22/15
4.2.1.3 Crank Placement and Ergonomics	14 days	Wed 9/9/15	Tue 9/22/15
4.2.1.4 Modularity, Maintenance, and repair	14 days	Wed 9/9/15	Tue 9/22/15
4.2.2 Compile information and summarize main points	3 days	Sun 9/20/15	Tue 9/22/15
4.3 Product Definition	**7 days**	**Wed 9/9/15**	**Tue 9/15/15**
4.3.1 Create subsystem requirements list	5 days	Wed 9/9/15	Sun 9/13/15
4.3.2 Evaluate requirements	2 days	Mon 9/14/15	Tue 9/15/15
4.4 Conceptual Design	**13 days**	**Wed 9/16/15**	**Mon 9/28/15**
4.4.1 Develop multiple concepts	3 days	Wed 9/16/15	Fri 9/18/15
4.4.2 Discuss concepts in the context of the group	1 day	Sat 9/19/15	Sat 9/19/15
4.4.3 Refine concepts to create complete frame subsystem concept	1 day	Sun 9/20/15	Sun 9/20/15
4.4.4 Evaluate concepts based on criteria	3 days	Tue 9/22/15	Thu 9/24/15
4.4.5 Refine top concepts based on based features of leading concepts	3 days	Fri 9/25/15	Sun 9/27/15
4.4.6 Analyze solution variants against criteria	1 day	Mon 9/28/15	Mon 9/28/15
4.6 Product Development	**68 days**	**Tue 9/29/15**	**Fri 1/15/16**
4.6.1 Begin Modeling top solution variants	3 days	Tue 9/29/15	Thu 10/1/15
4.6.2 Finish creating basic framework to solution variant	4 days	Fri 10/2/15	Mon 10/5/15
4.6.3 Relate design to manufacturability and refine model (Using shelf components)	3 days	Tue 10/6/15	Thu 10/8/15
4.6.4 Layout Bill of Materials and find corresponding market solutions	1 day	Wed 10/14/15	Wed 10/14/15
4.6.5 Add dimensions to solution variants	1 day	Sun 11/8/15	Sun 11/8/15
4.6.6 Analyze solution variants against criteria	**7 days**	**Mon 11/9/15**	**Sun 11/15/15**
4.6.6.1 Evaluate for ergonomics	7 days	Mon 11/9/15	Sun 11/15/15
4.6.6.2 Perform simple calculations for power transfer efficiency, energy recovery benefits vs. costs, etc.	7 days	Mon 11/9/15	Sun 11/15/15
4.6.7 Compare solution variant to other subsystems	1 day	Mon 11/9/15	Mon 11/9/15
4.6.8 Refine model for system integration	**1 day**	**Mon 11/16/15**	**Mon 11/16/15**
4.6.8.1 Define set interfacing locations	1 day	Mon 11/16/15	Mon 11/16/15
4.6.9 Complete analysis again	3 days	Tue 11/17/15	Thu 11/19/15
4.6.10 Finalize detailed model	7 days	Fri 11/20/15	Mon 11/30/15
4.6.11 Finalize method of connecting subsystem to structure	3 days	Fri 11/20/15	Sun 11/22/15
4.6.12 Create bill of materials	1 day	Mon 11/30/15	Mon 11/30/15
4.6.13 Order needed Materials and parts	**14 days**	**Tue 12/1/15**	**Fri 1/15/16**
4.6.13.1 Allow for shipping time	14 days	Tue 12/1/15	Fri 1/15/16

Table D.5 (Cont.)

Task Name	Duration	Start	Finish
4.7 Final Prototype Manufacturing	**21 days**	**Tue 12/1/15**	**Fri 1/22/16**
4.7.1 Obtain needed parts	1 day	Sat 1/16/16	Sat 1/16/16
4.7.2 Manufacturing the subsystem	**21 days**	**Tue 12/1/15**	**Fri 1/22/16**
4.7.2.1 Energy Storage (if being used)	**21 days**	**Tue 12/1/15**	**Fri 1/22/16**
4.7.2.1.1 Create Components	**14 days**	**Tue 12/1/15**	**Fri 1/15/16**
4.7.2.1.1.1 Connection pieces to frame	3 days	Tue 12/1/15	Thu 12/3/15
4.7.2.1.1.2 Energy recovery systems	14 days	Tue 12/1/15	Fri 1/15/16
4.7.2.1.2 Install Components	**7 days**	**Sat 1/16/16**	**Fri 1/22/16**
4.7.2.1.2.1 Energy recovery Connections	2 days	Sat 1/16/16	Sun 1/17/16
4.7.2.1.2.2 Energy recovery system	7 days	Sat 1/16/16	Fri 1/22/16
4.7.2.1.3 Chain path	**14 days**	**Tue 12/1/15**	**Fri 1/15/16**
4.7.2.1.3.1 Manufacture needed pieces of chain path connections	7 days	Tue 12/1/15	Mon 12/7/15
4.7.2.1.3.2 Install Components to frame	7 days	Tue 12/8/15	Fri 1/15/16
4.7.2.1.3.3Install Chain	1 day	Fri 1/15/16	Fri 1/15/16
4.8 Testing and Analysis of Prototype	**7 days**	**Sat 1/23/16**	**Fri 1/29/16**
4.8.1 Chain Tension and Shifting/Chain Derailing	3 days	Sat 1/23/16	Mon 1/25/16
4.8.2 Ergonomics and Human Power Output	7 days	Sat 1/23/16	Fri 1/29/16
4.8.3 Energy Storage (if being used)	7 days	Sat 1/23/16	Fri 1/29/16
4.9 Final Product Development	**10 days**	**Sat 1/30/16**	**Mon 2/8/16**
4.9.1 Optimize subsystem by makes necessary changes based on testing	3 days	Sat 1/30/16	Mon 2/1/16
4.9.2 Preform final check against requirements list to ensure vehicle makes are required specification	7 days	Sat 1/30/16	Fri 2/5/16
4.9.3 Record performance of vehicle	3 days	Sat 2/6/16	Mon 2/8/16
5 Performance and Comfort (Fairing) subsystem	**140 days**	**Wed 9/2/15**	**Mon 2/29/16**

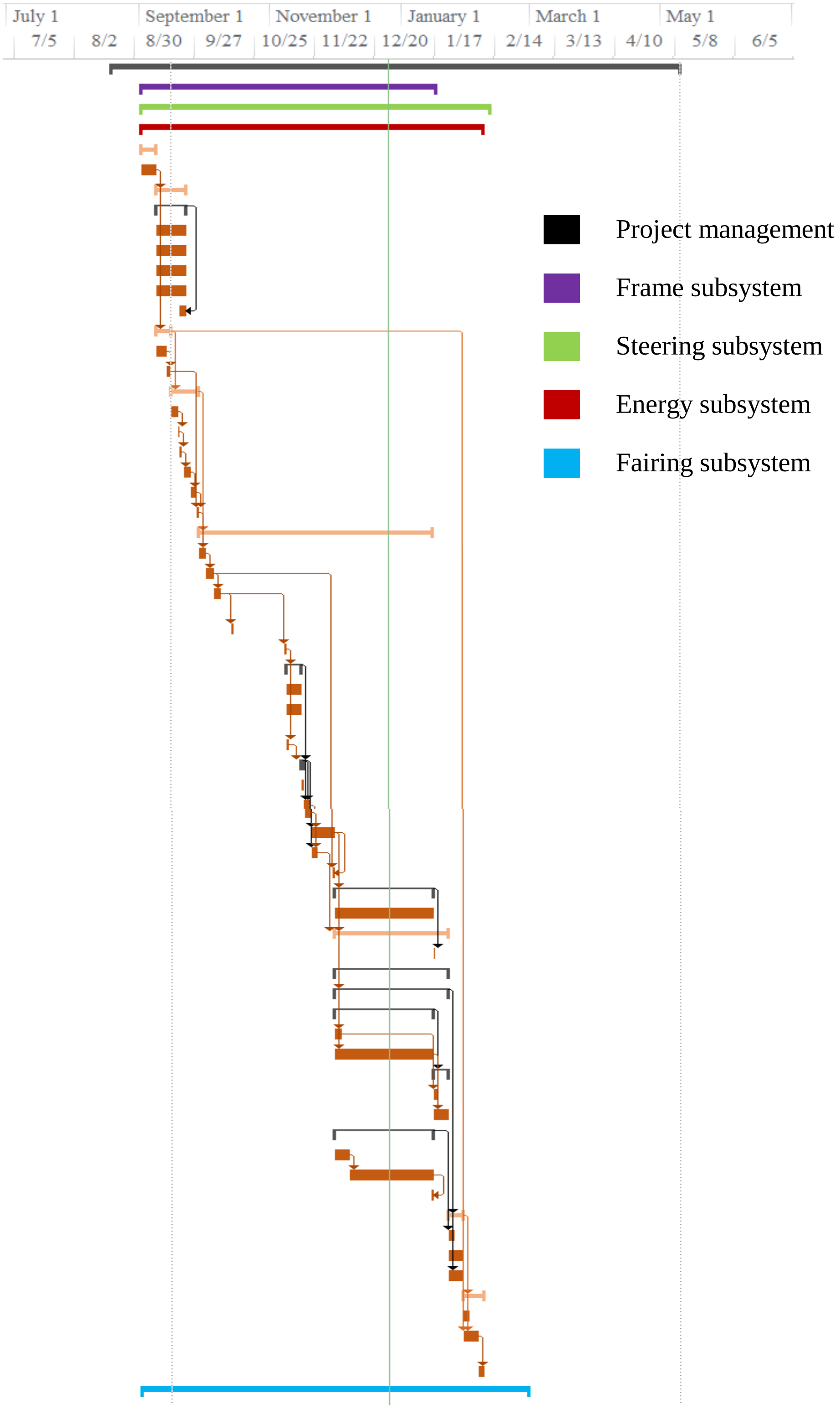


Figure D.5 Gantt chart corresponding to energy supply (drivetrain) subsystem planning

Table D.6 Detailed overview of performance and comfort (fairing) subsystem planning

Task Name	Duration	Start	Finish
1 Lead Project planning	**220 days**	**Wed 8/19/15**	**Tue 5/10/16**
2 Structure (Frame) subsystem	**97 days**	**Wed 9/2/15**	**Sun 1/17/16**
3 Controls (Steering) subsystem	**122 days**	**Wed 9/2/15**	**Thu 2/11/16**
4 Energy Supply (Drivetrain) subsystem	**119 days**	**Wed 9/2/15**	**Mon 2/8/16**
5 Performance and Comfort (Fairing) subsystem	**140 days**	**Wed 9/2/15**	**Mon 2/29/16**
5.1 Initialize	**7 days**	**Wed 9/2/15**	**Tue 9/8/15**
5.1.1 Schedule Meeting times	7 days	Wed 9/2/15	Tue 9/8/15
5.2 Research Background Information	**14 days**	**Wed 9/9/15**	**Tue 9/22/15**
5.2.1 Research different areas of frame design	**14 days**	**Wed 9/9/15**	**Tue 9/22/15**
5.2.1.1 Manufacturing Methods	14 days	Wed 9/9/15	Tue 9/22/15
5.2.1.2 Fairing Shapes	14 days	Wed 9/9/15	Tue 9/22/15
5.2.1.3 Ergonomics for dimensions, comfort, and visibility	14 days	Wed 9/9/15	Tue 9/22/15
5.2.1.4 Aerodynamics	14 days	Wed 9/9/15	Tue 9/22/15
5.2.2 Compile information and summarize main points	3 days	Sun 9/20/15	Tue 9/22/15
5.3 Product Definition	**7 days**	**Wed 9/9/15**	**Tue 9/15/15**
5.3.1 Create subsystem requirements list	5 days	Wed 9/9/15	Sun 9/13/15
5.3.2 Evaluate requirements	2 days	Mon 9/14/15	Tue 9/15/15
5.4 Conceptual Design	**28 days**	**Wed 9/16/15**	**Sun 10/18/15**
5.4.1 Develop multiple concepts	14 days	Wed 9/16/15	Tue 9/29/15
5.4.2 Discuss concepts in the context of the group	3 days	Wed 9/30/15	Fri 10/2/15
5.4.3 Refine concepts to create complete frame subsystem concept	3 days	Sat 10/3/15	Mon 10/5/15
5.4.4 Evaluate concepts based on criteria	3 days	Wed 10/7/15	Wed 10/14/15
5.4.5 Refine top concepts based on based features of leading concepts	3 days	Thu 10/15/15	Sat 10/17/15
5.4.6 Analyze solution variants against criteria	1 day	Sun 10/18/15	Sun 10/18/15
5.5 Product Development	**53 days**	**Mon 10/19/15**	**Fri 1/15/16**
5.5.1 Begin Modeling top solution variants	3 days	Mon 10/19/15	Wed 10/21/15
5.5.2 Finish creating basic framework to solution variant	4 days	Thu 10/22/15	Sun 10/25/15
5.5.3 Relate design to manufacturability and refine model (Using shelf components)	3 days	Mon 10/26/15	Wed 10/28/15
5.5.4 Layout Bill of Materials and find market solutions	1 day	Thu 10/29/15	Thu 10/29/15
5.5.5 Add dimensions to solution variants	1 day	Sun 11/8/15	Sun 11/8/15
5.5.6 Analyze solution variants against criteria	**7 days**	**Mon 11/9/15**	**Sun 11/15/15**
5.5.6.1 Evaluate for ergonomics	7 days	Mon 11/9/15	Sun 11/15/15
5.5.6.2 Perform simple calculations for turn radius, stability, etc.	7 days	Mon 11/9/15	Sun 11/15/15
5.5.7 Compare solution variant to other subsystems	1 day	Mon 11/9/15	Mon 11/9/15
5.5.8 Refine model for system integration	**1 day**	**Mon 11/16/15**	**Mon 11/16/15**
5.5.8.1 Define set interfacing locations	1 day	Mon 11/16/15	Mon 11/16/15
5.5.9 Complete analysis again	3 days	Tue 11/17/15	Thu 11/19/15
5.5.10 Finalize detailed model	7 days	Fri 11/20/15	Mon 11/30/15
5.5.11 Finalize method of connecting subsystem to structure	3 days	Fri 11/20/15	Sun 11/22/15
5.5.12 Create bill of materials	1 day	Mon 11/30/15	Mon 11/30/15
5.5.13 Order needed Materials and parts	**14 days**	**Tue 12/1/15**	**Fri 1/15/16**
5.5.14 Allow for shipping time	14 days	Tue 12/1/15	Fri 1/15/16

Table D.6 (Cont.)

Task Name	Duration	Start	Finish
5.6 Final Prototype Manufacturing	**39 days**	**Tue 12/1/15**	**Tue 2/9/16**
5.6.1 Obtain needed parts	1 day	Sat 1/16/16	Sat 1/16/16
5.6.2 Manufacturing the subsystem	**39 days**	**Tue 12/1/15**	**Tue 2/9/16**
5.6.2.1 Fairing (assuming a layup process will be used, only using one mold)	**39 days**	**Tue 12/1/15**	**Tue 2/9/16**
5.6.2.1.1 Create Mold	**11 days**	**Tue 12/1/15**	**Fri 12/11/15**
5.6.2.1.1.1 Divide shapes into segments and cut the segment to correct shapes	3 days	Tue 12/1/15	Thu 12/3/15
5.6.2.1.1.2 Combine the segments together	1 day	Fri 12/4/15	Fri 12/4/15
5.6.2.1.1.3 "Sand" the segments to create smooth surface to perform lay up	7 days	Sat 12/5/15	Fri 12/11/15
5.6.2.1.2 Create Fairing structure	**13 days**	**Wed 1/13/16**	**Mon 1/25/16**
5.6.2.1.2.1 Create Layup on top of mold	7 days	Wed 1/13/16	Tue 1/19/16
5.6.2.1.2.2 Pour Resin/heat/let product cure	3 days	Wed 1/20/16	Fri 1/22/16
5.6.2.1.2.3 Remove fairing from mold	3 days	Sat 1/23/16	Mon 1/25/16
5.6.2.1.3 Create Fairing structure	**15 days**	**Tue 1/26/16**	**Tue 2/9/16**
5.6.2.1.3.1 Combine fairing segment to create complete fairing	1 day	Tue 1/26/16	Tue 1/26/16
5.6.2.1.3.2 Attach Fairing to frame subsystem	7 days	Wed 1/27/16	Tue 2/2/16
5.6.2.1.3.3 Create working "Door" if necessary	7 days	Wed 2/3/16	Tue 2/9/16
5.7 Testing and Analysis of Prototype	**10 days**	**Wed 2/10/16**	**Fri 2/19/16**
5.7.1 Visibility	3 days	Wed 2/10/16	Fri 2/12/16
5.7.2 Aerodynamics/Drag reductions	10 days	Wed 2/10/16	Fri 2/19/16
5.7.3 Ergonomics	2 days	Wed 2/10/16	Thu 2/11/16
5.7.4 Driver Ability to enter/exit vehicle	2 days	Wed 2/10/16	Thu 2/11/16
5.8 Final Product Development	**10 days**	**Sat 2/20/16**	**Mon 2/29/16**
5.8.1 Optimize subsystem by makes necessary changes based on testing	2 days	Sat 2/20/16	Sun 2/21/16
5.8.2 Preform final check against requirements list to ensure vehicle makes are required specification	7 days	Sat 2/20/16	Fri 2/26/16
5.8.3 Record performance of vehicle	3 days	Sat 2/27/16	Mon 2/29/16

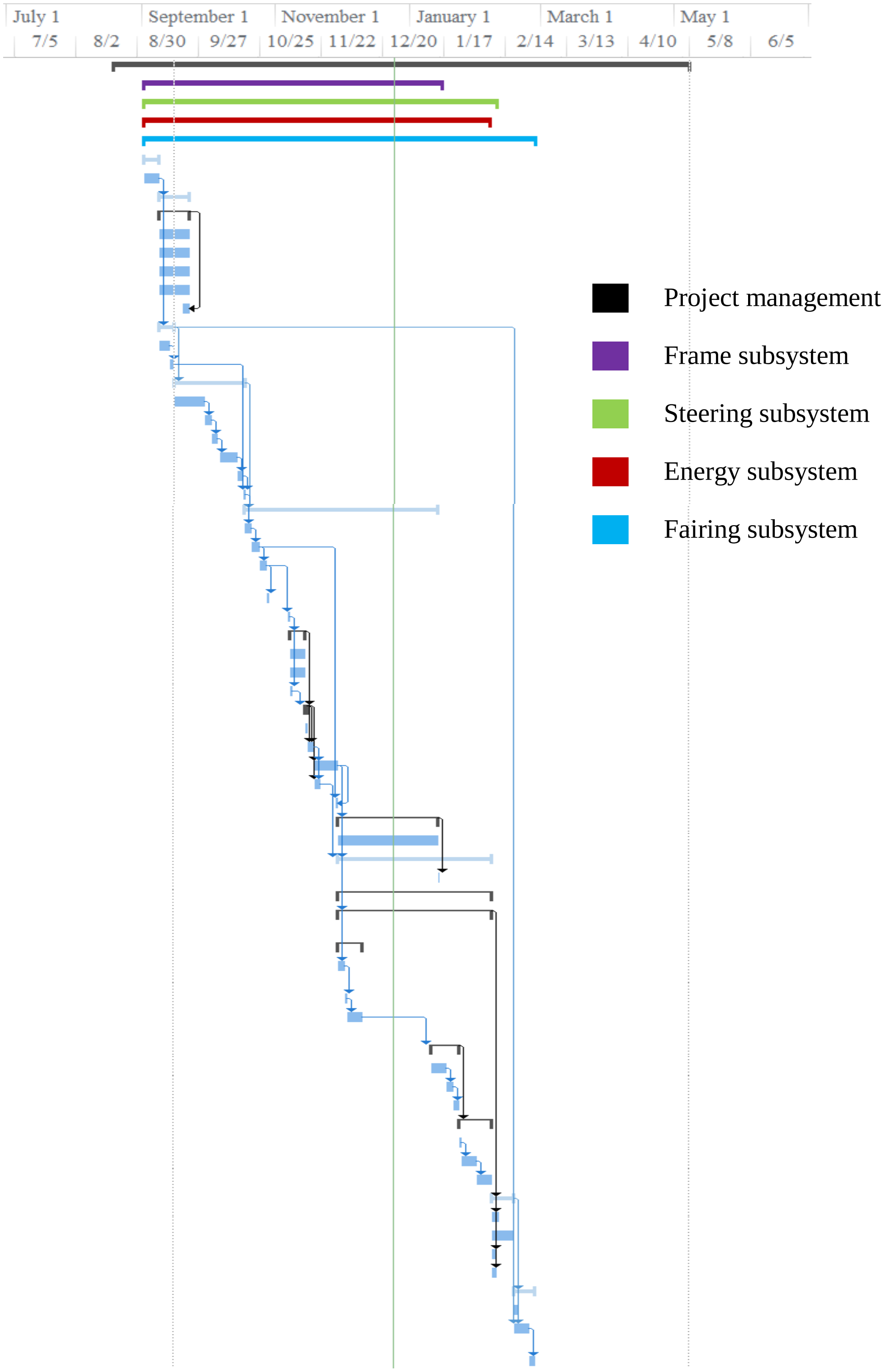


Figure D.6 Gantt chart corresponding to performance and comfort (fairing) subsystem planning

APPENDIX E: SYSTEM ENINGEERING PEER REVIEW/INSPECTION GUIDELINES

The purpose of peer reviews is to use the advantages of having multiple individuals examine concepts to try and eliminate possible flaws or bad features of the design. To have a more efficient review the following method is suggested [2]. One thing to note is the review guidelines are typically meant for large systems with many designers involved. For student use the times involved for preparation and amount of material presented may be drastically less. The key reason for presenting the guidelines is to highlight the different aspects involved in peer (and design) reviews. As a result, aspects such as complete individual preparation logs may be tedious and non-useful. It is up to the student's digression of what the necessary features should be recorded. That being said. it is imperative to record the summary of the meeting including design changes, requests, and defects and follow up documentation, in order to properly track how the design has developed.

A. Planning

The moderator of the peer review/inspection performs the following activities.

1. Determine whether peer review/inspection entrance criteria have been met

2. Determine Whether an overview of the product is needed

3. Select the peer review/inspection team and assign roles (for guidance on roles see Table E.1) Reviewers have a vested interest in the work product (e.g. they are peers representing areas affected.

4. Determine if the size of the product is within the prescribed guidance for the type of inspection (See Figure E.1 for meeting rate guidelines) If the product exceeds the guidelines, break the product into parts and inspect each part separately. It is highly recommended times do not exceed 2 hours.

5. Schedule the overview (if one is needed).

6. Schedule peer review/inspection meeting time and place.

7. Prepare and distribute the inspection announcement and package. Include in the package the product to be reviewed and the appropriate checklist for the peer review/inspection

8. Record total time spent in planning

B. Overview Meeting

1. Moderator runs the meeting, and the author presents background information to the reviewers.

2. Record total time spent in the overview

C. Peer Review/Inspection Preparation

1. Examine materials for understanding and possible defects

2. Prepare for assigned role in peer review/inspection

3. Complete and turn in individual preparation log to the moderator.

4. The moderator reviews the individual preparation logs and makes Go or No-Go decision and organizes inspection meeting.

5. Record total time spent in preparation

D. Peer Review/Inspection Meeting

1. The moderator introduces people and identifies their peer review/inspection roles

2. The reader presents work products to the peer review/inspection team in a logical and orderly manner

3. Peer reviewers/inspectors find and classify defects by severity, category, and type (See table E.2)

4. The recorder writes the major and minor defects on the inspection deflect list

5. Steps 1 through 4 are repeated until the review of the product is completed.

6. Open issues are assigned to peer reviewers/inspectors if irresolvable discrepancies occur.

7. Summarize the number of defects and their classification on the detailed inspection report

8. Determine the need for a re-inspection of third hour. Optional: Trivial defects can be given directly to the author at the end of the inspection.

9. The moderator obtains an estimate for rework time and completion date from the author, and does the same for action items if appropriate.

10. The moderator assigns writing of change request and/or problem reports (if needed)

11. Record time spent time in the peer review/inspection meeting

E. Third Hour

1. Completed assigned action items and provide information to the author

2. Attend third hour meeting at author's request.

3. Provide time spent in third-hour to moderator

F. Rework

1. All major defects noted in the inspection defect list are resolved by the author.

2. Minor and trivial defects (which would not result in faulty execution) are resolved at the discretion of the author as time and cost permit

3. Record total time spent in the rework on the inspection defect list

G. Follow up

1. The moderator verifies all major defects have been corrected and no secondary defects have been introduced.

2. The moderator ensures all open issues are resolved and verifies all success criteria for the peer review/inspection are met

3. Record total time spent in rework and follow up

4. File the inspection package

5. The inspection summary report is disturbed

6. Communicate that the peer review/inspection has been passed.

Table E.1 Roles of participants in peer/inspection reviews [2]

Moderator	Responsible for conducting inspection process and collecting inspection data. Plays key role in stages of process except rework. Required to perform special duties during an inspection in addition to inspector's tasks
Inspectors	Responsible for finding defects in work product from a general point of view, as well as defects that affect their area of expertise.
Author	Provides information about work product during all stages of process. Responsible for concerning all major defects and any minor and trivial defects that cost schedule permit. Performs duties of an inspector.
Reader	Guides team through work product during inspection meeting. Reads or paraphrases work product in detail. Should be an inspector from same (or next) life cycle phase as author. Performs duties of an inspector in addition to reader's role.
Recorder	Accurately records each defect found during inspection meeting on the Inspection Defect List. Performs duties of an inspector in addition to recorder's role.

Table E.2 Meeting rate guidelines for various types of inspection [2]

Type	Inspection Meeting	
	Target per 2 Hrs	Range
RO	20 pages	10 to 30 pages
R1	20 pages	10 to 30 pages
I0	30 pages	20 to 40 pages
I1	35 pages	25 to 45 pages
I2	500 lines of source code**	400 to 600 lines of source code**
IT1	30 pages	20 to 40 pages
IT2	35 pages	25 to 45 pages

***** Assume a 2-hour meeting. Scale down planned meeting duration for shorter work products.
**Flight software and other highly complex code segments should proceed at about half this rate

Table E.3 Classifications of defects [2]

Severity

Major

- An error that would cause a malfunction or prevents attainment of an expected or specified result
- Any error that would in the future result in an approved change request or failure report

Minor

- A violation of standards, guidelines, or rules that would not result in a deviation from requirement if not corrected, but could result in difficulties in terms of operations, maintenance or future development.

Trivial

- Editorial errors such as spelling, punctuation, and grammar that do not cause errors or change requests. Record only as redlines. Presented directly to the author

> Author is required to correct all major defects and should correct minor and trivial defects as time and cost permit

Category

- Missing
- Wrong
- Extra

Type

Type defects are derived from headings on checklist used for the inspection. Defect type can be standardized across inspection from all phases of the life cycle. A suggested standard set of defect types are:

Table E.3 (Cont.)

- Clarity
- Completeness
- Compliance
- Consistency
- Correctness/Logic
- Data Usage
- Fault Tolerance
- Functionality
- Interface
- Level of Detail
- Maintainability
- Performance
- Reliability
- Testability
- Traceability
- Other

Example

The following is an example of a defect classification that would be recorded on the inspection defect list:

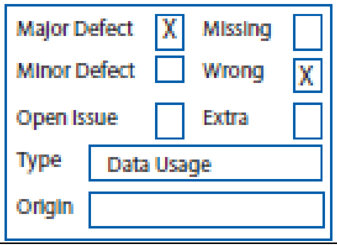
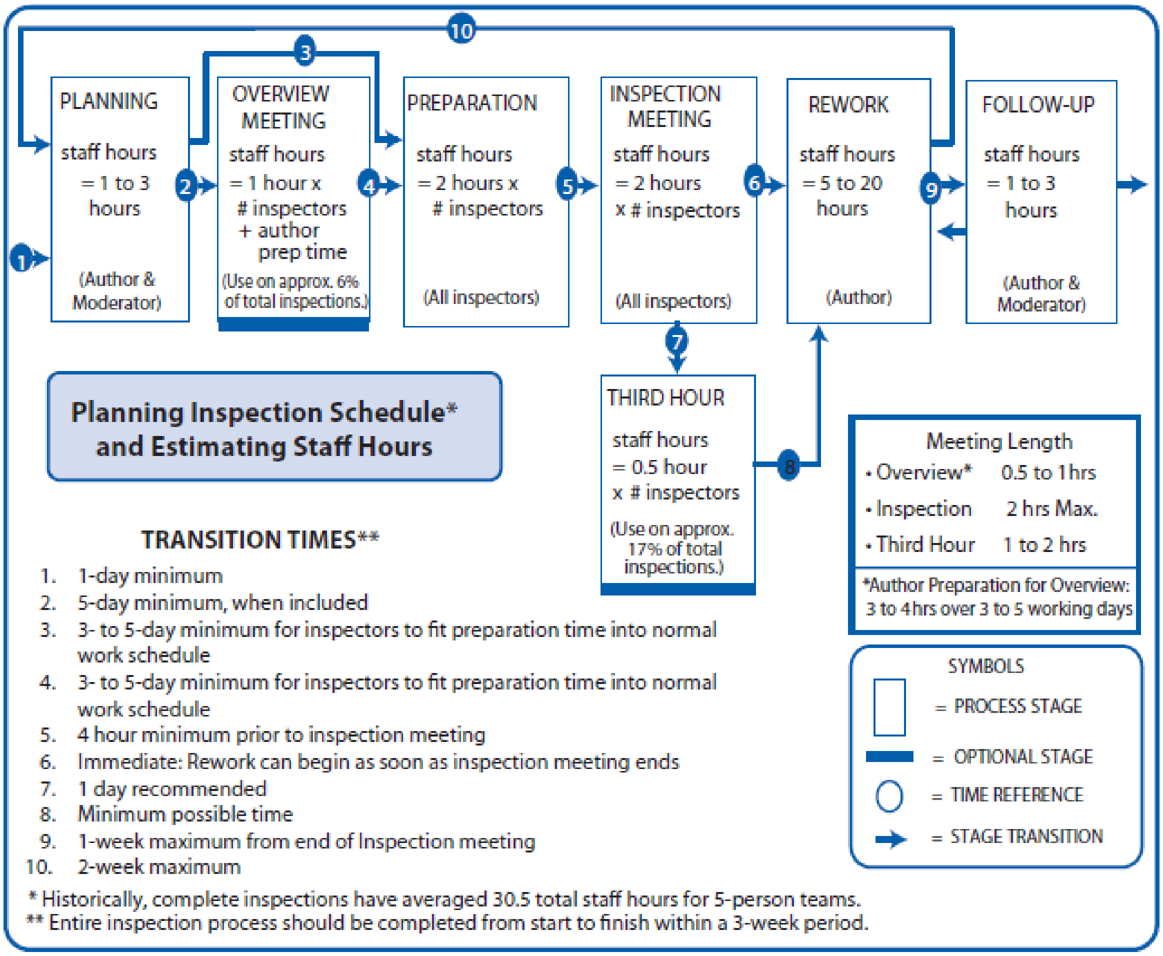
Description	Classification
Line 169 – While counting the number of leading spaces in variable NAME, the wrong "I" used to calculate "J"	 Major Defect ☒ Missing ☐ Minor Defect ☐ Wrong ☒ Open Issue ☐ Extra ☐ Type: Data Usage Origin:

Table E.4 Types of inspection [2]

SY1	System Requirements
SY2	System Design
SU2	Subsystem Design
R1	Software Requirements
I0	Architecture Design
I1	Detailed Design
I2	Source Code
IT1	Test Plan
IT2	Test Procedures & Functions



TRANSITION TIMES**

1. 1-day minimum
2. 5-day minimum, when included
3. 3- to 5-day minimum for inspectors to fit preparation time into normal work schedule
4. 3- to 5-day minimum for inspectors to fit preparation time into normal work schedule
5. 4 hour minimum prior to inspection meeting
6. Immediate: Rework can begin as soon as inspection meeting ends
7. 1 day recommended
8. Minimum possible time
9. 1-week maximum from end of Inspection meeting
10. 2-week maximum

* Historically, complete inspections have averaged 30.5 total staff hours for 5-person teams.
** Entire inspection process should be completed from start to finish within a 3-week period.

Figure E.1 Planning inspection schedule and estimating staff hours [2]

Table E.5 10 Basic Rules for inspection [2]

- Inspections are carried out at a number of points inside phases of the life cycle. Inspections are not substitutes for milestone reviews
- Inspections are carried out by peer representing areas of life cycle affected by material being inspected (Usually limited to 6 or fewer people
- Management is not present during inspections. Inspections are not to be used as a tool to evaluate workers
- Inspections are led by a trained monitor
- Trained inspectors are assigned roles.
- Inspections are carried out in a prescribed series of steps
- Inspection times are limited to to 2 hours
- Checklists of questions are used to define tasks and to stimulate defect finding
- Material covered during inspection meeting within an optional page rate, which has been found to give maximum error-finding ability
- Statistics on number of defects, types of defects, and time expended by engineers on inspections are kept.

Table E.6 Guidelines for successful inspections [2]

- Train moderators, inspectors, and managers
- No more than 25% of developers' time should be devoted
- Inspect 100% of work product
- Be prepared
- Share responsibility for work product quality
- Be willing to associate and communicate
- Avoid judgmental language
- Do not evaluate author
- Have at least one positive and negative input
- Raise issues; don't resolve them
- Avoid discussions of style
- Stick to technical issues
- Distribute inspection documents as soon as possible
- Let author determine when work product is ready for inspection
- Keep accurate statistics

APPENDIX F: REQUIREMENTS GENERATION FOR HPV DESIGN

There are many factors that go into requirements generation. This appendix section will go through a single method that can be used and the results of the requirements generation for a given design process involving HPVs. First, the example format will be discussed and explained. Second, the results of the subsystem requirements will be given. Lastly, the subsystem requirements will be complied into a single requirements document. The single requirements document is presented to allow for additionally high system level requirements, as well as eliminate repeated requirements defined by multiple subsystems.

F.1 Requirements Format

The format for arranging the subsystem requirements follows closely to the format given by Pahl *et al* [1]. In this format, there are four main categories; a requirement importance level, a requirements list, requirements responsibility, and requirement justifications. All four of the categories have entries that correspond to a given item in the requirement list, as seen in table F.3. The importance of the requirement can either be labeled as a demand or wish. Labeling a requirement as a demand ensures the final product must fulfil that requirement. A requirement labeled as wish, means it is hopefully the requirement is fulfilled, but it is not mandatory. Lastly, a general notes tab was added to allow for comments that may otherwise seem misplaced. The requirements list is composed of different topics to better arrange the requirements into similar features. Table F.1 provides a list of requirement topics with descriptions. The requirement responsibility is given to show which group or individual should be held accountable for the final product fulfilling the requirement in the final design. The requirement justification gives reasoning to the requirement being valid, thus a purpose for having them. The single system requirements document will be arranged in the same format, but it will include a combination of all the subsystem requirements.

Table F.1 Topics for requirement generation (Adapted from [1])

Requirement Topic	**Examples**
Geometry	Size, height, breadth, length, diameter, space requirement, number, arrangement, connection, extension, surface
Kinematics	Type of motion, direction of motion, velocity, acceleration, dynamic performance
Forces	Direction of force, magnitude, frequency, weight, load, deformation, stiffness, stiffness, elasticity inertia forces, resonance, protection
Energy	Output, efficiency, loss, friction, ventilation, state, pressure, temperature, heating, cooling, supply, storage, capacity, conversation
Material	Flow and transport of materials, physical and chemical properties of initial and final product, auxiliary materials, prescribed materials (food regulations, etc.),
Signals	Inputs and outputs, form, display, control equipment, component and system interactions and adjustments
Safety	Direct and indirect safety systems, operational and environment safety, safety for failures
Ergonomics	Man-Machine relationship, type of operation, operating height, clarity of layout, sitting comfort, lighting, shape compatibility, ease of use, instructional indications
Production	Factory limitations, maximum possible dimensions, preferred production methods, means of production, achievable quality, and tolerances, wastage, number of parts, standardizations
Quality Control	Possibilities of testing and measuring, application of special regulations and standards
Assembly	Special regulations, installation, siting, foundations, time
Transport	Limitations due to lifting gear, clearance, means of transport (height and weight), nature and conditions of dispatch
Operation	Quietness, wear, special uses, marketing area, destination (sulphurous, topical)
Maintenance	Servicing intervals, inspection, exchange and repairing, painting, cleaning
Recycling	Reuse, reprocessing, waste disposal, storage
Costs	Maximum permissible manufacturing costs, cost of tooling, investment and deprecation
Schedules	End date of development, project planning and control, delivery date

The given format is adaptable as columns can be added or taken away as deemed necessary. As a result the format given resembles that of a problem definition and specifications document, PDS, design tool, closely following the format of Summers [132]. Table F.2 shows an example PDS design tool with additional categories, such as date given, verification method, checked by, and etc. These are example categories that could be added or taken away to the discussed requirements format. The PDS design tool also introduces the ideas of importance level for non-mandatory requirements, wishes. By doing this an arbitrary level of preference can be given to wishes to help differentiate perceived importance levels. By doing this more appropriate level of focus can be applied to the requirements at the level concept, embodiment, and detail stages of design. Another category that could be added would be if the requirement needs to be verified before each vehicle use, such as brakes. The idea is similar to the idea of pre-flight checklists.

Table F.2 Example PDS for a burrito folder (Adapted from [132])

No.	Req.	Dem.	Req. Wt.	Just.	Tar. Val.	Given By	Given On	Veri. Method	Checked By	Checked On
1	Safe	YES		General consumer use		Legal	9/3/ 2004	Checklist	George	12/4/ 2004
2	Cost	YES		Must be less than $50	50 ($)	Prof.	9/3/ 2004	BOM	George	12/1/ 2004
2.1	Cost		9	Try to minimize cost	0 ($)	Team	10/15/ 2004	BOM	George	12/1/ 2004
3	Speed		3	Operate as fast as possible	0 (sec)	Prof.	9/3/ 2004	Test	Penny	12/1 /2004

F.2 Requirement Results

To provide examples of subsystem requirements, the following tables outline the requirements developed for the defined HPV systems and subsystems. The requirements generation is also provided to give a general guideline of the requirements used in the design of a HPV. For formatting and space purposes the justifications were excluded from the tables with the requirements, but added afterward the table. They were still included however, because detailing reasons for the requirements gives insight to considerations of the overall design. Students assisted in created the frame requirements, and were given the finalized requirements as an example. The other subsystem and system requirements are the results of other student effort given the outlined method.

Table F.3 Example of frame subsystem requirements

ME 431/HPVC (Class/Project)	Requirements List for Frame	10/22/2015 (Date)
D/W (Demand/Want)		Responsible
	1.) Geometry	Frame
D	a. Width must be less than 36 inches	Frame
W	b. Width must be less than 25 inches	Frame
W	c. Length must be less than 90 inches	Frame
W	d. Height must be less 36 inches	Frame
D	e. Normally a minimum of at least 6 inches above the ground	Frame
	2.) Kinematics	
D	a. Rigid during dynamic performance	Frame
D	b. Stable dynamic performance at high and low speeds	
D	c. Able to withstand dynamic forces	Frame
W	d. Able to account for different road conditions	Frame
W	e. Allows for improved control of the vehicle	
	3.) Forces	
D	a. Has a roll protection system capable of protecting rider from a 600lbs vertical force and a 300lb side force	Frame
W	b. Frame Weight is minimal	Frame
D	c. Strong enough to allow for human weight	Frame
	4.) Material	
D	a. Material is constant throughout	Frame
W	b. Material Properties include large stiffness	Frame
W	c. Materials used allow for manufacturability of various shapes/Use of tools	Frame
W	d. Allows for reworking	Frame
	5.) Signals	
D	a. Has defined interaction points for steering connections	Frame/Steering
D	b. Has a defined location and attachment process for wheels	Frame

Table F.3 (Cont.)

ME 431/HPVC (Class/Project)	Requirements List for Frame	10/22/2015 (Date)
D/W (Demand/Want)		Responsible
	5.) Signals	
D	c. Provides multiple places to attach fairing	Frame / Fairing
D	d. Allows adequate space for drivetrain system	Frame / Drivetrain
W	e. Allows adequate space for Energy recovery system	Frame / Drivetrain
D	f. Allows adequate room for a seat	Frame
W	g. Allows adequate room for seat adjustments	Frame
	6.) Safety	
D	a. Harness has a secure attachment to frame	Frame
D	b. Manufactured using safe methods	Frame
D	c. Allows for visibility of the road in front of the vehicle	Frame
D	d. Allows for visibility of the road to both sides of vehicle	Frame
D	e. Allows for visibility of the road in behind the vehicle	Frame
W	d. Allows user to fully see in all directions	
	7.) Ergonomics	
W	a. Seat for the user allows for maximum comfort	Frame
W	b. Seat for the user allows for varying angle	Frame
D	c. Seating position of the user allows for clear visibility of the road in front of them	Frame
W	d. Seat is adjustable for users of heights of 5'0" - 6'5"	Frame
D	e. Allows user easy access of entering and exiting	Frame
D	f. Allows for storage of various items	Frame
	8.) Production	
D	a. Design allows for easier fabrication when possible	Frame
W	b. Uses standardization when possible	Frame
W	c. Utilize current tooling	Frame
D	d. Use proper manufacturing methods to produce higher quality parts	Frame
D	e. Costs less than $1000 to create structure	Frame
W	f. Manufacturing methods used encourage repeatability	Frame
	9.) Assembly	
W	a. Some components are be disassemble to allow for smaller storage	Frame
D	b. Can fit within a car in a given assembly state	Frame
W	c. Allows for modularity of various subsystems	Frame
	10.) Maintenance	
W	a. Allows for quick repairs	Frame
D	b. Minimizes repairs needed	Frame

Table F.4 is list of the justifications for the frame requirements. They are organized by the same numbering and categories as table F.3 for simplicity.

Table F.4 Justifications for frame requirements

Requirement	Justifications/Additional Notes
Size	
1a.	In order to fit through a normal doorway
1b.	For improved aerodynamics (Smaller vehicle will "block" less air / allow average person to fit)
1c.	Constrain length within reason/better overall vehicle stabilization
1d.	For improved aerodynamics
1e.	Account for being able to go over different terrains (Getting over speed bumps/pot holes/etc.)
Kinematics	
2a.	Design limits flexing issues
2b.	Desirable of vehicle to be controllable (Factor of Wheelbase and wheel Camber)
2c.	Able to get over speed bumps, pot holes, and generally uneven road conditions
2d.	Not all roads all the same conditions, especially across different aspects of the world (dampen dynamic forces / include elements of suspension)
2e.	Comfortable and safe riding vehicle (Factor of wheel base length/center of gravity)
Forces	
3a.	Protects rider in roll over situation/impact collision (Also ASME HPVC rule)
3b.	To maximize power efforts generated from rider, especially on uphill slopes
3c.	Person using vehicle doesn't cause it to break
Material	
4a.	Reduces cost and modularity complexities
4b.	Means less material needs to be used which reduces costs
4c.	The material is widely applicable to various machining applications / reduces costs
4d.	Changes to design and iterations that need to occur after production because of integrating other subsystems, as well as service and maintenance
Signals	
5a.	Steering will have to be added somehow
5b.	Wheels having a define placement allows other subsystems to be be define accordingly
5c.	Allows for a method to attach the fairing
5d.	Allows for a method to add the drivetrain
5e.	Allows for space to add an energy recovery system

Table F.4 (Cont.)

Requirement	Justifications/Additional Notes
Signals	
5f.	Allows for space for the rider to be in the vehicle
5g.	Allows for the rider to be comfortable. Also allows for other seat locations
Safety	
6a.	Can hold a person weight without causing damages to the frame
6b.	Reduce the risk of injuries and accidents
6c.	Able to see the road in front of the rider
6d.	Able to see the road to the side of the vehicle
6e.	Able to see what is happening behind the vehicle
6f.	User can clearly see, behind them in front of them, and to their side/also affects ergonomics
Ergonomics	
7a.	Comfortable for riders of different sizes/Maximize power output of rider (Upright vs. Laying down)
7b.	Comfortable for riders of different sizes/Maximize power output of rider (Upright vs. Laying down)
7c.	Able to see the road in front of them and the seating position does not stop that
7d.	Works for riders of different heights 5'0" to 6'5"
7e.	Entering and exiting affects comfort and safety of the person getting in and out of the vehicle
7f.	Provides rider convenience (Also ASME HPVC rule)
Production	
8a.	Lower complexity and costs
8b.	Helps with modularity and sets common size/components/etc.
8c.	New tooling can be purchase, but at the cost of capital investments. That being said if the project is at the beginning years and will be repeated more capital investment for the project will have less impact (in terms of cost) for the future iterations
8d.	Helps with product quality and repeatability
8e.	Cheap to produce, goal of less than $500 including welding material, tubes, shipping, and tooling
8f.	Better designed for mass manufacturing/consumerism
Assembly	
9a.	Better for consumers to store things
9b.	Makes the vehicle from convenience to people to take to other places (also a transportation requirement)
9c.	Allows for modularity of various subsystems such as the frame, steering, drivetrain, and fairing
Maintenance	
10a.	Means service for the vehicle will be easier
10b.	Requires less service to the vehicle

Table F.5 Example of steering subsystem requirements

ME 431/HPVC (Class/Project)	Requirements List	10/22/2015 (Date)
D/W (Demand/Want)		Responsible
	1.) Geometry	
W	a. Wheel base width must be less than 36 inches	Steering
D	b. Must be proportional to frame	Steering
D	c. Must fit in fairing	Steering / Fairing
D	d. Must sit high enough to not scrape	Steering
	2.) Kinematics	
D	a. Allows desired range of motion for turning radius	Steering / Frame
D	b. Stable during high and low speeds	Steering / Frame
D	c. Able to maintain control encountering obstacles (speed bumps)	Steering
D	d. Allows for restriction of range of motion in order to prevent accidents during potential loss of control	Steering
W	e. Able to achieve desired turning radius in different environments (humidity, dirt, snow)	Steering
	3.) Forces	
D	a. controls should be easy to use	Steering
W	b. Weight must be kept to a minimum	Steering
D	c. Strong enough to allow for human weight (Person using vehicle doesn't cause it to break)	Steering
W	d. controls must be able to withstand pulling and pushing of the driver to give them more security in the vehicle	Steering
D	e. Damping must prevent speed vibration	Steering
	4.) Material	
D	a. Material is constant throughout	Steering
W	b. Material Properties include stiffness appropriate for linkages	Steering
W	c. Materials used allow for manufacturability of various shape/Use of tools	Steering
W	d. Allows for reworking (changes to design and iterations that need to occur after production because of integrating other subsystems)	Steering
	5.) Signals	
D	a. Has defined interaction points for linkage connections	Steering
D	b. Has a defined location and attachment process for wheels	Steering
W	c. Does not interfere with fairing	Steering

Table F.5 (Cont.)

ME 431/HPVC (Class/Project)	Requirements List	10/22/2015 (Date)
D/W (Demand/Want)		Responsible
	6.) Safety	
W	a. Brakes should be efficient enough for safe stop	Steering
D	b. Safety in manufacturing	Steering
W	c. Steering does not obstruct visibility	Steering
W	d. Restrictions put in place to prevent wheels from hurting driver.	Steering
	7.) Ergonomics	
D	a. Seat - Location/form/Attachments	Steering
W	b. Positioning-increase angle	Steering
W	c. Configuration - Comfortable for riders of different sizes/Maximize power output of rider (Upright vs. Laying down)	Steering
D	d. Width- must have room for elbow clearance	Steering
D	f. Clearance-Frame cannot impede steering motion of driver	Frame / Steering
	8.) Production	
D	a. Easily obtainable parts from suppliers	Steering
D	b. Low cost of manufacture	Steering
W	c. Standard/Universal Parts used when possible	Steering
D	d. Uses sound, repeatable manufacturing methods	Steering
W	e. Ease of adaptability to different configurations of frame, drivetrain, etc.	Steering
W	Cheap to produce	Steering
	9.) Assembly	
W	a. Less than 5 points that must be precisely assembled	Steering
W	b. Must fit within a car	Steering
W	c. Less than 3 points that must be precisely assembled	Steering
	d. Assembly within the skill set of this group	Steering
	10.) Operation	
D	Minimal vibrations during use	Steering
D	Remains stable in use	Steering
	11.) Maintenance	
W	Allows for quick repairs	Steering
D	Minimizes repairs needed	Steering

Table F.6 Justification of steering requirements

Requirement	Justifications/Additional Notes
Geometry	
1a.	In order to fit through a normal doorway
1b.	Constrain length within reason/better overall vehicle stabilization
1c.	For improved aerodynamics
1d.	Account for being able to go over different terrains
Kinematics	
2a.	Need to be able to calculate how sharply the vehicle can turn
2b.	The vehicle should not role when at high speeds
2c.	Do not want to lose control capabilities because of the speed bump
2d.	Do not want to destroy the fairing or the wheels in the case of a failure
2e.	The turning radius should be unaffected by read conditions
Forces	
3a.	Controls must not tire out driver
3b.	Overall weight must be kept to a minimum
3c.	Welds should not break due to driver weight
3d.	Driver must be able to hold themselves in the vehicle by holding the controls
3e.	Speed wobbles must be prevented
Signals	
5a.	Defines how the steering will work
5b.	Defines how the wheels will attach and how wide the vehicle will be
5c.	Keeps wheels from rubbing against fairing
Safety	
6a.	Braking properly will make the vehicle safer
6b.	During manufacturing safety should be addressed.
Ergonomics	
7a.	Seat must give clearance for all steering options, whether under or above
7b.	Seat angle should be increased
7c.	Along with seat position, steering mechanisms must be easy for all riders
7d.	Clearance for riders arms during driving
7e.	Under seat clearance
7f.	Cannot block motion of driver
Production	
8a.	Easily obtainable parts from suppliers
8b.	Low cost of manufacture
8c.	Standard/Universal Parts used when possible
8d.	Uses sound, repeatable manufacturing methods
8e.	Ease of adaptability to different configurations of frame, drivetrain, etc.
8f.	Cheap to produce

Table F.6 (Cont.)

Requirement	Justifications/Additional Notes
Assembly	
9a.	Less than 5 points that must be precisely assembled
9b.	Must fit within a car
9c.	Less than 3 points that must be precisely assembled
9d.	Assembly within the skill set of this group
Operation	
10a.	Vibration would cause many problems
10b.	Do not want the vehicle to roll or tip while driving
Maintenance	
11a.	Allows for quick repairs
11b.	Minimizes repairs needed

Table F.7 Example of drivetrain subsystem requirements

ME 431/HPVC (Class/Project)	Requirements List	10/22/2015 (Date)
D/W (Demand/Want)		Responsible
	1.) Efficiency	
D	a. Operates at a minimum of 80% efficiency	Drivetrain
W	b. No frivolous power loss to chain geometry	Drivetrain
D	c. Chain does not slip/derail	Drivetrain
D	d. High and low speed settings	Drivetrain / Steering
D	e. High and low torque settings	Drivetrain / Steering
	2.) Safety	
D	a. Eliminates potential contact with user	Drivetrain
D	b. Able to withstand dynamic forces without chain derailment(speed bump/pot holes)	Drivetrain
	3.) Durability	
D	a. Able to perform under endurance high conditions without chain slippage or material wear	Drivetrain
	4.) Assembly	
W	a. Easily assembled and disassembled	Drivetrain
W	b. Allows for modularity (easily integrated into frame)	Drivetrain / Frame
	5.) Operation	
W	a. Minimal vibrations during use	Drivetrain
D	b. Provides reliable power to back wheel	Drivetrain
	6.) Maintenance	
D	a. Allows for fast (mid-race) repairs	Drivetrain
W	b. Minimizes potential for derailment	Drivetrain
	7.) Costs	
W	a. Inexpensive to produce per unit	Drivetrain
W	b. Inexpensive to maintain	Drivetrain
	8.) ERS	
D	a. Poses no threat to user at extreme speeds	Drivetrain
D	b. Does not draw power from drivetrain	Drivetrain
D	c. Provides more power than is expended	Drivetrain
D	d. Output is the same order of magnitude of forces as the drivetrain	Drivetrain

Justifications for the drivetrain requirements were not established by the students.

Table F.8 Example of fairing subsystem requirements

ME 431/HPVC (Class/Project)	Requirements List	10/22/2015 (Date)
D/W (Demand/Want)		Responsible
	1.) Geometry	
W	a. Must not be wider than the wheelbase	Fairing
D	b. Must be able to remain intact after going over speed bump	Fairing
D	c. Must fit over frame and roll bars	Fairing
	2.) Kinematics	
D	a. Must not deform at speed	Fairing
W	b. Must not sway when cornering	Fairing
D	c. Must be more aerodynamic than having no fairing	Fairing
	3.) Forces	
W	a. Must be resilient enough to not break if the vehicle ends up upside down or on its side	Fairing
W	b. Must weigh less than a PVC equivalent	Fairing
D	c. Must be strong enough to not be broken by somebody leaning on	Fairing
	4.) Material	
W	a. Material must be strong	Fairing
D	b. Material must be relatively inexpensive	Fairing
D	c. Must be able to be repaired	Fairing
W	d. Material must be light	Fairing
	5.) Safety	
D	a. No sharp edges	Fairing
D	b. Must protect the rider from abrasion if the vehicle ends up on its side	Fairing
W	c. Must have at least 100 degrees of forward-looking visibility	Fairing
D	d. Must be able to see behind the vehicle as well as to the sides in some capacity	Fairing
	6.) Ergonomics	
D	a. Must not hinder pedaling/steering	Fairing
W	b. Must have a comfortable amount of room in the main space	Fairing
D	c. Must have enough room to account for a sliding seat	Fairing
W	d. Must protect the user from the elements	Fairing
	7.) Production	
D	a. Must have a smooth finish	Fairing
W	b. Can be remade using the same form	Fairing

Table F.9 Faring requirement justifications

Requirement	Justifications/Additional Notes
Geometry	
1a.	In order to fit through a doorway
1b.	Elastic bending and some scraping is acceptable, but a broken fairing is of no use
1c.	It must fit
Kinematics	
2a.	Warping under speed means that there is an increase of drag
2b.	If the fairing sways, the center of gravity changes and this could result in a loss of traction
2c.	For racing purposes, it would be much better to not have a fairing if the fairing is not very aerodynamic
Forces	
3a.	If the fairing breaks in such an event, there will be jagged edges, which is a safety issue
3b.	It could be made much more cheaply if PVC is lighter
3c.	Bumps and other such things will happen, and the fairing should be able to deal with that
Material	
4a.	This is necessary to meet other requirements
4b.	This is necessary to stay within our budget
4c.	It is quite possible that it gets damaged during transport or during the event
4d.	If it is too heavy, the gain from aerodynamics will be irrelevant in some cases
Safety	
5a.	We will not pass safety inspection with sharp edges
5b.	Even with the roll cage, flailing limbs could still come in contact with the road
5c.	This is pretty close to the minimum range for being able to deal with obstacles in front of the vehicle
5d.	This is necessary for safe operation
Ergonomics	
6a.	It would be very hinder some to have your knees or hands scraping against the fairing
6b.	It would be nice for people with slight claustrophobia, but not necessary
6c.	A sliding seat won't do much good if your head is pressed against the windscreen
6d.	To be practical for day to day use, this is necessary
Production	
7a.	Necessary for good aerodynamics
7b.	If it cracks rather badly, it may be more practical to remake it, and the foam for the form is rather expensive

Lastly, all the requirements were combined into a single requirements list for the overall system in table F.10 . The justifications for the requirements remained the same and thus that can be found in the previous tables. Justifications for requirements of the system as a whole are explained in table F.11. By combining the requirements from the subsystems into one requirements document, the students are given more insight to requirements that affect another subsystem. In other words, combining the requirements illustrates connectivity between the subsystems and highlights them through the requirement responsibility.

Table F.10 Example of HPV system requirements

ME 431 / HPVC (Class/Project)	Requirements List for HPV System	10/22/2015 (date)
D/W (Demand/Want)		Responsible
	1.) Geometry	Frame
D	a. Width must be less than 36 inches	Frame / Steering
W	b. Width must be less than 25 inches	Frame
W	c. Length must be less than 90 inches	Frame
W	d. Height must be less 36 inches	Frame
D	e. Normally a minimum of at least 6 inches above the ground	Frame / Steering
D	f. Fairing must fit over frame and roll bars	Frame / Fairing
D	g. Steering must fit inside fairing	Steering / Fairing
D	h. Steering must be proportional to frame	Steering / Frame
	2.) Kinematics	
D	a. Rigid during dynamic performance	Frame / Fairing
D	b. Stable during dynamic performance at high and low speeds	Frame / Fairing
D	c. Able to withstand dynamic forces	Frame
W	d. Able to account for different road conditions	Frame
W	e. Allows for improved control of the vehicle	Frame
W	f. Must not sway when cornering	Fairing
D	g. Having a fairing must show aerodynamic benefits	Fairing
D	h. Allows for desired range of motion	Steering / Frame
D	i. Able to maintain speed when countering obstacles	Steering/ Frame / Fairing
D	j. Able to maintain control when encountering obstacles	Steering
D	k. Allows for restrictions of range of motion in order to prevent accidents during potential loss of control	Steering

Table F.10 (Cont.)

ME 431 / HPVC (Class/Project)	Requirements List for HPV System	10/22/2015 (date)
D/W (Demand/Wish)		Responsible
	2.) Kinematics	
W	l. able to achieve desired turning radius in different environments	Steering
W	m. Able to perform under endurance high conditions without material wear or drivetrain slippage	Drivetrain
	3.) Forces	
D	a. Has a roll protection system capable of protecting rider from a 600lbs vertical force and a 300lb side force	Frame
W	b. Frame Weight is minimal	All
D	c. Strong enough to allow for human weight	Frame / Steering
D	d. Must remain intact after going over a speed bump	All
D	e. Controls should be easy to use	Steering
W	f. Must be resilient enough to not break if vehicle ends upside down or on its side	All
W	g. Fairing must weigh less than PVC equivalent	Fairing
D	h. Fairing must be strong enough not to break from someone leaning against it	Fairing
D	i. Included damping must prevent speed vibrations	Steering
D	j. Controls must be able to withstand pulling and pushing forces of the driver	Steering
	4.) Material	
D	a. Material is constant throughout	Frame
W	b. Material properties include appropriate stiffness for given application	Frame / Fairing / Steering
W	c. Materials used allow for manufacturability of various shapes/Use of tools	Frame / Steering
D	d. Allows for reworking and/or repairs	Frame / Fairing / Steering
W	e. Material must allow for lighter Design	Frame /Fairing
D	f. Remains relatively inexpensive	Frame / Fairing
	5.) Signals	
D	a. Has defined interaction points for steering linkage connections	Frame / Steering
D	b. Has a defined location and attachment process for wheels	Frame / Steering
D	c. Provides multiple places to attach fairing	Frame / Fairing
D	d. Frame allows space for drivetrain system	Frame / Drivetrain
W	e. Frame allows space for energy recovery system	Frame / Drivetrain
D	f. Frame allows adequate room for a seat	Frame
W	g. Frame allows adequate room for seat adjustments	Frame
D	h. Fairing and Steering system do not each other's ability	Fairing / Steering

Table F.10 (Cont.)

ME 431 / HPVC (Class/Project)	Requirements List for HPV System	10/22/2015 (date)
D/W (Demand/Wish)		Responsible
	6.) Safety	
D	a. Harness has a secure attachment to frame	Frame
D	b. Manufactured using safe methods	All
D	c. Allows for visibility of the road in front of the vehicle	Frame / Fairing
D	d. Allows for visibility of the road to both sides of the vehicle	Frame / Fairing
D	f. Allows for visibility of the road in behind the vehicle to some extent	Frame / Fairing
W	g. Allows user to fully see in all directions	Frame / Fairing
D	h. Eliminates sharp edges whereas possible	All
W	i. No Sharp Edges	All
D	j. Must protect the rider from abrasion if the vehicle lands on its side	Frame / Fairing
D	k. Brakes should be efficient enough for a safe stop	Steering
W	l. Restrictions put in place to prevent wheels from hurting driver	Steering
D	m. Prevents chain derailment	Drivetrain
D	n. Eliminates possibilities of snagging clothes and sharp contact with driver	Drivetrain
D	o. Reduces chance of vehicle failures	All
	7.) Ergonomics	
W	a. Seat for the user allows for maximum comfort	Frame
W	b. Seat for the user allows for varying angle	Frame
D	c. Seating position of the user allows for clear visibility of the road in front of them	Frame
W	d. Seat is adjustable for users between the heights of 5'0" to 6'5"	Frame / Fairing
D	e. Allows user easy access of entering and exiting	Frame
D	f. Allows for storage of various items	Frame
	7.) Ergonomics	
D	g. Fairing must not hinder pedaling	Fairing / Drivetrain
D	h. Fairing must not hinder steering	Fairing / Steering
W	i. Must have comfortable amount of room in sitting space	Fairing / Frame
W	j. Protects rider from the elements	Fairing
W	k. Provides enough elbow room to be comfort to steer	Steering / Frame / Fairing
	8.) Production	
D	a. Design allows for easier fabrication when possible	Frame
W	b. Uses standardization when possible	Frame

Table F.10 (Cont.)

ME 431 / HPVC (Class/Project)	Requirements List for HPV System	10/22/2015 (date)
D/W (Demand/Wish)		Responsible
	8.) Production	
W	c. Utilize current tooling	Frame
D	d. Use proper manufacturing methods to produce higher quality parts	Frame
W	e. Manufacturing methods used encourage repeatability	Frame
W	f. Has a smooth finish	Fairing
W	g. Fairing can be remade from the same molds	Fairing
W	h. Easily obtainable parts from given suppliers	All
	9.) Assembly	
W	a. Some components are be disassemble to allow for smaller storage	Frame
D	b. Can fit within a car in a given assembly state	Frame
W	c. Allows for modularity of various subsystems	All
W	d. Easily assembled and disassembled	Drivetrain
W	Minimizes the number of precision located required for assembly	All
	10.) Maintenance	
W	a. Allows for quick repairs	All
D	b. Minimizes repairs needed	All
	11.) Costs	
D	a. Costs less than $1000 to create structure	Frame
D	b. Costs less than $2000 to create fairing	Fairing
W	c. Costs less than $600 to create structure	Frame
W	d. Costs less than $1000 to create fairing	Fairing
D	e. Parts for wheels, drivetrain, and steering are less than $1500	Drivetrain / Steering
D	f. Required new tooling costs less than $2000	All
W	Inexpensive to produce per unit	All
	12.) Schedule	
W	a. Design must be completed by the end of January 2016	All
W	b. Vehicle excluding fairing must be manufactured by the end of February 2016	Frame / Steering / Drivetrain
W	c. Complete vehicle must be manufactured by the middle of March 2016	All
W	d. All testing must be finished by end of March 2016	All
D	e. Design report and all analysis must be completed by the beginning of April 2016	All

Table F.10 (Cont.)

ME 431 / HPVC (Class/Project)	Requirements List for HPV System	10/22/2015 (date)
D/W (Demand/Wish)		Responsible
	13.) Energy	
D	a. Energy recovery system, ERS, poses no threat to user at any speed	Drivetrain
W	b. ERS does not draw power from drivetrain	Drivetrain
D	c. ERS provides more power than it requires	Drivetrain
D	d. ERS output is on the same order of magnitude as the drivetrain's operational level of forces and energy	Drivetrain
D	e. Operates at a minimum efficiency of 80%	Drivetrain
W	f. No frivolous Power loss due to chain geometry	Drivetrain
D	g. Operates for high and low speeds and torques	Drivetrain
D	h. Provides reliable provide to driven wheel	Drivetrain
	14.) Transport	
W	a. Must fit within a van in fully assembled state	All
D	b. Must fit within a van an a assembled or partial disassembled state	All
W	c. Must be able to fit within a car	All

Table F.11 Justifications of new HPV System requirements

Requirement	Justifications/Additional Notes
Costs	
11b.	General conservative estimate with for spending based on research
11c.	General realistic estimate using smart purchases
11d.	General realistic estimate using smart purchases
11e.	General conservative estimate with for spending based on research
11f.	General conservative estimate with for spending based on research. Also limits some unnecessary spending
Schedule	
12a.	General timeframe of when tasks should be completed
12b.	General timeframe of when tasks should be completed
12c.	General timeframe of when tasks should be completed. Also vehicle must be complete for competition by May. This would also allow for some time to complete testing
12d.	General timeframe of when tasks should be completed
12e.	Required timeline guide by ASME
Transport	
14a.	Team will be using a van to travel to competition
14b.	Team will be using a van to travel to competition

APPENDIX G: EXAMPLES OF HPV CONCEPT GENERATION

The following are the various subsystem designs created by students working on the 2016 HPV design for Clemson. The students involve range from freshmen undergraduate students to graduate students.

G.1 Frame Concepts Created Using Brainwriting

The following is a sample of the some of the frame concepts generated. Table G.1 provides brief descriptions to each of the concepts. All of the frame concepts were made for tadpole tricycle design, because that type of vehicle was predetermined in the design process.

Table G.1 Description of frame concepts

Concept Acronyms	Acronym Meaning	Brief description/Notes
ASDM	Asymmetric design with two main members	Idea of making is easier for the rider to enter/exit from one side.
CRCF	Curved RPS and curved front piece	Shaped for front collision and fairing attachments
DMFS	Double main members in addition to a main member, accompanied by a suspension system	Idea on incorporating seat into main members of "RPS". Main member is used primarily to connect front and back wheels.
DMOR	Dual main members with an open roll cage	
FSDM	Full suspension with double main members	
FSMR	Full suspension, missing roll cage	
RFSR	Rounded front supporting roll Cage	Has a roll cage also used for flexing support and fairing attachments. Round Front is used to add ability to attach aspects of the fairing and provide collision protection.

Table G.1 (Cont.)

Concept Acronyms	Acronym Meaning	Brief description/Notes
SMCR	Single member covered roll cage.	Idea of one main member and a roll cage that completely surrounding the person. Has multiple supports for rigidity)
SMOR	Single member with an open roll cage	Also include a front bumper for fairing attachments and collision protection.
SMRR	Single member rigid roll cage	Idea of making the roll cage multiple parts to stop the frame from flexing, while having one main member for the majority of the connection of the front and back wheels.
TRHF	"Triangular" roll cage higher frame	Longer wheelbase based on crank position

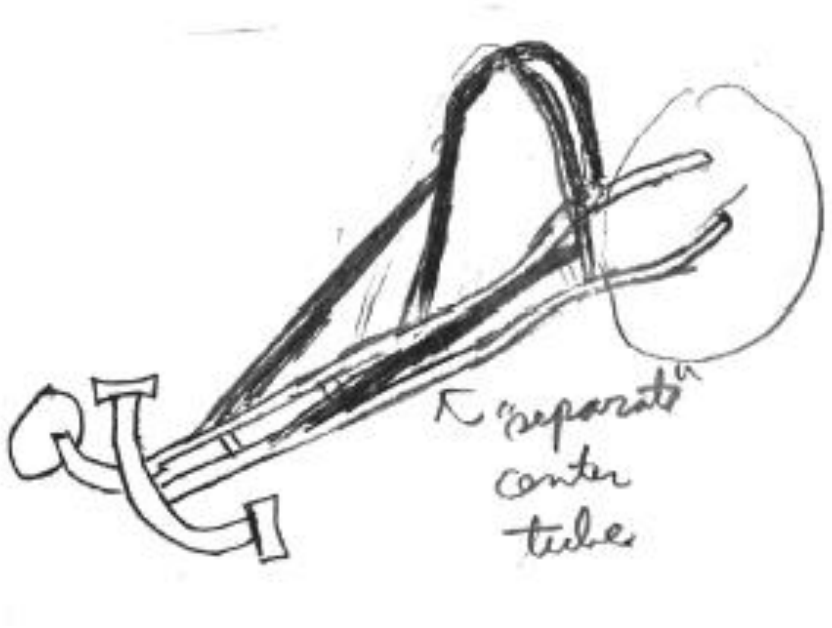


Figure G.1 Frame concept 1: ASDM

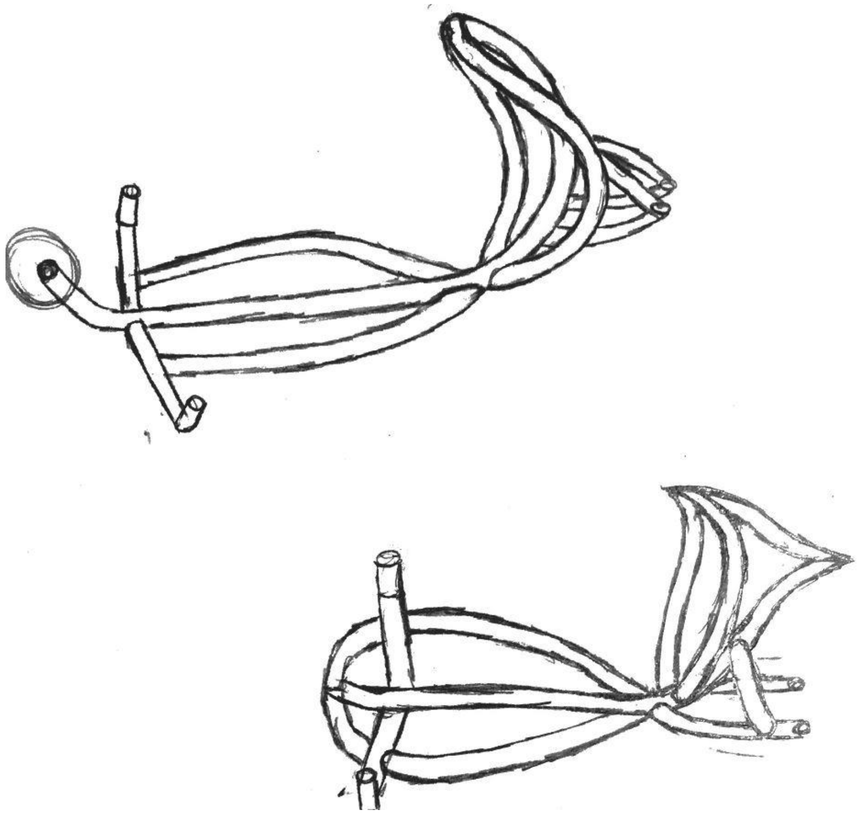


Figure G.2 Frame concept 2: CRCF

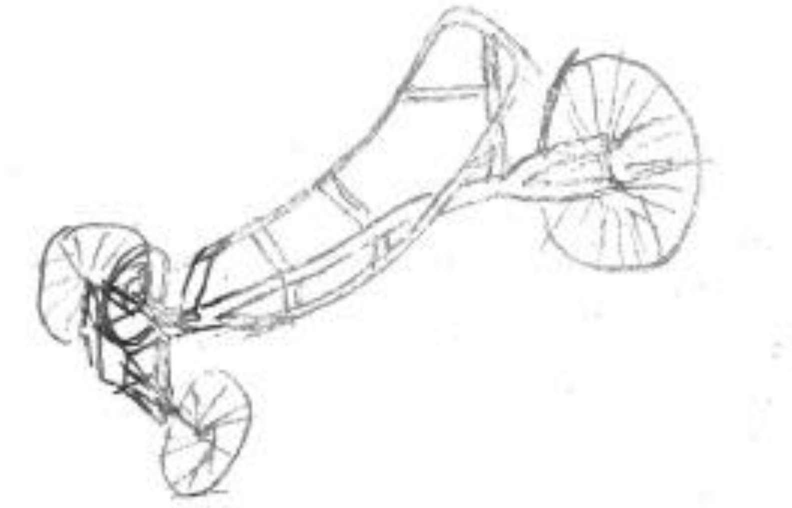


Figure G.3 Frame concept 3: DMFS

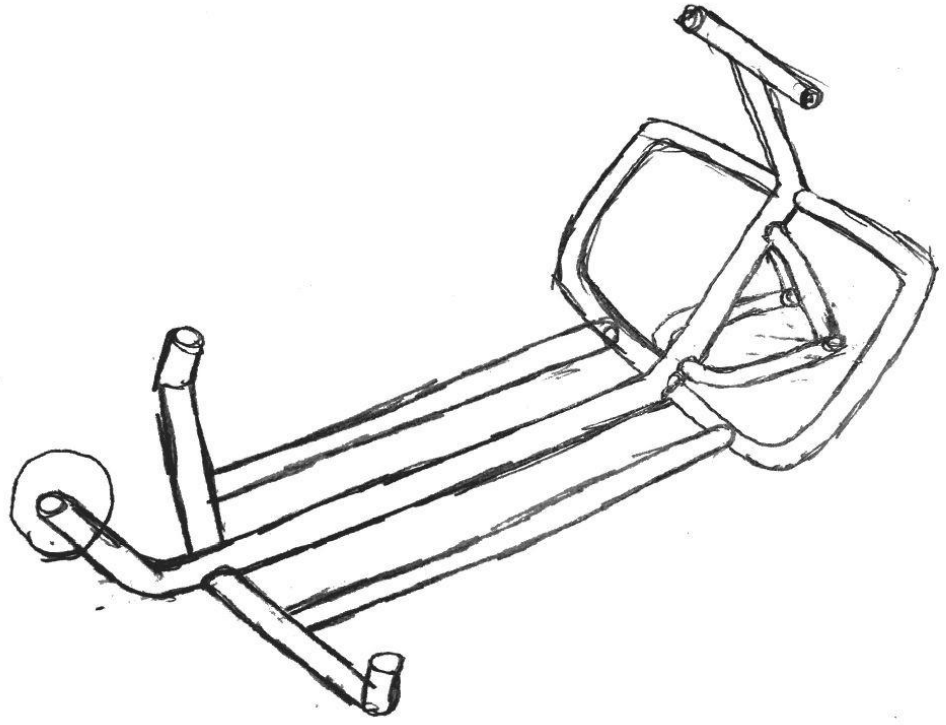


Figure G.4 Frame concept 4: DMOR

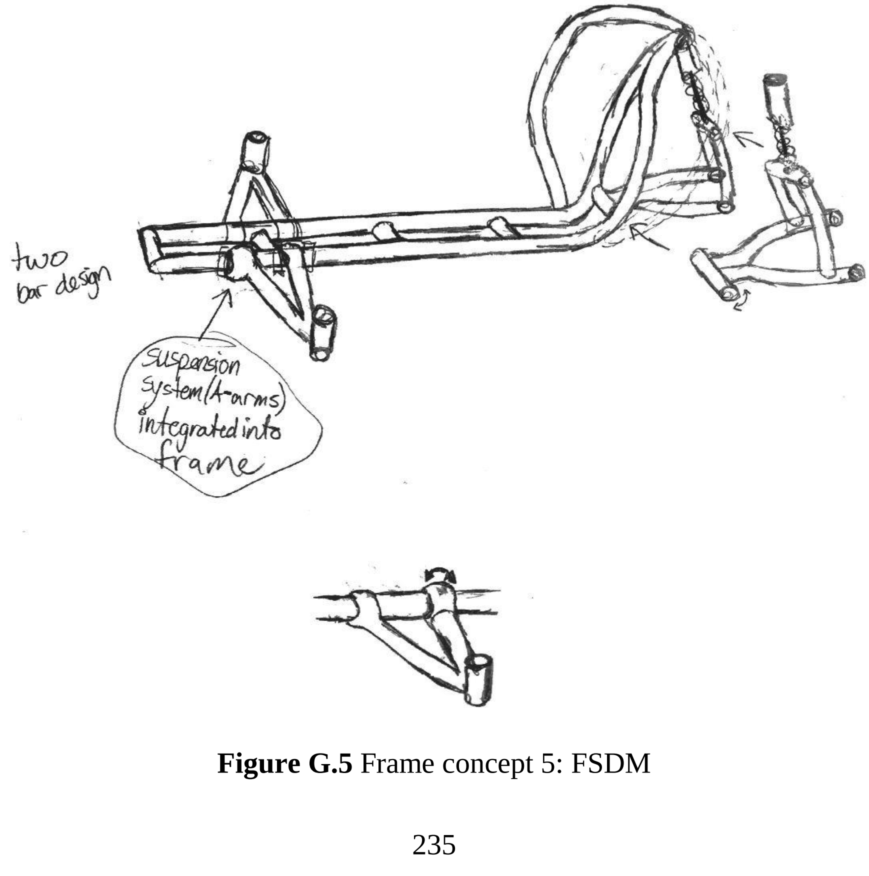


Figure G.5 Frame concept 5: FSDM

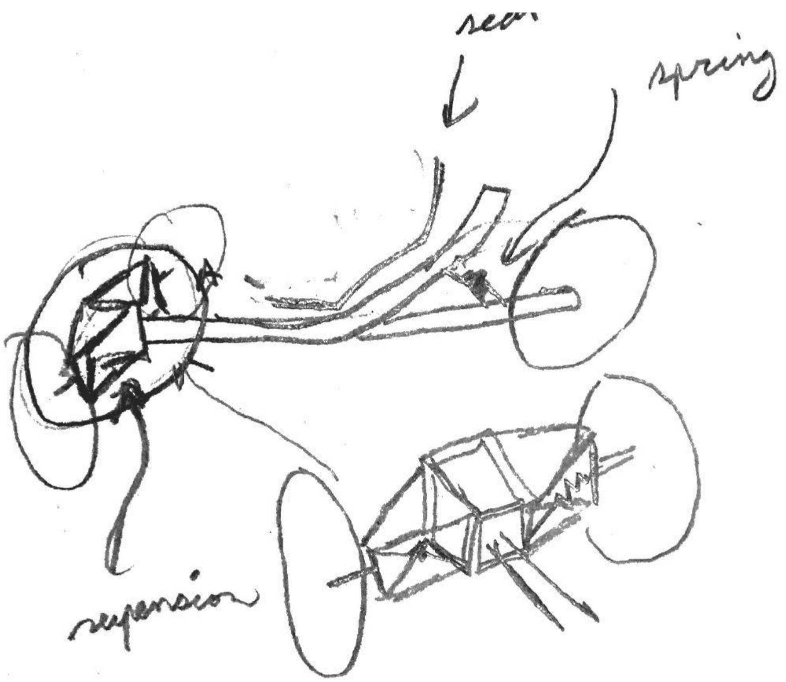


Figure G.6 Frame concept 6: FSMR

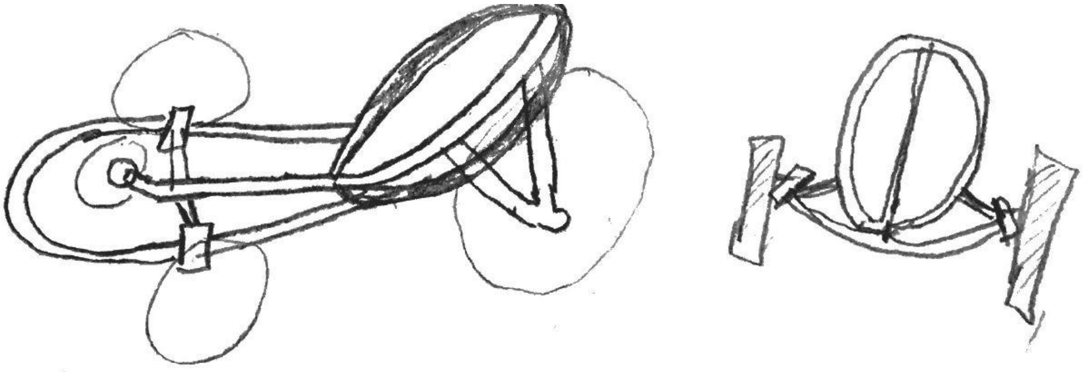


Figure G.7 Frame concept 7: RFSR

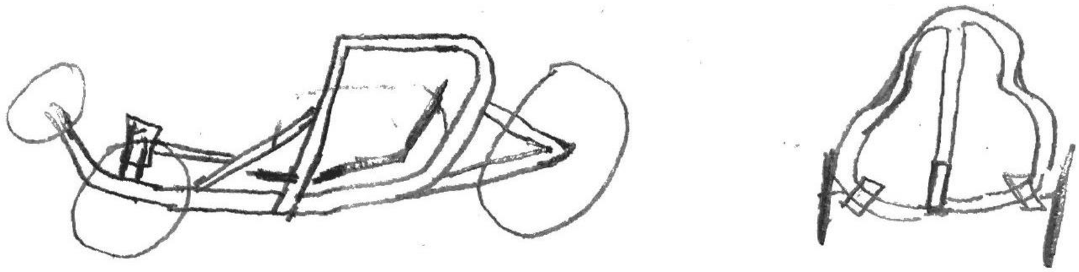


Figure G.8 Frame concept 8: SMCR

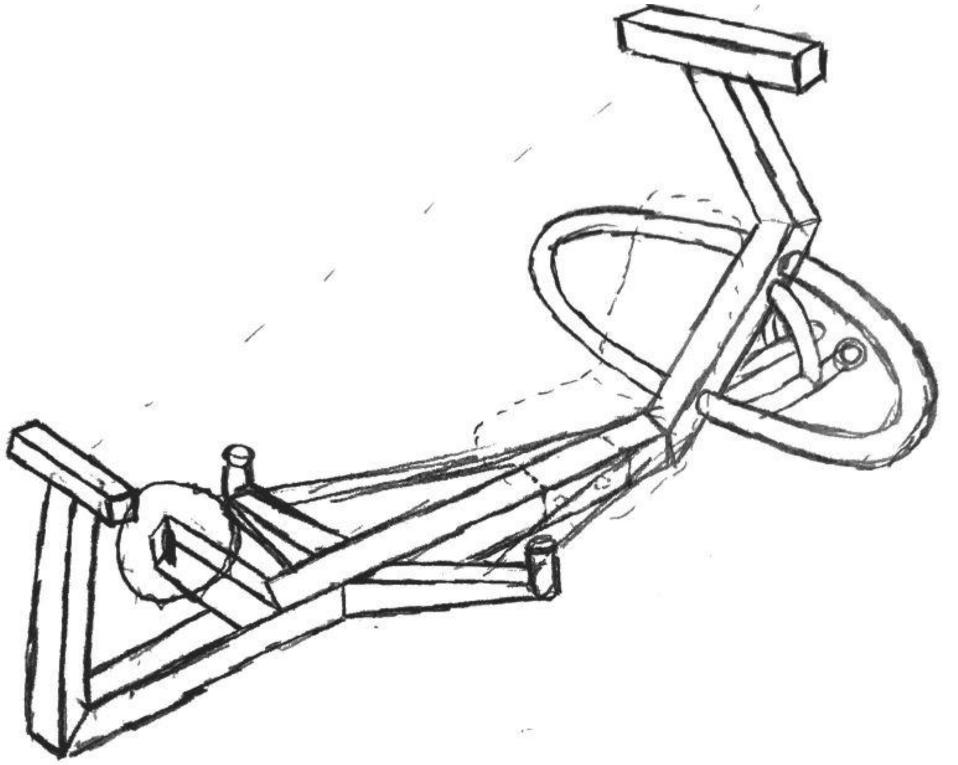


Figure G.9 Frame concept 9: SMOR

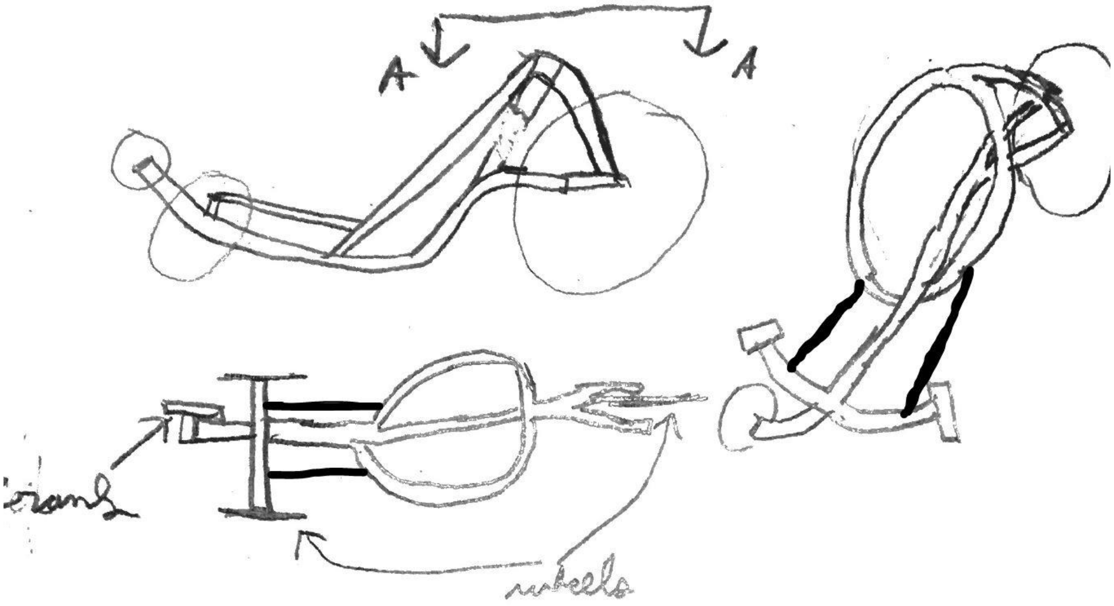


Figure G.10 Frame concept 10: SMRR

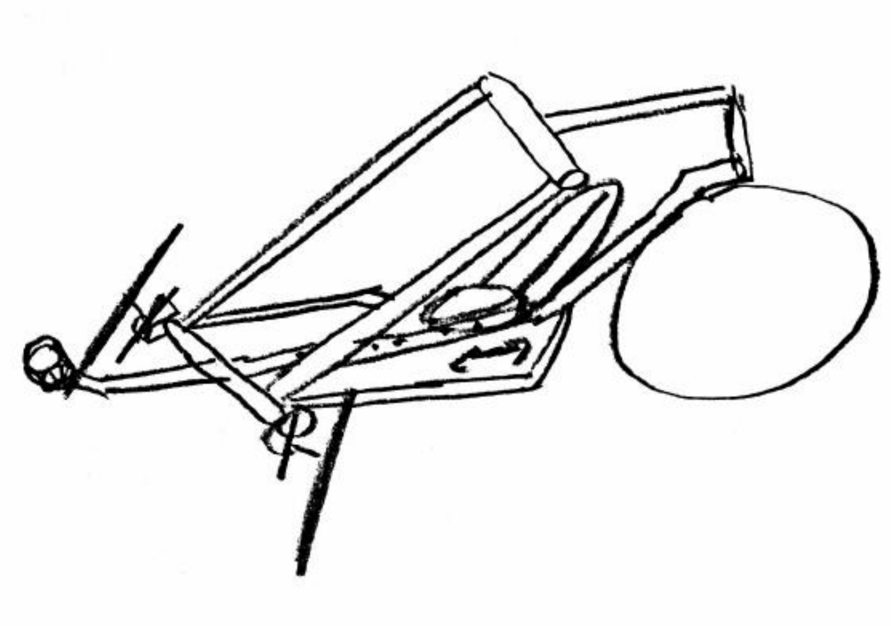


Figure G.11 Frame concept 11: TRHF

G.2 Steering Concepts Created Using Brainwriting

Table G.2 Description of steering concepts

Concept Acronyms	Acronym Meaning	Brief description/Notes
DKSS	Direct knuckle steering	Stems are attached directly to head tubes for simple and effect steering system
JSSS	Joysticks steering system	Joysticks are rotated by rider. The joysticks then control the rotation of the wheels through a system of linked tie rods.
SBOS	Straight bar over steering	Similar to joysticks setup but the controls are rotated about the main member and less linkages are need. Rotation may be difficult to create.
UBUS	U-bar under seat steering	A drag link system is used to connection a U-bar to the wheel rotation. The U-bar rotates in the same direction as the waist of the rider.
SWSS	Steering wheel steering system	Steering system uses a steering wheel configuration to control the rotation of the wheels.

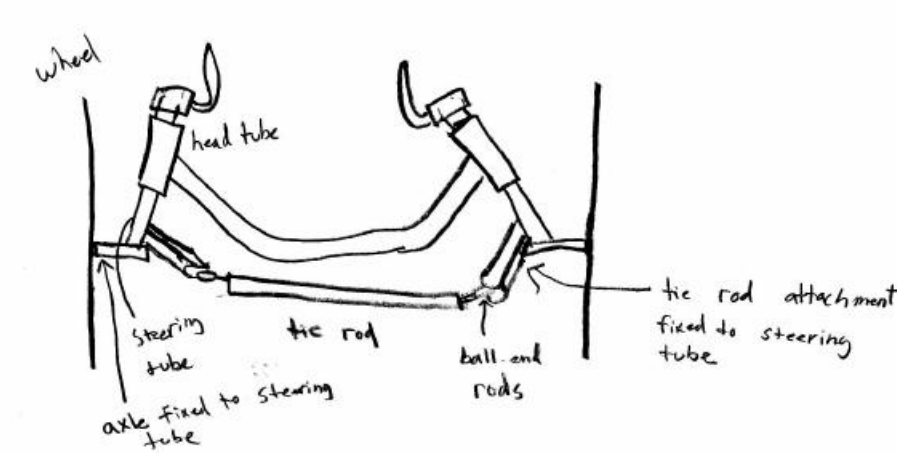


Figure G.12 Steering concept 1: DKSS

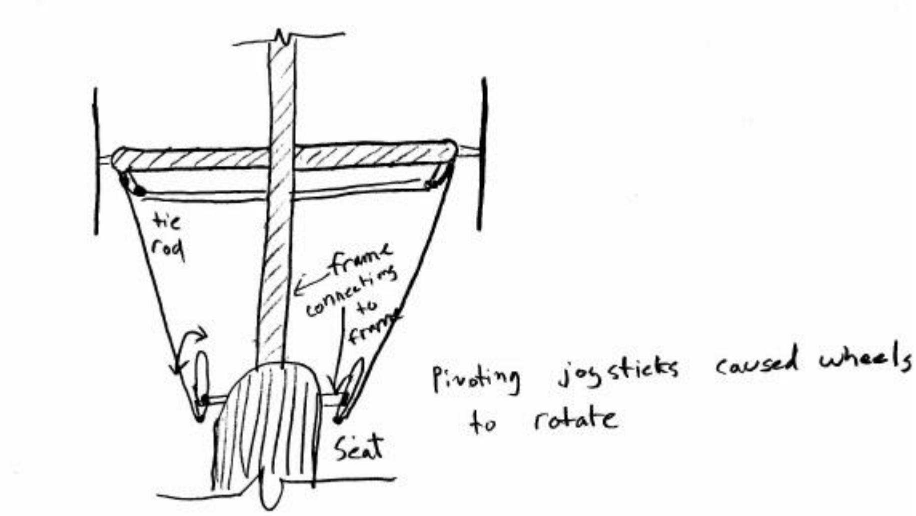


Figure G.13 Steering concept 2: JSSS

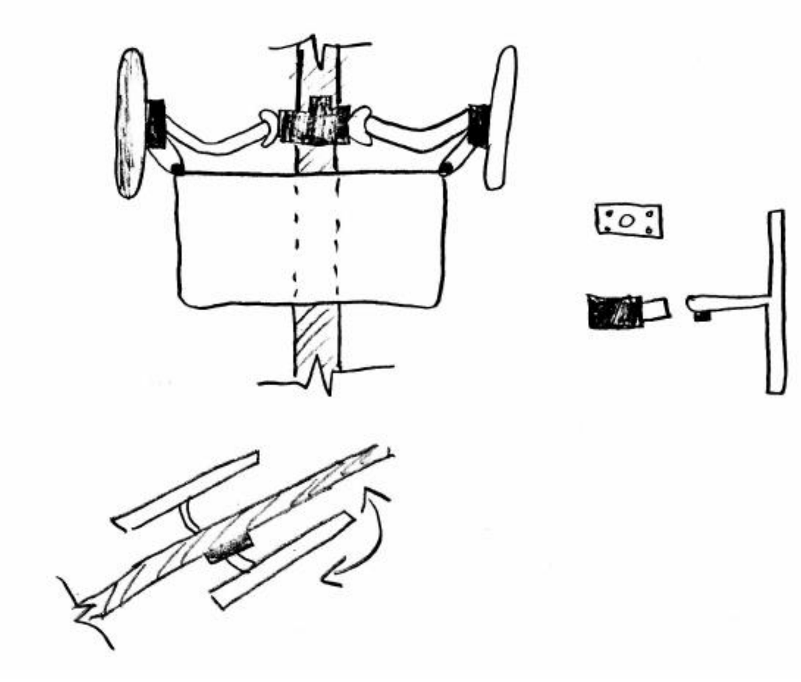


Figure G.14 Steering concept 2: SBOS

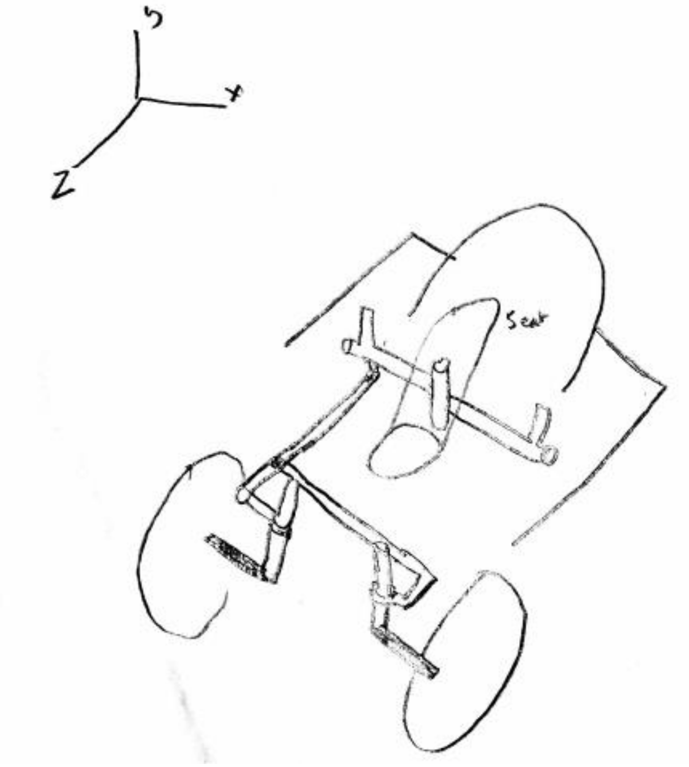


Figure G.15 Steering concept 4: UBUS

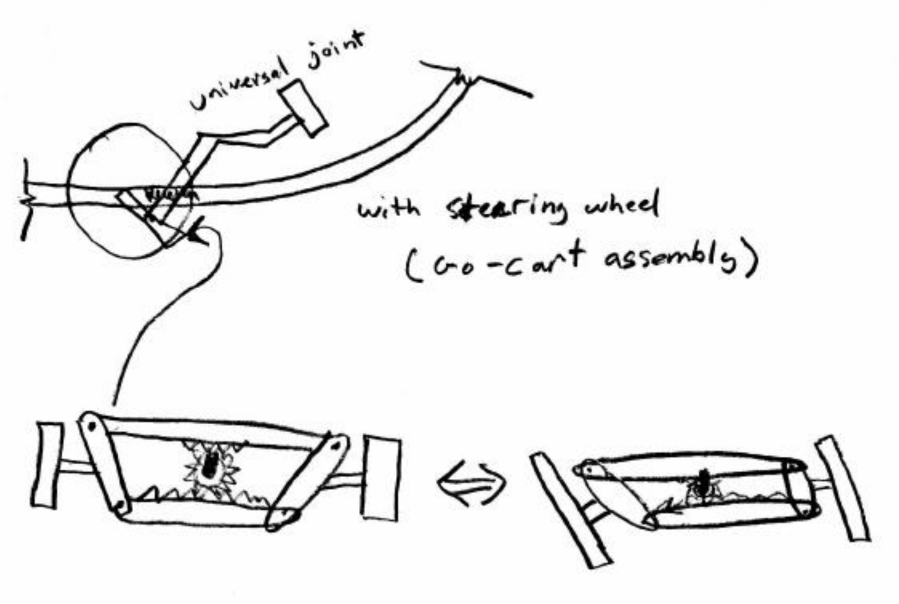


Figure G.16 Steering concept 4: SWSS

G.3 Drivetrain Concepts Using Brainwriting

Table G.3 Description of drivetrain concepts with energy recovery

Concept Acronyms	Acronym Meaning	Brief description/Notes
FWER	Fly wheel energy recovery system	Is a drivetrain system for transferring energy from the front of the rear wheel and includes a dampened flywheel system for energy recovery for braking. The flywheel is engaged by using a clutch system incorporated into the brake.
SPER	Solar panel for energy recovery	A solar panel, battery and motor would be added to a drivetrain system for additional energy recovery
PEMR	Piezo electric energy recovery	Idea of adding piezo-electric materials to a suspension system to recover voltage from the dampening of the suspension. Would require a motor and battery to make full use of it.
RBSO	Regenerative braking system one	Adding a regenerative braking system to the front brakes to recover energy when braking
RBST	Regenerative braking system two	Adding a regenerative braking system to the rear brakes to recover energy when braking. When used with a design the uses only front disc brakes this method allows for additional brakes that also supply energy.

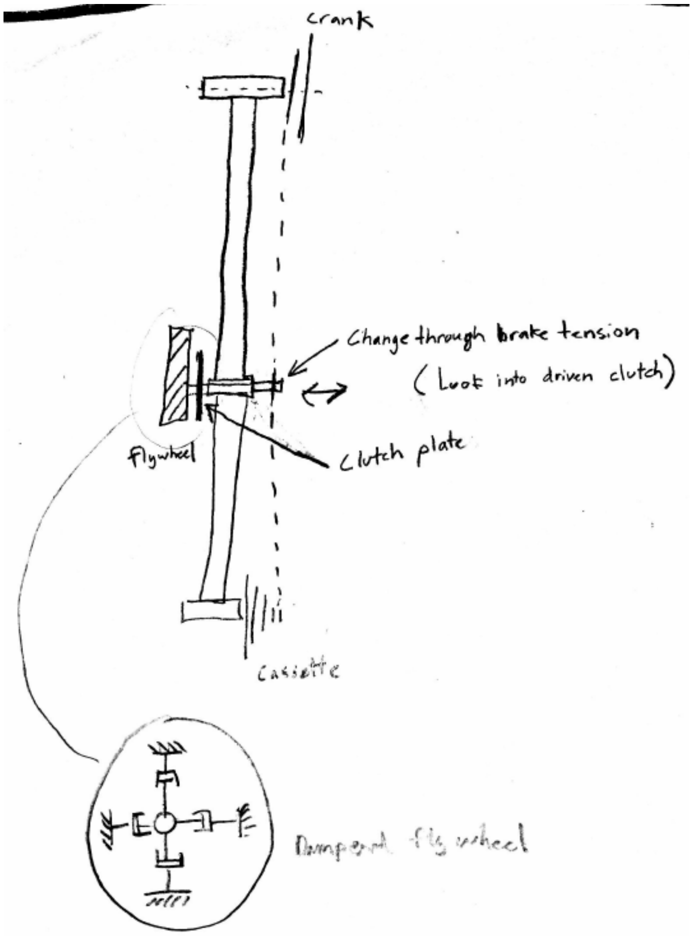


Figure G.17 Energy recovery drivetrain concept 1: FWER

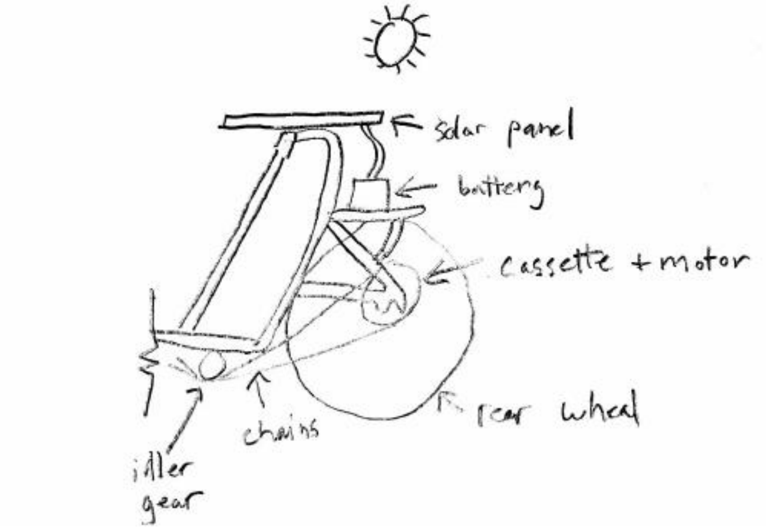


Figure G.18 Energy recovery drivetrain concept 1: SPER

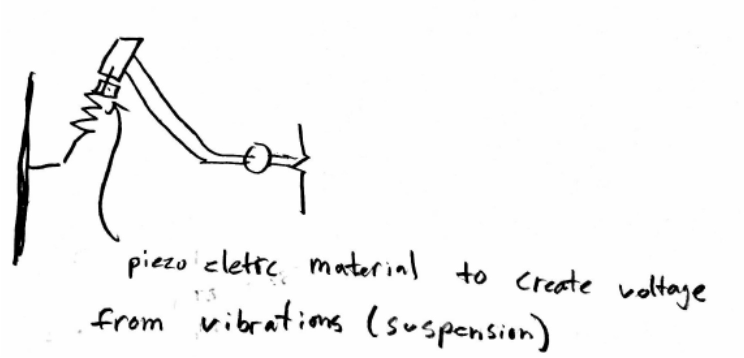


Figure G.19 Energy recovery drivetrain concept 1: PEMR

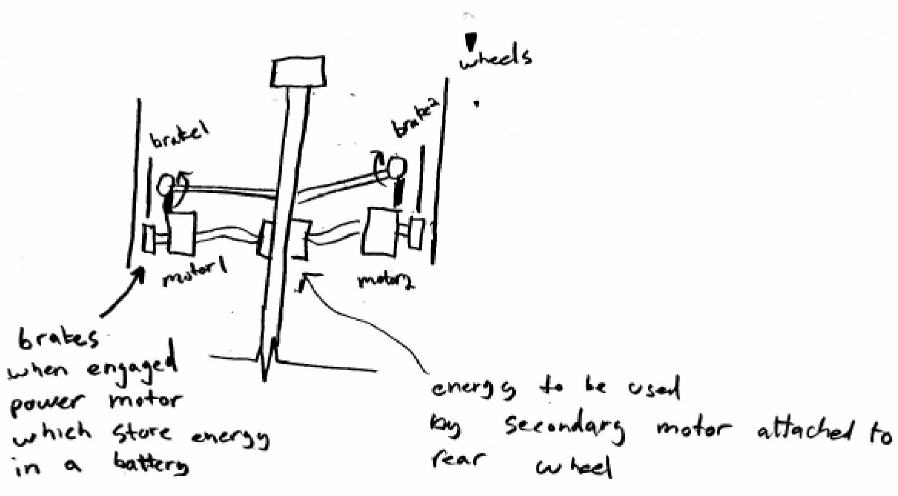


Figure G.20 Energy recovery drivetrain concept 1: RBSO

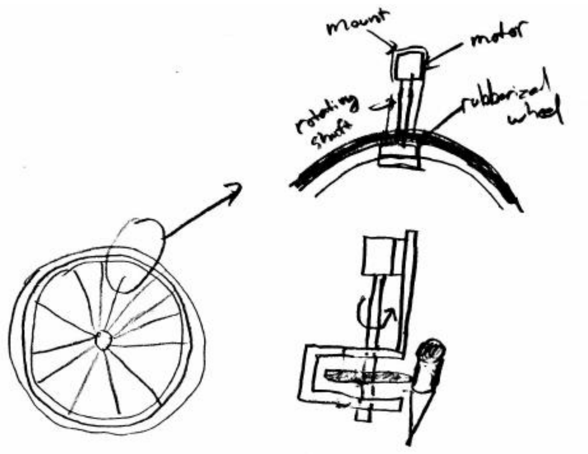


Figure G.21 Energy recovery drivetrain concept 1: RBST

Table G.4 Description of drivetrain concepts with energy recovery without energy recovery

IGDS	Idler gear drivetrain system	Single chain used in combination with idler gears to transfer rider power to rear wheel. Idler gears help define the chain path
SCCT	Single chain with chain tubing	Similar to IDGS, but chain tubing is used to control chain slack and reduce the number of idler gears needed.
DCJS	Dual chain and jack shaft	A jack shaft is used to simplify the chain paths and lower the chain length require for each chain path.

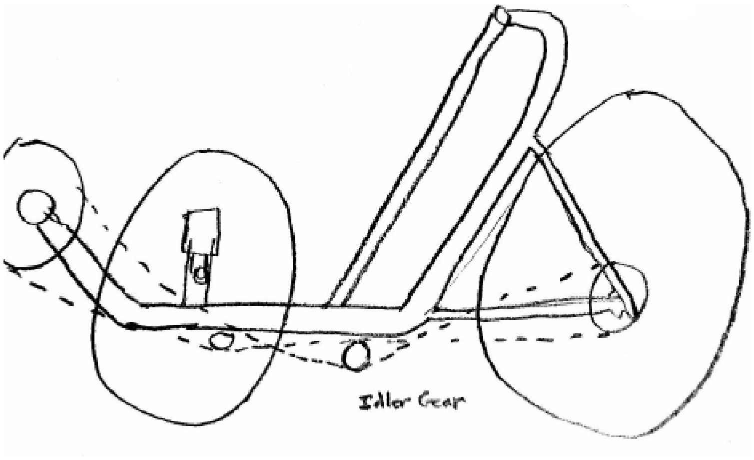


Figure G.22 Non-energy recovery drivetrain concept 1: IGDS

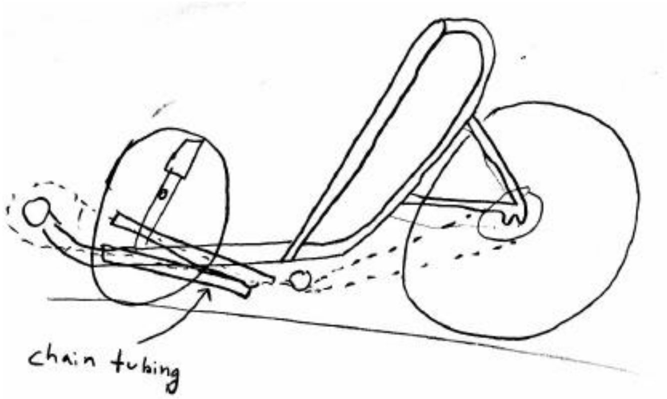


Figure G.23 Non-energy recovery drivetrain concept 2: SCCT

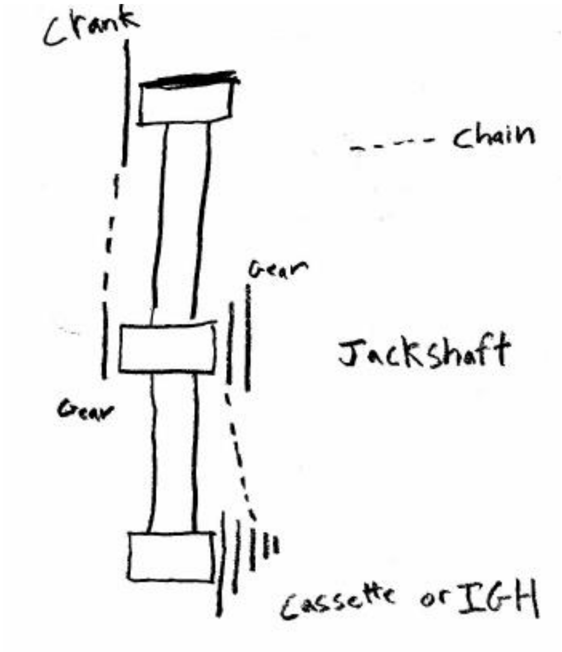


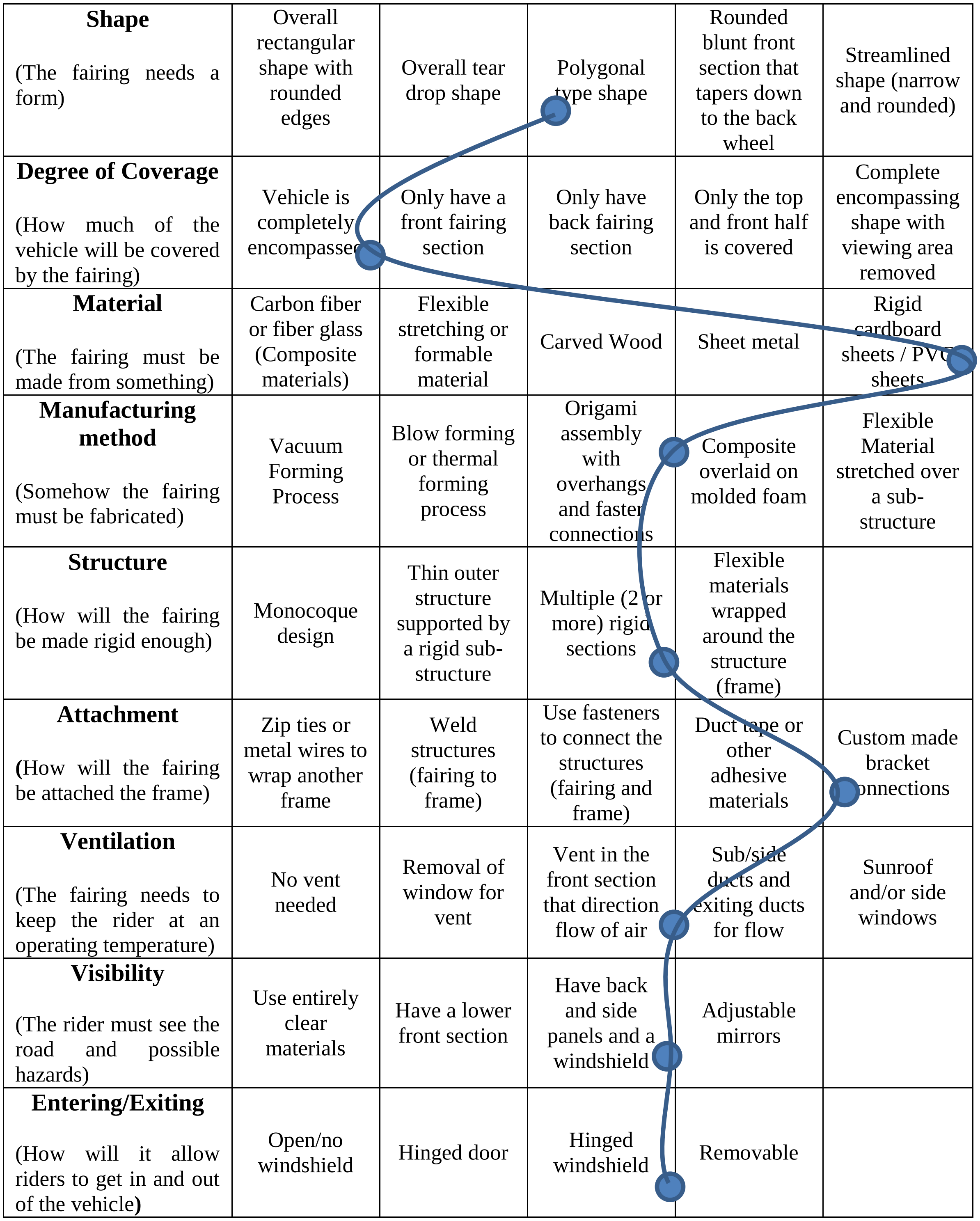
Figure G.24 Non-energy recovery drivetrain concept 3: DCJS

G.4 Fairing Concepts Created Using Morphological Analysis

Table G.5 Morph Chart created for fairing morphological analysis

Shape (The fairing needs a form)	Overall rectangular shape with rounded edges	Overall tear drop shape	Polygonal type shape	Rounded blunt front section that tapers down to the back wheel	Streamlined shape (narrow and rounded)
Degree of Coverage (How much of the vehicle will be covered by the fairing)	Vehicle is completely encompassed	Only have a front fairing section	Only have back fairing section	Only the top and front half is covered	Complete encompassing shape with viewing area removed
Material (The fairing must be made from something)	Carbon fiber or fiber glass (Composite materials)	Flexible stretching or formable material	Carved Wood	Sheet metal	Rigid cardboard sheets / PVC sheets
Manufacturing method (Somehow the fairing must be fabricated)	Vacuum Forming Process	Blow forming or thermal forming process	Origami assembly with overhangs and faster connections	Composite overlaid on molded foam	Flexible Material stretched over a sub-structure
Structure (How will the fairing be made rigid enough)	Monocoque design	Thin outer structure supported by a rigid sub-structure	Multiple (2 or more) rigid sections	Flexible materials wrapped around the structure (frame)	
Attachment **(**How will the fairing be attached the frame)	Zip ties or metal wires to wrap another frame	Weld structures (fairing to frame)	Use fasteners to connect the structures (fairing and frame)	Duct tape or other adhesive materials	Custom made bracket connections
Ventilation (The fairing needs to keep the rider at an operating temperature)	No vent needed	Removal of window for vent	Vent in the front section that direction flow of air	Sub/side ducts and exiting ducts for flow	Sunroof and/or side windows
Visibility (The rider must see the road and possible hazards)	Use entirely clear materials	Have a lower front section	Have back and side panels and a windshield	Adjustable mirrors	
Entering/Exiting (How will it allow riders to get in and out of the vehicle**)**	Open/no windshield	Hinged door	Hinged windshield	Removable	

Table G.6 Fairing concept 1 from morph chart: FFPS

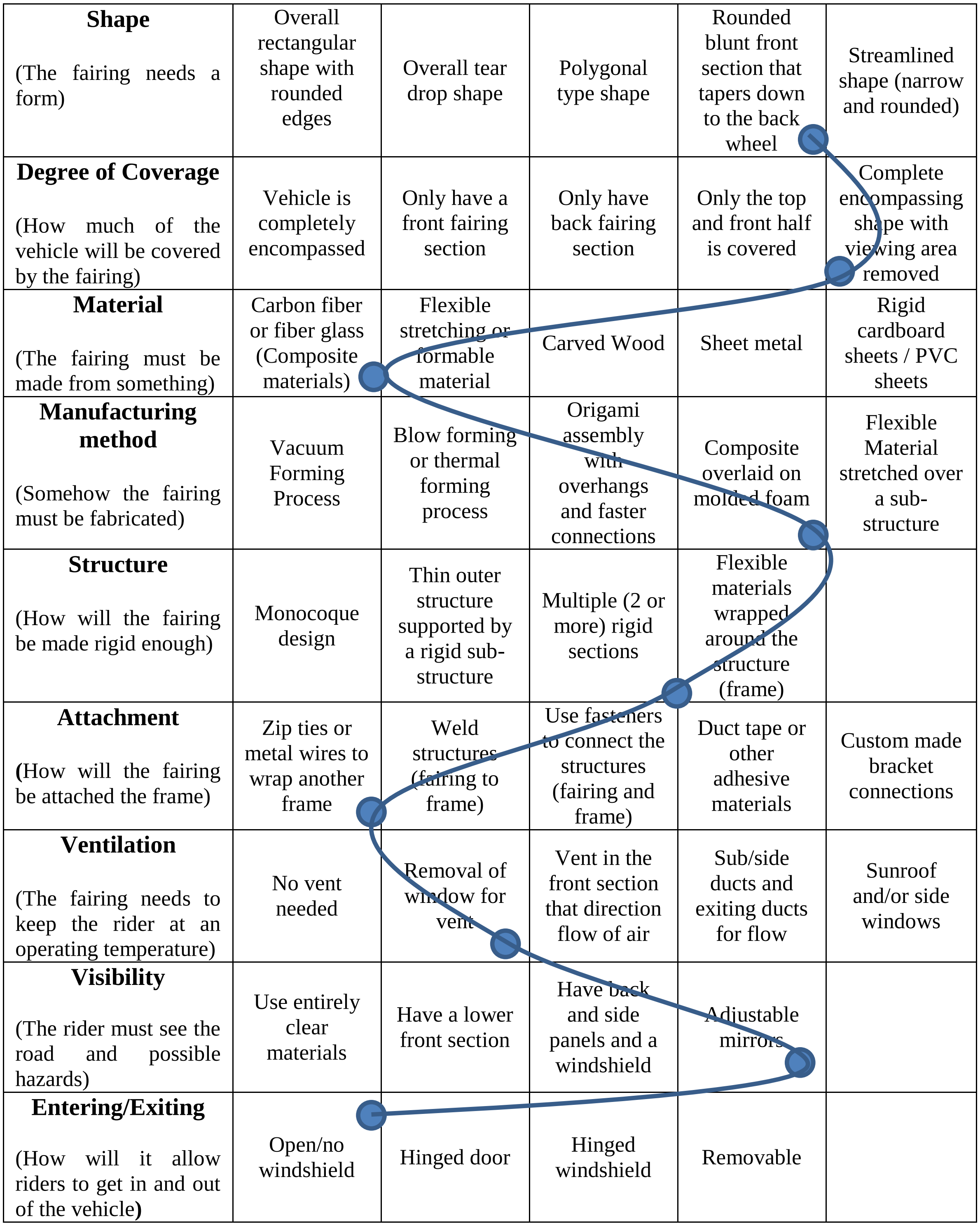


Shape (The fairing needs a form)	Overall rectangular shape with rounded edges	Overall tear drop shape	Polygonal type shape	Rounded blunt front section that tapers down to the back wheel	Streamlined shape (narrow and rounded)
Degree of Coverage (How much of the vehicle will be covered by the fairing)	Vehicle is completely encompassed	Only have a front fairing section	Only have back fairing section	Only the top and front half is covered	Complete encompassing shape with viewing area removed
Material (The fairing must be made from something)	Carbon fiber or fiber glass (Composite materials)	Flexible stretching or formable material	Carved Wood	Sheet metal	Rigid cardboard sheets / PVC sheets
Manufacturing method (Somehow the fairing must be fabricated)	Vacuum Forming Process	Blow forming or thermal forming process	Origami assembly with overhangs and faster connections	Composite overlaid on molded foam	Flexible Material stretched over a sub-structure
Structure (How will the fairing be made rigid enough)	Monocoque design	Thin outer structure supported by a rigid sub-structure	Multiple (2 or more) rigid sections	Flexible materials wrapped around the structure (frame)	
Attachment (How will the fairing be attached the frame)	Zip ties or metal wires to wrap another frame	Weld structures (fairing to frame)	Use fasteners to connect the structures (fairing and frame)	Duct tape or other adhesive materials	Custom made bracket connections
Ventilation (The fairing needs to keep the rider at an operating temperature)	No vent needed	Removal of window for vent	Vent in the front section that direction flow of air	Sub/side ducts and exiting ducts for flow	Sunroof and/or side windows
Visibility (The rider must see the road and possible hazards)	Use entirely clear materials	Have a lower front section	Have back and side panels and a windshield	Adjustable mirrors	
Entering/Exiting (How will it allow riders to get in and out of the vehicle**)**	Open/no windshield	Hinged door	Hinged windshield	Removable	

Table G.7 Fairing concept 2 from morph chart: BTFB

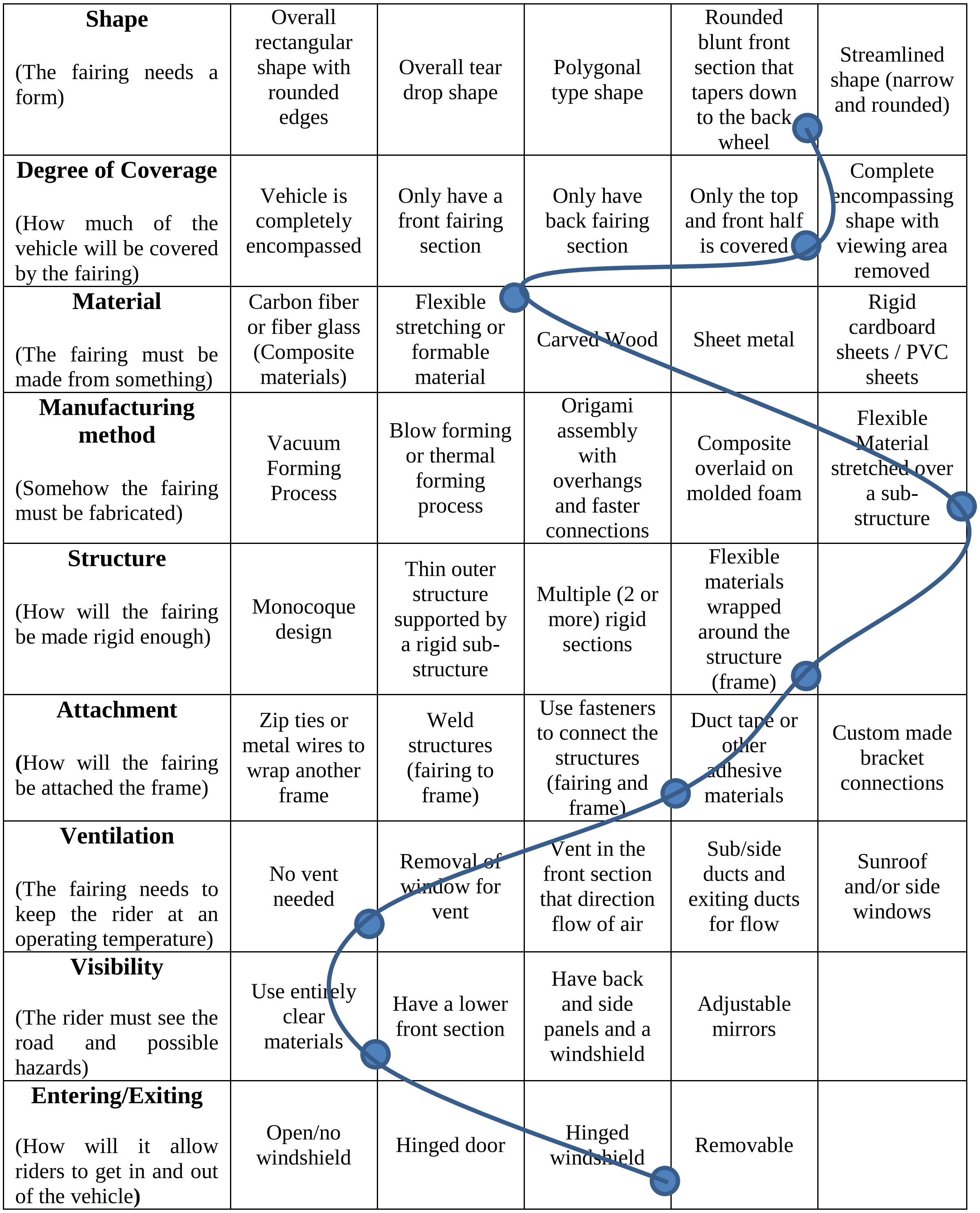
Shape (The fairing needs a form)	Overall rectangular shape with rounded edges	[✓ Overall tear drop shape]	Polygonal type shape	Rounded blunt front section that tapers down to the back wheel	Streamlined shape (narrow and rounded)
Degree of Coverage (How much of the vehicle will be covered by the fairing)	[✓ Vehicle is completely encompassed]	Only have a front fairing section	Only have back fairing section	Only the top and front half is covered	Complete encompassing shape with viewing area removed
Material (The fairing must be made from something)	Carbon fiber or fiber glass (Composite materials)	[✓ Flexible stretching or formable material]	Carved Wood	Sheet metal	Rigid cardboard sheets / PVC sheets
Manufacturing method (Somehow the fairing must be fabricated)	Vacuum Forming Process	[✓ Blow forming or thermal forming process]	Origami assembly with overhangs and faster connections	Composite overlaid on molded foam	Flexible Material stretched over a sub-structure
Structure (How will the fairing be made rigid enough)	[✓ Monocoque design]	Thin outer structure supported by a rigid sub-structure	Multiple (2 or more) rigid sections	Flexible materials wrapped around the structure (frame)	
Attachment **(**How will the fairing be attached the frame)	Zip ties or metal wires to wrap another frame	Weld structures (fairing to frame)	Use fasteners to connect the structures (fairing and frame)	Duct tape or other adhesive materials	[✓ Custom made bracket connections]
Ventilation (The fairing needs to keep the rider at an operating temperature)	[✓ No vent needed]	Removal of window for vent	Vent in the front section that direction flow of air	Sub/side ducts and exiting ducts for flow	Sunroof and/or side windows
Visibility (The rider must see the road and possible hazards)	[✓ Use entirely clear materials]	Have a lower front section	Have back and side panels and a windshield	Adjustable mirrors	
Entering/Exiting (How will it allow riders to get in and out of the vehicle**)**	Open/no windshield	Hinged door	Hinged windshield	[✓ Removable]	

Table G.8 Fairing concept 3 from morph chart: MPCF



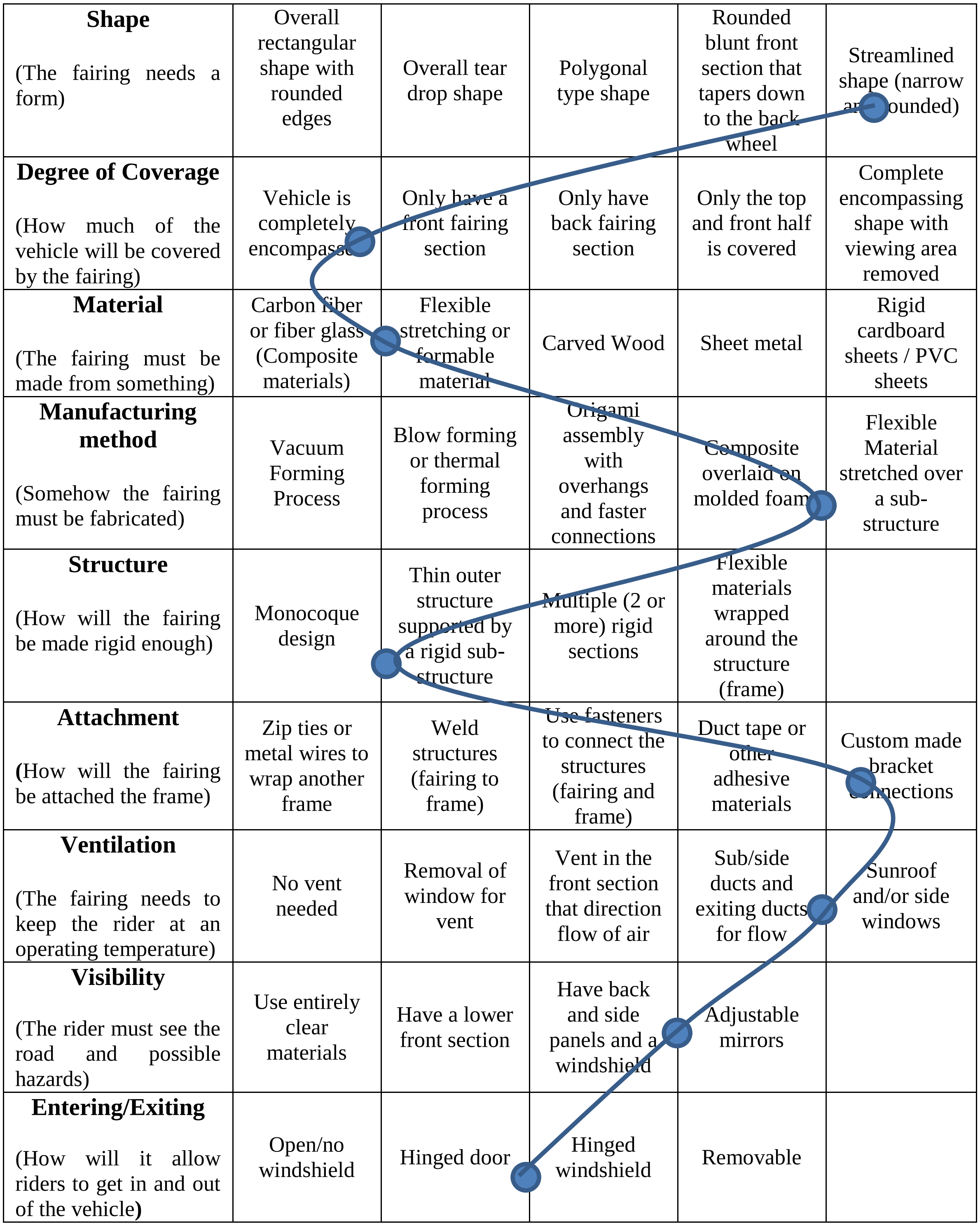
Shape (The fairing needs a form)	Overall rectangular shape with rounded edges	Overall tear drop shape	Polygonal type shape	Rounded blunt front section that tapers down to the back wheel	Streamlined shape (narrow and rounded)
Degree of Coverage (How much of the vehicle will be covered by the fairing)	Vehicle is completely encompassed	Only have a front fairing section	Only have back fairing section	Only the top and front half is covered	Complete encompassing shape with viewing area removed
Material (The fairing must be made from something)	Carbon fiber or fiber glass (Composite materials)	Flexible stretching or formable material	Carved Wood	Sheet metal	Rigid cardboard sheets / PVC sheets
Manufacturing method (Somehow the fairing must be fabricated)	Vacuum Forming Process	Blow forming or thermal forming process	Origami assembly with overhangs and faster connections	Composite overlaid on molded foam	Flexible Material stretched over a sub-structure
Structure (How will the fairing be made rigid enough)	Monocoque design	Thin outer structure supported by a rigid sub-structure	Multiple (2 or more) rigid sections	Flexible materials wrapped around the structure (frame)	
Attachment **(**How will the fairing be attached the frame)	Zip ties or metal wires to wrap another frame	Weld structures (fairing to frame)	Use fasteners to connect the structures (fairing and frame)	Duct tape or other adhesive materials	Custom made bracket connections
Ventilation (The fairing needs to keep the rider at an operating temperature)	No vent needed	Removal of window for vent	Vent in the front section that direction flow of air	Sub/side ducts and exiting ducts for flow	Sunroof and/or side windows
Visibility (The rider must see the road and possible hazards)	Use entirely clear materials	Have a lower front section	Have back and side panels and a windshield	Adjustable mirrors	
Entering/Exiting (How will it allow riders to get in and out of the vehicle**)**	Open/no windshield	Hinged door	Hinged windshield	Removable	

Table G.9 Fairing concept 4 from morph chart: EPWP



Shape (The fairing needs a form)	Overall rectangular shape with rounded edges	Overall tear drop shape	Polygonal type shape	Rounded blunt front section that tapers down to the back wheel	Streamlined shape (narrow and rounded)
Degree of Coverage (How much of the vehicle will be covered by the fairing)	Vehicle is completely encompassed	Only have a front fairing section	Only have back fairing section	Only the top and front half is covered	Complete encompassing shape with viewing area removed
Material (The fairing must be made from something)	Carbon fiber or fiber glass (Composite materials)	Flexible stretching or formable material	Carved Wood	Sheet metal	Rigid cardboard sheets / PVC sheets
Manufacturing method (Somehow the fairing must be fabricated)	Vacuum Forming Process	Blow forming or thermal forming process	Origami assembly with overhangs and faster connections	Composite overlaid on molded foam	Flexible Material stretched over a sub-structure
Structure (How will the fairing be made rigid enough)	Monocoque design	Thin outer structure supported by a rigid sub-structure	Multiple (2 or more) rigid sections	Flexible materials wrapped around the structure (frame)	
Attachment **(**How will the fairing be attached the frame)	Zip ties or metal wires to wrap another frame	Weld structures (fairing to frame)	Use fasteners to connect the structures (fairing and frame)	Duct tape or other adhesive materials	Custom made bracket connections
Ventilation (The fairing needs to keep the rider at an operating temperature)	No vent needed	Removal of window for vent	Vent in the front section that direction flow of air	Sub/side ducts and exiting ducts for flow	Sunroof and/or side windows
Visibility (The rider must see the road and possible hazards)	Use entirely clear materials	Have a lower front section	Have back and side panels and a windshield	Adjustable mirrors	
Entering/Exiting (How will it allow riders to get in and out of the vehicle**)**	Open/no windshield	Hinged door	Hinged windshield	Removable	

Table G.10 Fairing concept 5 from morph chart: SFFV



Shape (The fairing needs a form)	Overall rectangular shape with rounded edges	Overall tear drop shape	Polygonal type shape	Rounded blunt front section that tapers down to the back wheel	Streamlined shape (narrow and rounded)
Degree of Coverage (How much of the vehicle will be covered by the fairing)	Vehicle is completely encompassed	Only have a front fairing section	Only have back fairing section	Only the top and front half is covered	Complete encompassing shape with viewing area removed
Material (The fairing must be made from something)	Carbon fiber or fiber glass (Composite materials)	Flexible stretching or formable material	Carved Wood	Sheet metal	Rigid cardboard sheets / PVC sheets
Manufacturing method (Somehow the fairing must be fabricated)	Vacuum Forming Process	Blow forming or thermal forming process	Origami assembly with overhangs and faster connections	Composite overlaid on molded foam	Flexible Material stretched over a sub-structure
Structure (How will the fairing be made rigid enough)	Monocoque design	Thin outer structure supported by a rigid sub-structure	Multiple (2 or more) rigid sections	Flexible materials wrapped around the structure (frame)	
Attachment **(**How will the fairing be attached the frame)	Zip ties or metal wires to wrap another frame	Weld structures (fairing to frame)	Use fasteners to connect the structures (fairing and frame)	Duct tape or other adhesive materials	Custom made bracket connections
Ventilation (The fairing needs to keep the rider at an operating temperature)	No vent needed	Removal of window for vent	Vent in the front section that direction flow of air	Sub/side ducts and exiting ducts for flow	Sunroof and/or side windows
Visibility (The rider must see the road and possible hazards)	Use entirely clear materials	Have a lower front section	Have back and side panels and a windshield	Adjustable mirrors	
Entering/Exiting (How will it allow riders to get in and out of the vehicle**)**	Open/no windshield	Hinged door	Hinged windshield	Removable	

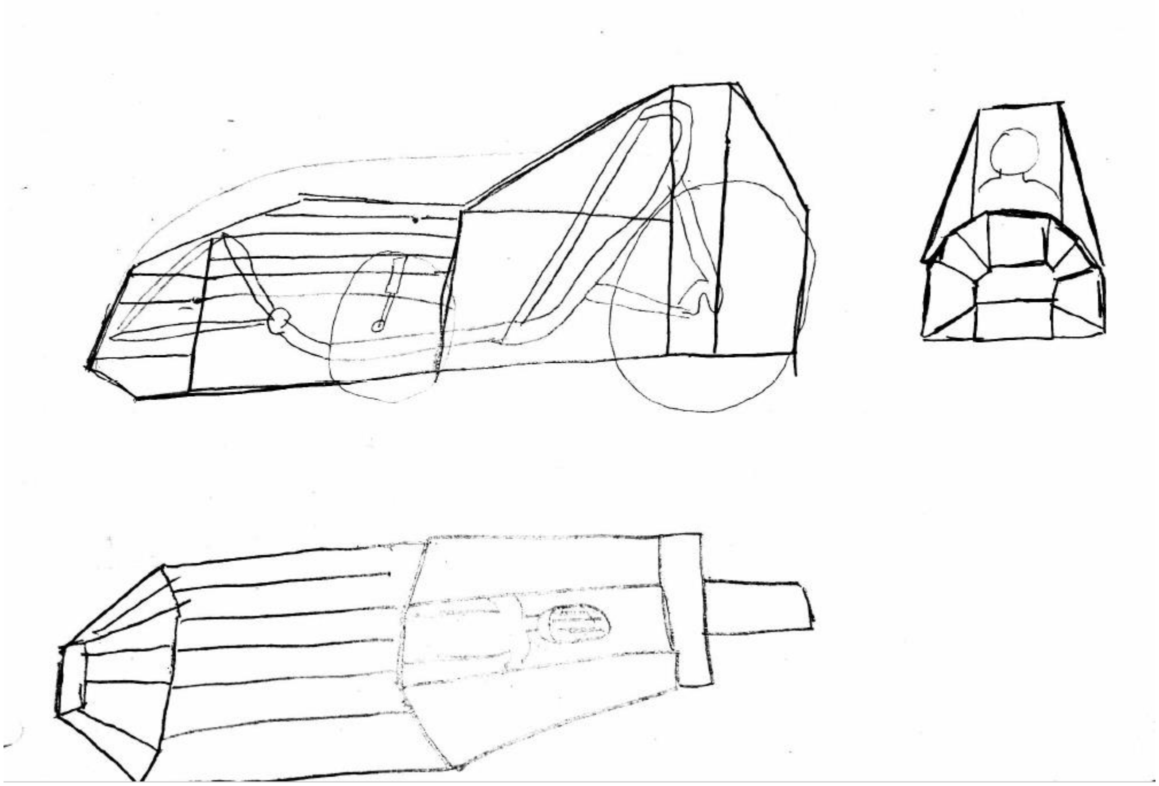


Figure G.25 Sketched version of faring concept 1: FFPS

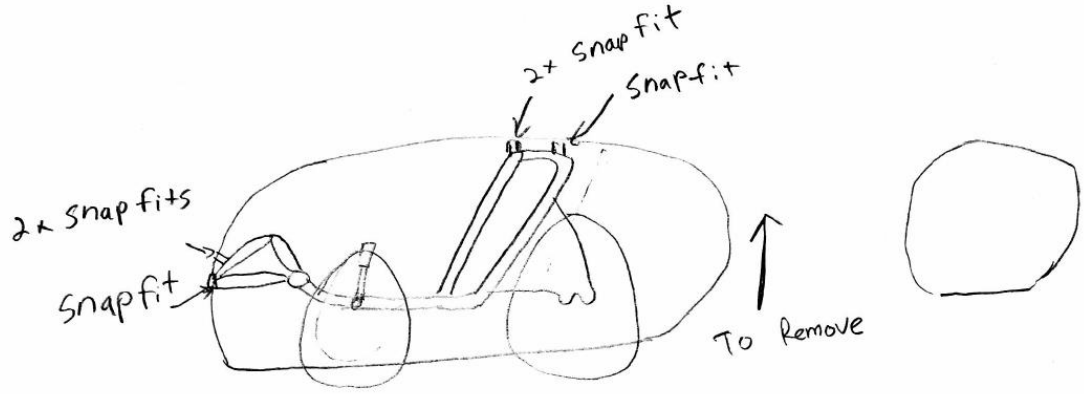


Figure G.26 Sketched version of faring concept 2: BTFB

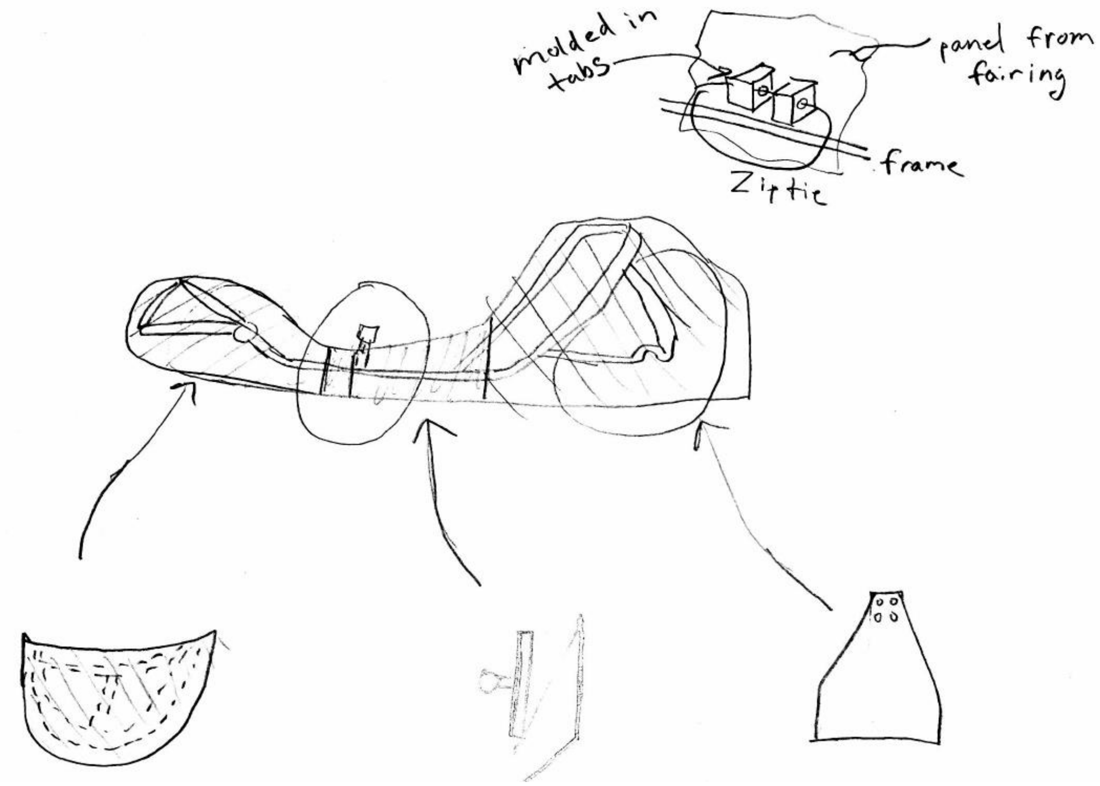


Figure G.27 Sketched version of faring concept 3: MPCF

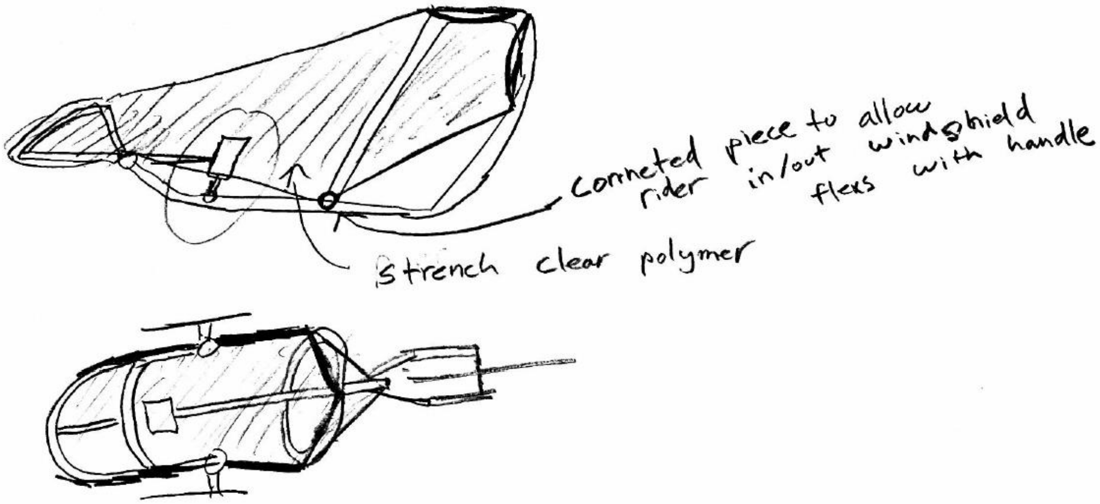


Figure G.28 Sketched version of faring concept 4: EPWP

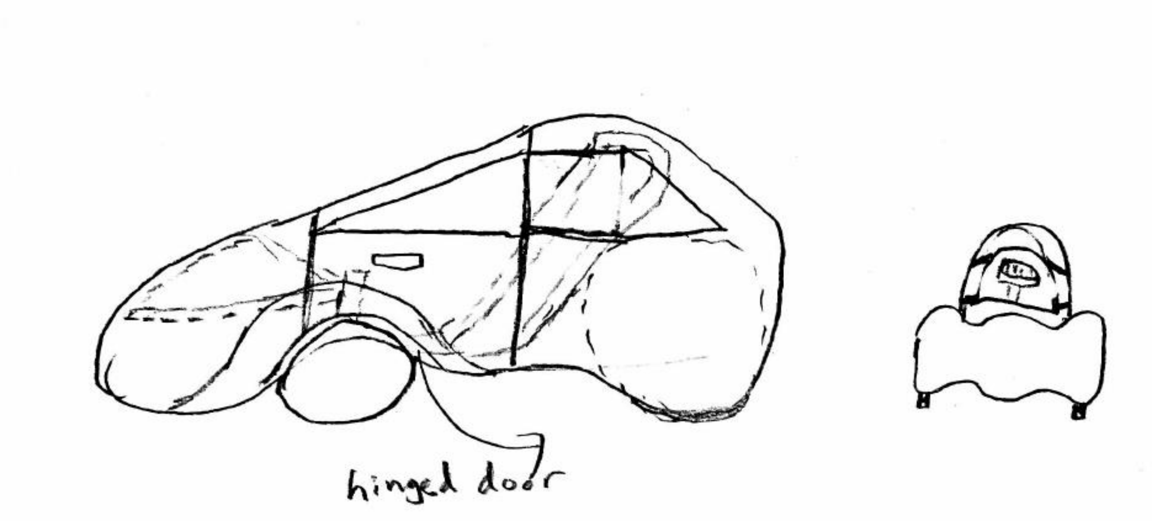


Figure G.29 Sketched version of faring concept 5: SFFV

Table G.11 Description of fairing concepts

Concept Acronyms	Acronym Meaning	Brief description/Notes
FFPS	Fully faired polygon shape	Idea based on cardboard/corrugated plastic fairing from HPVC 2015 event and Clemson's fairing of 2015.
BTFB	Blown thermal formed bubble	Idea of blown forming a single piece that could be removed and attached for rider entry. Idea based on instructional manufacturing page [40]
MPCF	Multi-piece composite fairing	Idea of combining various pieces to make a completely enclosed fairing. Composite materials allow for easier manufacturing of complex shapes. Considered adding a windshield made of Lexan fastened to a metal substructure
EPWP	Environmental protection wrapper polymer	Simple fairing meant for environmental protection more than aerodynamic. May require additional sub structures for support. Idea of "Saran wrapping" the frame.
SFFV	Streamlined fully faired vehicle	Made of composite to mold as complex as shapes as necessary.

APPENDIX H: EXAMPLES OF HPV CONCEPT EVALUATION

The drivetrain and fairing concept evaluations are not given, because the students spent most of their time developing the frame and steering systems first. After doing this the idea discussed for the drivetrain changed until a solution was found that worked with the given frame and steering configurations. A formal concept evaluation of the fairing system was not completed, because the students reasoned a particular concept was better given the manufacturing method chosen. That being said the essential requirements that would be used for evaluation are given for the fairing and drivetrain subsystems. The remaining frame and steering system concept evaluations were completed using the method discussed in Appendix C.2.

H.1 Frame Concept Evaluation

Table H.1 Essential requirements for frame evaluation criteria

Essential Requirements	Features or topics that can be used to evaluate requirements
Structural Integrity	
Stability	Ability to adapt to various road conditions. Factor of suspension, ground clearance, symmetry, center of gravity, and wheelbase length
Flexing	Structural Rigidity, ability of the frame to avoid "flexing"/ Ability to withstand loading forces causing moments to the vehicle
Durability	Ability to withstand various impact loads and vehicle dynamics over time
Environmental Adaptiveness	Ability to be on various road surfaces, minimize vibrations when in use. Factor a ground clearance and suspension
Manufacturability	
Components	Includes total number of parts, difference among, and standardization among components, aspects of the frame are designed for multifunctional to reduce extra required manufacturing
Ease of fabrication	Complexity of Design and difficulty to produce parts
Assembly	Minimize assembly task and adding features together, minimize likelihood of failure and stacked error
Cost	Cheapest to produce – based on combination of the above features

Table H.1 (Cont.)

Essential Requirements	Features or topics that can be used to evaluate requirements
Performance and Ergonomics	
Position and Comfort	Seat Angle/Position/Power available based on position/Fatigue of rider
Entering/Exiting	Ability to control vehicle. Factor of Wheelbase Length/Center of gravity/vehicle rigidity
Controls	Has ground locations/base to give easier access to enter or exit the vehicle
Weight (Distribution)	Vehicle stability/Speed based on required input power, persons center of gravity in vehicle
Safety	
Harness Support	Locations and ability to adequately support a person's weight
RPS System	Abrasion Protection from surfaces/Crashes involving rubbing along surfaces/ Frame ability to protect against that, ability to support impact loads/forces from versus directions
Visibility	Account for front, rear, and side visibility, position of the rider
Integratability	
Seat	Allows for the seat to change position/angle for rider comfort/different types of seats that could be used
Steering	Allows for adjustability/different types of configurations/improvements to steering abilities/room for human controls
Fairing	Creates defined attachment locations for the fairing
Drivetrain	Allow for space and add-on locations to place drivetrain features, and addition complexity the design adds to the drivetrain system

Table H.2 Frame concept selection using SMCR as a datum

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR	FSMR	FSDM	SMOR	CRCF	TRHF
Structural Integrity										
Stability	0	1	-1	1	0	1	1	-1	0	0
Flexing	0	1	-1	0	1	-1	-1	-1	-1	1
Durability	0	-1	-1	1	1	-1	-1	-1	0	0
Environmental Adaptiveness	0	1	0	0	0	1	-1	0	0	1
Score	0	2	-3	2	2	0	-2	-3	-1	2
Normalized Score	0.600	1.000	0.000	1.000	1.000	0.600	0.200	0.000	0.400	1.000

Table H.2 (Cont.)

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR	FSMR	FSDM	SMOR	CRCF	TRHF
Manufacturability										
Components	0	-1	-1	-1	1	-1	-1	1	-1	1
Ease of fabrication	0	0	1	-1	1	1	-1	1	-1	0
Assembly	0	-1	-1	0	0	-1	-1	0	-1	0
Cost	0	-1	0	0	0	-1	-1	0	0	0
Score	0	-3	-1	-2	2	-2	-4	2	-3	1
Normalized Score	0.667	0.167	0.500	0.333	1.000	0.333	0.000	1.000	0.167	0.833
Performance and Ergonomics										
Position and Comfort	0	0	-1	1	0	1	-1	0	0	1
Entering/Exiting	0	1	1	0	0	1	1	0	0	1
Controls	0	0	-1	1	0	0	1	0	0	-1
Weight (Distribution)	0	-1	-1	1	0	-1	-1	-1	0	0
Score	0	0	-2	3	0	1	0	-1	0	1
Normalized Score	0.400	0.400	0.000	1.000	0.400	0.600	0.400	0.200	0.400	0.600
Safety										
Harness Support	0	1	-1	1	0	-1	-1	0	-1	0
RPS System	0	-1	-1	-1	-1	-1	-1	-1	-1	0
Visibility	0	1	-1	-1	0	1	1	1	1	0
Score	0	1	-3	-1	-1	-1	-1	0	-1	0
Normalized Score	0.750	1.000	0.000	0.500	0.500	0.500	0.500	0.750	0.500	0.750
Integratability										
Seat	0	-1	-1	-1	0	0	0	-1	-1	1
Steering	0	1	-1	0	0	1	1	0	0	0
Fairing	0	-1	-1	0	1	-1	-1	-1	-1	1
Drivetrain	0	-1	-1	0	0	1	0	-1	-1	0
Score	0	-2	-4	-1	1	1	0	-3	-3	2
Normalized Score	0.667	0.333	0.000	0.500	0.833	0.833	0.667	0.167	0.167	1.000
"Total Normalized Score"	0.617	0.580	0.100	0.667	0.747	0.573	0.353	0.423	0.327	0.837
Non-Weighted Rank	4	5	10	3	2	6	8	7	9	1

Table H.3 Weighting for different cases for evaluation

	Case						
	1	2	3	4	5	6	7
Structural Integrity	2	1	1	1	1	5	1.833
Manufacturability	1	2	1	1	1	4	1.667
Performance and Ergonomics	1	1	2	1	1	1	1.167
Safety	1	1	1	2	1	3	1.500
Integratability	1	1	1	1	2	2	1.333
Total	6	6	6	6	6	15	7.5
						Perceived Weighting	Combined Score

Table H.4 Frame selection results using SMCR datum

Concepts	SMCR	DMFS	ASDM	SMRR	RFSR	FSMR	FSDM	SMOR	CRCF	TRHF
Case 1	0.614	0.65	0.083	0.722	0.789	0.578	0.330	0.350	0.339	0.860
Case 1 Rank	5	4	10	3	2	6	9	7	8	1
Case 2	0.625	0.511	0.167	0.611	0.789	0.533	0.290	0.520	0.3	0.840
Case 2 Rank	3	7	10	4	2	5	9	6	8	1
Case 3	0.581	0.55	0.083	0.722	0.689	0.578	0.360	0.390	0.339	0.800
Case 3 Rank	4	6	10	2	3	5	8	7	9	1
Case 4	0.639	0.65	0.083	0.639	0.706	0.561	0.380	0.480	0.356	0.820
Case 4 Rank	4	3	10	4	2	6	8	7	9	1
Case 5	0.625	0.539	0.083	0.639	0.761	0.617	0.410	0.380	0.3	0.860
Case 5 Rank	4	6	10	3	2	5	7	8	9	1
Case 6	0.643	0.649	0.133	0.656	0.838	0.540	0.280	0.450	0.327	0.880
Case 6 Rank	5	4	10	3	2	6	9	7	8	1
Case 7 (Combined)	0.626	0.603	0.111	0.663	0.777	0.562	0.330	0.430	0.327	0.850
Case 7 Rank	4	5	10	3	2	6	8	7	9	1

Table H.5 Justifications for SMCR datum evaluations

Essential Requirements	DMFS	ASDM	SMRR	RFSR	FSMR
Structural Integrity					
Stability	Longer wheel base and suspension	Asymmetric design is off balance during turns	Lower center of gravity will give more stable turns	Similar aspects	Dual Suspension handles terrain better
Flexing/Bending	Framework has more connectivity	Asymmetric design lowers the frame connectivity on one side making it less rigid on that side	Similar designs	Similar designs but has additionally rigidity caused by front piece	The lack for supports from roll cage causes less support thus less structures to disable flexing
Durability	Weaken connection to back wheel that is more likely to break over time	asymmetrical design will likely cause weaker side to break first	Similar design, but rear triangle is better supported	Better overall connectivity. Front brace will also help in the event of a crash	Poorly protected structure. Relies on less components
Environmental Adaptiveness	Similar aspects plus suspension	Similar aspects	Similar aspects	Similar Aspects	Dual Suspension handles terrain better

Essential Requirements	FSDM	SMOR	CRCF	TRHF
Structural Integrity				
Stability	Dual Suspension handles terrain better, longer wheelbase more stable	Similar aspects but more flexing will cause less balance	Similar aspects	Similar aspects
Flexing/Bending	Supports further away from the center member will disable flexing more	Similar aspects but additional supports from RPS will make structure more rigid	Similar aspects but additional supports from RPS will make structure more rigid	More support from "triangular" places will make a more rigid structure
Durability	Poorly protected structure. Longer design is more susceptible to loads. Type of suspension may be more likely to break.	Not braced for side impacts, but better in frontal collisions. Top of vehicle is less covered	Similar aspects	Similar Aspects
Environmental Adaptiveness	More likely to tip on slanted surfaces based on	Similar Aspects	Similar aspects	Wider weight distributions from RPS will give more balance

Table H.5 (Cont.)

Essential Requirements	DMFS	ASDM	SMRR	RFSR	FSMR
Manufacturability					
Components	More to produce plus the added complexity of parts in the suspension system	Most of the parts product require unique designs	Rear Triangle harder to fabricate	Similar design but less complex bends required	Few pars and all are relatively easy to create, but suspension adds complexity
Ease of Fabrication	Difficulty of making parts is about the same, but more parts are going to need to be produced. Suspension may give added complexity.	Overall simpler curves and straight pieces are used	Rear Triangle harder to fabricate	Simpler curves and overall use of standard items	Little machining needed to create parts
Assembly	Suspension will be harder to create	Asymmetric design requires unique assembly on each side	Similar amount of assembly requirements	Similar amount of assembly requirements	Suspension assembly will require more work
Cost	Difference in components and assembly requirements will raise cost	Similar Materials needed	Similar Materials needed	Similar Materials needed	Dual suspension may require greater investment

Essential Requirements	FSDM	SMOR	CRCF	TRHF
Manufacturability				
Components	More parts they require more machining features such as miters	Simple design with easy to create parts	Strange curves and miter may be harder to create.	Simple straight piece used
Ease of Fabrication	Front suspension will require more time effort and realize	Less curved members are being used	Harder to produce multiple curved typed pieces	Mostly straight pieces used, but precision drill holes for seat adjustment may be more difficult
Assembly	Front suspension may cause difficulties to attach, Dual member design will require more work	Similar amount of assembly required	Assembly requirements are about the same, but may be more difficult to weld rear section to RPS	Similar assembly requirements
Cost	Overall suspension may increase costs	Similar raw materials being used	Similar raw materials being used	Similar raw materials used

Table H.5 (Cont.)

Essential Requirements	DMFS	ASDM	SMRR	RFSR	FSMR
Performance and Ergonomics					
Position and Comfort	General Seating position are the same	Rider is more upright (towards a 90 degree angle, which causes less power to be available from the rider)	Curve of the main member is supposed to match the lumbar of person and account for wheel space	Similar seating design	Similar seating designs, but rear suspension puts less pain on rider back based on terrain
Entering/Exiting	Greater Foot space to get in	Asymmetric design is suppose is allow the rider to enter/exit vehicle easier	Similar aspects	Similar aspects	More open and more foot space available
Controls	Longer Wheelbase harder/lower turning radius, but suspension may allow from slight leaning controls	Flat base requires rider to be slightly higher up	Lower center of gravity allows for better control	Similar designs	Flat base requires rider to be slightly higher up, but suspension may allow from slight leaning controls
Weight	Higher Center of gravity with similar weights, meaning the weight distribution will be less advantageous in turns	Not symmetric weight distribution will cause uneven vehicle dynamics	Lower center of gravity allows for better control when turning, similar weights	Similar designs	Symmetric weighting, but less use of the weighting away from the center member will cause the design to be more susceptible to moments

Essential Requirements	FSDM	SMOR	CRCF	TRHF
Performance and Ergonomics				
Position and Comfort	Rider is more upright (towards a 90 degree angle, which causes less power to be available from the rider)	Similar seating designs	Similar seating designs	Rider is more upright, but at a higher elevation to allow for more comfort and power available
Entering/Exiting	More Open and foot space available	Similar aspects	Similar aspects	More Open and foot space available
Controls	Type of front suspension may allow for leaning controls in addition to turning controls	Similar Aspects	Similar aspects	High center of gravity affect turning
Weight	Symmetric weighting, but less use of the weighting away from the center member will cause the design to be more susceptible to moments	Symmetric weighting, but less use of the weighting away from the center member will cause the design to be more susceptible to moments	Similar designs	Similar weight distributions

Table H.5 (Cont.)

Essential Requirements	DMFS	ASDM	SMRR	RFSR	FSMR
Safety					
Harness Support	Two members can be used to support the person's weight instead of one	Unsymmetrical loading will be caused by supporting the person's weight	Two members can be used to support the person's weight instead of one	Similar harness supports	Rear suspension limits harness support abilities same the same sized tube.
RPS System	RPS is not completely around person	Does protect person as much on one side	Similar Designs, but person is less incased by RPS	Similar Designs, but person is less incased by RPS	No RPS
Visibility	Not a front left blind spot caused by the frame	More blind spots caused by side bars	More side blind spots caused to the rider	Similar visibility	Complete open side front and rear visibility

Essential Requirements	FSDM	SMOR	CRCF	TRHF
Safety				
Harness Support	Rear suspension limits harness support abilities same the same sized tube.	Similar Harness supports	Harness Supported by curved geometry although it is a similar one bar support	Similar harness supports
RPS System	Little to no RPS	RPS does not incase person as much	RPS does not incase person as much	Similar Designs
Visibility	Complete open side and front visibility	Complete open side and front visibility	Complete open side and front visibility	Similar visibilities

Table H.5 (Cont.)

Essential Requirements	DMFS	ASDM	SMRR	RFSR	FSMR
Integratability/Modularity					
Seat	Are more connecting piece to center member, which takes away ability to add attachment that allow seat adjustability, but roll cage could be used to add different types of seating (Mesh)	Are more connecting piece to center member, which takes away ability to add attachment that allow seat adjustability	Curvature of Main member allows for one specific type of seat	Similar types of seating	Similar types of seating
Steering	Would be more complex to create due to front suspension, but overall would be more adaptable to road conditions. In terms of allows different types of steering configurations it would be about the same	Would be about the same in terms of versatility, but limited room for human controls	Allows for similar steering abilities	Allows for similar steering abilities	Would be more complex to create due to front suspension, but overall would be more adaptable to road conditions. In terms of allows different types of steering configurations it would be about the same. Setup allows for more human room
Fairing	Has less overall spaces where fairing attachments could be applied	Has less overall spaces where fairing attachments could be applied. Additionally the asymmetric design limits fairing shapes	Allow for similar amounts of fairing attachments	Has similar amount of fairing attachments, but more front attachments instead of rear attachments which makes the overall fairing stability dispersed and improved	Little to no places that allow integrating the fairing
Drivetrain	Similar designs but multiple center pieces connecting to main member will limit space for drivetrains	Division of main member takes away space from drivetrain ability and adds complexity to designs using an addition jack shaft	Similar aspects	Similar aspects	Very open and straight forward path for drivetrain

Table H.5 (Cont.)

Essential Requirements	FSDM	SMOR	CRCF	TRHF
Integratability/Modularity				
Seat	Are more connecting piece to center member, which could takes away ability to add attachment that allow seat adjustability, but constant flat main member will allow for better overall adjustments	Bar added for rigidity take away from seat placement options	Bar added for rigidity take away from seat placement options	One main member is flat and allows for easy adjustability of the seat
Steering	Would be more complex to create due to front suspension, but overall would be more adaptable to road conditions. In terms of allows different types of steering configurations it would be about the same. Setup allows for more human room	Allows for similar steering abilities	Allows for similar steering abilities	Allows for similar steering abilities
Fairing	Little to no places that allow integrating the fairing	Upper and lower attachment allow for a good overall securing of the fairing, but only for monocoque models	Needs more side and frontal attachment locations	Great overall ability to attach fairing
Drivetrain	Very open and straight forward path for drivetrain, but split main member adds complexity	Similar aspects, but bar added for rigidity adds complexity to drivetrain path	Similar aspects, but bar added for rigidity adds complexity to drivetrain path	Similar Aspects

Table H.6 Frame concept selection using TRHF as a datum

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR	FSMR	FSDM	SMOR	CRCF	TRHF
Structural Integrity										
Stability	0	1	-1	1	0	1	1	-1	0	0
Flexing	-1	-1	-1	-1	1	-1	-1	-1	-1	0
Durability	0	-1	-1	1	1	-1	-1	-1	0	0
Environmental Adaptiveness	-1	1	-1	-1	-1	1	-1	-1	-1	0
Score	-2	0	-4	0	1	0	-2	-4	-2	0
Normalized Score	0.400	0.800	0.000	0.800	1.000	0.800	0.400	0.000	0.400	0.800
Manufacturability										
Components	-1	-1	-1	-1	0	-1	-1	0	-1	0
Ease of fabrication	0	0	1	-1	1	1	-1	1	-1	0
Assembly	0	-1	-1	0	0	-1	-1	0	-1	0
Cost	0	-1	0	0	0	-1	-1	0	0	0
Score	-1	-3	-1	-2	1	-2	-4	1	-3	0
Normalized Score	0.600	0.200	0.600	0.400	1.000	0.400	0.000	1.000	0.200	0.800
Performance and Ergonomics										
Position and Comfort	-1	-1	-1	1	-1	0	-1	-1	-1	0
Entering/Exiting	-1	1	1	-1	-1	1	1	-1	-1	0
Controls	1	1	-1	1	1	1	1	1	1	0
Weight (Distribution)	0	-1	-1	1	0	-1	-1	-1	0	0
Score	-1	0	-2	2	-1	1	0	-2	-1	0
Normalized Score	0.250	0.500	0.000	1.000	0.250	0.750	0.500	0.000	0.250	0.500
Safety										
Harness Support	0	1	-1	1	0	-1	-1	0	-1	0
RPS System	0	-1	-1	-1	-1	-1	-1	-1	-1	0
Visibility	0	1	-1	-1	0	1	1	1	1	0
Score	0	1	-3	-1	-1	-1	-1	0	-1	0
Normalized Score	0.750	1.000	0.000	0.500	0.500	0.500	0.500	0.750	0.500	0.750

Table H.6 (Cont.)

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR	FSMR	FSDM	SMOR	CRCF	TRHF
Integratability										
Seat	-1	-1	-1	-1	-1	-1	-1	-1	-1	0
Steering	0	1	-1	0	0	1	1	0	0	0
Fairing	-1	-1	-1	-1	1	-1	-1	-1	-1	0
Drivetrain	0	-1	-1	0	0	1	0	-1	-1	0
Score	-2	-2	-4	-2	0	0	-1	-3	-3	0
Normalized Score	0.500	0.500	0.000	0.500	1.000	1.000	0.750	0.250	0.250	1.000
"Total Normalized Score"	0.500	0.600	0.120	0.640	0.750	0.690	0.430	0.400	0.320	0.770
Non-Weighted Rank	6	5	10	4	2	3	7	8	9	1

Table H.7 Frame selection results using TRHF datum

Concepts	SMCR	DMFS	ASDM	SMRR	RFSR	FSMR	FSDM	SMOR	CRCF	TRHF
Case 1	0.483	0.633	0.100	0.667	0.792	0.708	0.425	0.333	0.333	0.775
Case 1 Rank	6	5	10	4	1	3	7	8	8	2
Case 2	0.517	0.533	0.200	0.600	0.792	0.642	0.358	0.500	0.300	0.775
Case 2 Rank	6	5	10	4	1	3	8	7	9	2
Case 3	0.458	0.583	0.100	0.700	0.667	0.700	0.442	0.333	0.308	0.725
Case 3 Rank	6	5	10	2	4	2	7	8	9	1
Case 4	0.542	0.667	0.100	0.617	0.708	0.658	0.442	0.458	0.350	0.767
Case 4 Rank	6	3	10	5	2	4	8	7	9	1
Case 5	0.500	0.583	0.100	0.617	0.792	0.742	0.483	0.375	0.308	0.808
Case 5 Rank	6	5	10	4	2	3	7	8	9	1
Case 6	0.527	0.620	0.160	0.607	0.850	0.657	0.367	0.450	0.337	0.797
Case 6 Rank	6	4	10	5	1	3	8	7	9	2
Case 7 (Combined)	0.509	0.607	0.133	0.629	0.783	0.679	0.409	0.417	0.326	0.779
Case 7 Rank	6	5	10	4	1	3	8	7	9	2

Table H.8 Justifications for TRHF datum evaluations

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR
Structural Integrity					
Stability	*	*	*	*	*
Flexing/Bending	*	Lack of dispersed connections to the steering arms will make the over frame less rigid	*	*	Two connecting bars to the steering arms will make the frame more rigid. In addition both use to concept of a side bar on each side plus a main bar to account for overall flexing and bending
Durability	*	*	*	*	*
Environmental Adaptiveness	*	Front suspension will help will uneven terrain more	*	*	*

Essential Requirements	FSMR	FSDM	SMOR	CRCF
Structural Integrity				
Stability	*	*	*	*
Flexing/Bending	*	*	*	*
Durability	*	*	*	*
Environmental Adaptiveness	Suspension will help will overall terrain more	*	*	*

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR
Manufacturability					
Components	*	*	*	*	Overall while the design includes more curves, the difficulty of manufacturing (bending) a curved tube is small. The overall number of parts and simplicity of design is similar
Ease of Fabrication	*	*	*	*	*
Assembly	*	*	*	*	*
Cost	*	*	*	*	*

Table H.8 (Cont.)

Essential Requirements	FSMR	FSDM	SMOR	CRCF
Manufacturability				
Components	*	*	Similar level of difficult in creating components and number of components	*
Ease of Fabrication	*	*	*	*
Assembly	*	*	*	*
Cost	*	*	*	*

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR
Performance and Ergonomics					
Position and Comfort	*	*	*	Variability might be small but the built in curve of the seat is meant to reflect the person's lumbar, which should give more comfort and power available	*
Entering/Exiting	*	Is more side room	Designed to be optimal for entering and exiting (on one side) the vehicle due to the asymmetric design	*	*
Controls	*	*	Unsymmetrical design give more unbalance and thus a less controlled vehicle	*	*
Weight	*	*	*	*	*

Essential Requirements	FSMR	FSDM	SMOR	CRCF
Performance and Ergonomics				
Position and Comfort	Similar designs in terms of seating position, angle and adjustability	*	*	*
Entering/Exiting	Open design allows for quick entering and exiting	Open design allows for quick entering and exiting	*	*
Controls	*	*	*	*
Weight	*	*	*	*

Table H.8 (Cont.)

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR
Safety					
Harness Support	*	*	*	*	*
RPS System	*	*	*	*	*
Visibility	*	*	*	*	*

Essential Requirements	FSMR	FSDM	SMOR	CRCF
Safety				
Harness Support	*	*	*	*
RPS System	*	*	*	*
Visibility	*	*	*	*

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR
Integratability/Modularity					
Seat	*	*	*	*	*
Steering	*	*	*	*	*
Fairing	*	*	*	*	Top and front tubes will better support fairing attachments
Drivetrain	*	*	*	*	*

Essential Requirements	FSMR	FSDM	SMOR	CRCF
Integratability/Modularity				
Seat	*	*	*	*
Steering	*	*	*	*
Fairing	*	*	*	*
Drivetrain	*	*	*	*

*For consistency with datum 1

Table H.9 Frame concept selection using SMRR as a datum

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR	FSMR	FSDM	SMOR	CRCF	TRHF
Structural Integrity										
Stability	-1	0	-1	0	-1	0	0	-1	-1	-1
Flexing	0	1	-1	0	1	-1	-1	-1	-1	1
Durability	-1	-1	-1	0	1	-1	-1	-1	-1	-1
Environmental Adaptiveness	0	1	0	0	0	1	-1	0	0	1
Score	-2	1	-3	0	1	-1	-3	-3	-3	0
Normalized Score	0.250	1.000	0.000	0.750	1.000	0.500	0.000	0.000	0.000	0.750
Manufacturability										
Components	-1	1	1	0	1	0	-1	1	0	1
Ease of fabrication	1	1	1	0	1	1	-1	1	0	1
Assembly	0	-1	-1	0	0	-1	-1	0	-1	0
Cost	0	-1	0	0	0	-1	-1	0	0	0
Score	0	0	1	0	2	-1	-4	2	-1	2
Normalized Score	0.667	0.667	0.833	0.667	1.000	0.500	0.000	1.000	0.500	1.000
Performance and Ergonomics										
Position and Comfort	-1	-1	-1	0	-1	-1	-1	-1	-1	-1
Entering/Exiting	0	1	1	0	0	1	1	0	0	1
Controls	-1	-1	-1	0	-1	-1	0	-1	-1	-1
Weight (Distribution)	-1	-1	-1	0	-1	-1	-1	-1	-1	-1
Score	-3	-2	-2	0	-3	-2	-1	-3	-3	-2
Normalized Score	0.000	0.333	0.333	1.000	0.000	0.333	0.667	0.000	0.000	0.333
Safety										
Harness Support	-1	0	-1	0	-1	-1	-1	-1	-1	-1
RPS System	1	-1	-1	0	0	-1	-1	-1	-1	1
Visibility	1	1	-1	0	1	1	1	1	1	1
Score	1	0	-3	0	0	-1	-1	-1	-1	1
Normalized Score	1.000	0.750	0.000	0.750	0.750	0.500	0.500	0.500	0.500	1.000

Table H.9 (Cont.)

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR	FSMR	FSDM	SMOR	CRCF	TRHF
Integratability										
Seat	1	0	0	0	1	1	1	0	0	1
Steering	0	1	-1	0	0	1	1	0	0	0
Fairing	0	-1	-1	0	1	-1	-1	-1	-1	1
Drivetrain	0	-1	-1	0	0	1	0	-1	-1	0
Score	1	-1	-3	0	2	2	1	-2	-2	2
Normalized Score	0.800	0.400	0.000	0.600	1.000	1.000	0.800	0.200	0.200	1.000
"Total Normalized Score"	0.543	0.630	0.233	0.753	0.750	0.567	0.393	0.340	0.240	0.817
Non-Weighted Rank	6	4	10	2	3	5	7	8	9	1

Table H.10 Frame selection results using SMRR datum

Concepts	SMCR	DMFS	ASDM	SMRR	RFSR	FSMR	FSDM	SMOR	CRCF	TRHF
Case 1	0.494	0.692	0.194	0.753	0.792	0.556	0.328	0.283	0.200	0.806
Case 1 Rank	6	4	10	3	2	5	7	8	9	1
Case 2	0.564	0.636	0.333	0.739	0.792	0.556	0.328	0.450	0.283	0.847
Case 2 Rank	5	4	8	3	2	6	9	7	10	1
Case 3	0.453	0.581	0.250	0.794	0.625	0.528	0.439	0.283	0.200	0.736
Case 3 Rank	6	4	9	1	3	5	7	8	10	2
Case 4	0.619	0.650	0.194	0.753	0.750	0.556	0.411	0.367	0.283	0.847
Case 4 Rank	5	4	10	2	3	6	7	8	9	1
Case 5	0.586	0.592	0.194	0.728	0.792	0.639	0.461	0.317	0.233	0.847
Case 5 Rank	6	5	10	3	2	4	7	8	9	1
Case 6	0.568	0.737	0.244	0.724	0.883	0.556	0.251	0.393	0.260	0.872
Case 6 Rank	5	3	10	4	1	6	9	7	8	2
Case 7 (Combined)	0.551	0.666	0.237	0.744	0.794	0.563	0.346	0.358	0.247	0.835
Case 7 Rank	6	4	10	3	2	5	8	7	9	1

Table H.11 Justifications for SMRR datum evaluations

Essential Requirements	SMCR	DMFS	ASDM	RFSR	FSMR
Structural Integrity					
Stability	*	Has front suspension, but an overall higher center of gravity. Comparing aspects on dynamic stability in unknown thus equal evaluations are used	*	*	Has dual suspension, but an overall higher center of gravity. Comparing aspects on dynamic stability in unknown thus equal evaluations are used
Flexing/Bending	*	*	*	*	*
Durability	*	*	*	Similar aspects with the main difference is front piece will likely support more damage from a frontal collision	*
Environmental Adaptiveness	*	*	*	*	*

Essential Requirements	FSDM	SMOR	CRCF	TRHF
Structural Integrity				
Stability	Has dual suspension, but an overall higher center of gravity. Comparing aspects on dynamic stability in unknown thus equal evaluations are used	*	*	*
Flexing/Bending	*	*	*	*
Durability	*	*	*	*
Environmental Adaptiveness	*	*	*	*

Essential Requirements	SMCR	DMFS	ASDM	RFSR	FSMR
Manufacturability					
Components	*	Components themselves are likelier easier to produce, the rear triangle in particular	Tubes themselves are easier to create	*	Front and rear suspension may be a little harder to create, but overall about the same complexity as rear triangle from SMRR
Ease of Fabrication	*	*	*	*	*
Assembly	*	*	*	*	*
Cost	*	*	*	*	*

Table H.11 (Cont.)

Essential Requirements	FSDM	SMOR	CRCF	TRHF
Manufacturability				
Components	Rear triangle and steering arms will be harder to create	*	Similar complexity. Rear triangle is easier, but multiple bends in tubes at changing angles is more difficult	*
Ease of Fabrication	Rear triangle and steering arms will be harder to create	*	Similar complexity. Rear triangle is easier, but multiple bends in tubes at changing angles is more difficult	*
Assembly	*	*	*	*
Cost	*	*	*	*

Essential Requirements	SMCR	DMFS	ASDM	RFSR	FSMR
Performance and Ergonomics					
Position and Comfort	*	*	*	*	**
Entering/Exiting	*	*	*	*	*
Controls	*	*	*	*	*
Weight	*	*	*	*	*

Essential Requirements	FSDM	SMOR	CRCF	TRHF
Performance and Ergonomics				
Position and Comfort	*	*	*	**
Entering/Exiting	*	*	*	*
Controls	Has dual suspension, but an overall higher center of gravity. Comparing aspects on dynamic stability in unknown thus equal evaluations are used	*	*	*
Weight	*	*	*	*

Table H.11 (Cont.)

Essential Requirements	SMCR	DMFS	ASDM	RFSR	FSMR
Safety					
Harness Support	*	Have similar harness mounting abilities, in terms of spaces attachments locations, supporting weight, and affects to the seats	Asymmetric design makes it more difficult to attach a harness	*	*
RPS System	*	Protects the rider less from abrasions and side loads	Protects the rider less from abrasions and side loads on one side	Overall riders are similarly protected	No RPS
Visibility	*	*	Side bars for rigidity affect riders side visibility more	*	*

Essential Requirements	FSDM	SMOR	CRCF	TRHF
Safety				
Harness Support	*	*	*	*
RPS System	Little to no RPS	Not protected well on side loads	Not protected well on side loads	*
Visibility	*	*	*	*

Essential Requirements	SMCR	DMFS	ASDM	RFSR	FSMR
Integratability/Modularity					
Seat	*	Allows for a little more seat modularity, but at a less efficient position	Allows for a little more seat modularity, but at a less efficient position	*	*
Steering	*	*	*	*	*
Fairing	*	*	*	*	*
Drivetrain	*	*	*	*	*

Essential Requirements	FSDM	SMOR	CRCF	TRHF
Integratability/Modularity				
Seat	*	Similar positions allowed for rider	Similar positions allowed for rider	*
Steering	*	*	*	*
Fairing	*	*	*	*
Drivetrain	*	*	*	*

* For consistency with datum 1
** For consistency with datum 2

Table H.12 Frame concept selection using FSDM as a datum

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR	FSMR	FSDM	SMOR	CRCF	TRHF
Structural Integrity										
Stability	-1	0	-1	0	-1	0	0	-1	-1	-1
Flexing	1	1	1	1	1	-1	0	1	1	1
Durability	1	1	1	1	1	-1	0	1	1	1
Environmental Adaptiveness	1	1	1	1	1	1	0	1	1	1
Score	2	3	2	3	2	-1	0	2	2	2
Normalized Score	0.750	1.000	0.750	1.000	0.750	0.000	0.250	0.750	0.750	0.750
Manufacturability										
Components	1	1	1	1	1	1	0	1	1	1
Ease of fabrication	1	1	1	1	1	1	0	1	1	1
Assembly	1	1	1	1	1	1	0	1	1	1
Cost	1	1	1	1	1	0	0	1	1	1
Score	4	4	4	4	4	3	0	4	4	4
Normalized Score	1.000	1.000	1.000	1.000	1.000	0.750	0.000	1.000	1.000	1.000
Performance and Ergonomics										
Position and Comfort	1	1	0	1	1	1	0	1	1	1
Entering/Exiting	-1	-1	1	-1	-1	0	0	-1	-1	-1
Controls	-1	-1	-1	0	-1	-1	0	-1	-1	-1
Weight (Distribution)	1	0	-1	1	1	0	0	0	1	1
Score	0	-1	-1	1	0	0	0	-1	0	0
Normalized Score	0.500	0.000	0.000	1.000	0.500	0.500	0.500	0.000	0.500	0.500
Safety										
Harness Support	1	1	-1	1	1	-1	0	1	0	1
RPS System	1	1	1	1	1	-1	0	-1	0	1
Visibility	-1	-1	-1	-1	-1	1	0	-1	0	-1
Score	1	1	-1	1	1	-1	0	-1	0	1
Normalized Score	1.000	1.000	0.000	1.000	1.000	0.000	0.500	0.000	0.500	1.000

Table H.12 (Cont.)

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR	FSMR	FSDM	SMOR	CRCF	TRHF
Integratability										
Seat	0	-1	-1	-1	0	0	0	-1	-1	1
Steering	-1	1	-1	-1	-1	1	0	-1	-1	-1
Fairing	1	-1	1	1	1	-1	0	1	0	1
Drivetrain	0	-1	-1	0	0	1	0	-1	-1	0
Score	0	-2	-2	-1	0	1	0	-2	-3	1
Normalized Score	0.750	0.250	0.250	0.500	0.750	1.000	0.750	0.250	0.000	1.000
"Total Normalized Score"	0.800	0.650	0.400	0.900	0.800	0.450	0.400	0.400	0.550	0.850
Non-Weighted Rank	3	5	8	1	3	7	8	8	6	2

Table H.13 Frame selection results using FSDM datum

Concepts	SMCR	DMFS	ASDM	SMRR	RFSR	FSMR	FSDM	SMOR	CRCF	TRHF
Case 1	0.792	0.708	0.458	0.917	0.792	0.375	0.375	0.458	0.583	0.833
Case 1 Rank	3	5	7	1	3	9	9	7	6	2
Case 2	0.833	0.708	0.500	0.917	0.833	0.500	0.333	0.500	0.625	0.875
Case 2 Rank	3	5	7	1	3	7	10	7	6	2
Case 3	0.750	0.542	0.333	0.917	0.750	0.458	0.417	0.333	0.542	0.792
Case 3 Rank	3	5	9	1	3	7	8	9	5	2
Case 4	0.833	0.708	0.333	0.917	0.833	0.375	0.417	0.333	0.542	0.875
Case 4 Rank	3	5	9	1	3	8	7	9	6	2
Case 5	0.792	0.583	0.375	0.833	0.792	0.542	0.458	0.375	0.458	0.875
Case 5 Rank	3	5	9	2	3	6	7	9	7	1
Case 6	0.850	0.833	0.550	0.933	0.850	0.367	0.317	0.550	0.650	0.883
Case 6 Rank	3	5	7	1	3	9	10	7	6	2
Case 7 (Combined)	0.817	0.711	0.450	0.911	0.817	0.422	0.372	0.450	0.583	0.861
Case 7 Rank	3	5	7	1	3	9	10	7	6	2

Table H.14 Justifications for FSDM datum evaluations

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR
Structural Integrity					
Stability	*	***	*	***	*
Flexing/Bending	*	*	Although design is asymmetric has more rigidity from RPS	*	*
Durability	*	More of an RPS to help in the case of collision and overall structural integrity	Has more structure and support one one side	*	*
Environmental Adaptiveness	*	*	*	*	*

Essential Requirements	FSMR	SMOR	CRCF	TRHF
Structural Integrity				
Stability	***	*	*	*
Flexing/Bending	Lack of RPS makes it less rigid	More Rigidity from side supports	More Rigidity from side supports	*
Durability	Lack of RPS gives less structure	Similar with lack of suspension, which is more likely to fail	*	*
Environmental Adaptiveness	*	*	*	*

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR
Manufacturability					
Components	*	***	***	***	*
Ease of Fabrication	*	*	*	***	*
Assembly	*	Front suspension is easier to assembly	Simply tubes and overall easy process	*	*
Cost	*	Lack of rear suspension drives down cost	*	*	*

Table H.14 (Cont.)

Essential Requirements	FSMR	SMOR	CRCF	TRHF
Manufacturability				
Components	***	*	***	*
Ease of Fabrication	*	*	***	*
Assembly	Both have suspension, but front suspension seems easier	*	Easier, because of suspension	*
Cost	Similar features have similar costs	*	*	*

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR
Performance and Ergonomics					
Position and Comfort	*	*	Allow for similar seat position	*	*
Entering/Exiting	*	Less room to put foot to get in and out of RPS	Specially designed for this aspect	*	*
Controls	*	*	*	***	*
Weight	*	Similar weight distributions	Weight is centered to one side	*	*

Essential Requirements	FSMR	SMOR	CRCF	TRHF
Performance and Ergonomics				
Position and Comfort	*	*	*	*
Entering/Exiting	Similar exiting and entering space	*	*	**
Controls	*	*	*	*
Weight	Similar weight distribution	Similar aspects	*	*

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR
Safety					
Harness Support	*	*	Asymmetric design distributes the weight of the person unevenly	*	*
RPS System	*	Similar, but allows for side load protection	Similar, except better protection on one side	***	***
Visibility	*	Side bars of rigidity gets in the way of sight	*	*	*

Table H.14 (Cont.)

Essential Requirements	FSMR	SMOR	CRCF	TRHF
Safety				
Harness Support	No roll cage to support harness	*	Similar locations and abilities to support weight	*
RPS System	No RPS	Similar, but a little less protection for side loads	Similar aspects	*
Visibility	Lack of RPS gives better rear visibility	Less because of top bar in the front	Similar aspects	*

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR
Integratability/Modularity					
Seat	*	*	*	*	*
Steering	*	Front suspension isn't required to be incorporating frame	*	*	*
Fairing	*	Lack of front piece and little less on the top	Better supports fairing attachments overall, expect for front piece	*	*
Drivetrain	*	*	*	*	*

Essential Requirements	FSMR	SMOR	CRCF	TRHF
Integratability/Modularity				
Seat	*	*	*	*
Steering	Front suspension isn't required to be incorporating frame	*	*	*
Fairing	Lack of RPS means lack of fairing attachment spots	More place to attach fairing in front and top piece as well	Worse for supporting fairing in the front, but better for supporting it in the back	*
Drivetrain	*	*	*	*

* For consistency with datum 1
** For consistency with datum 2
*** For consistency with datum 3

Table H.15 Combined results for complete frame concept selection

		SMCR	DMFS	ASDM	SMRR	RFSR	FSMR	FSDM	SMOR	CRCF	TRHF
Concept Selection 1 (SMCR Datum)	Normalized Score	0.626	0.603	0.111	0.663	0.777	0.562	0.330	0.433	0.327	0.851
	Rank	**4**	5	10	**3**	**2**	6	8	7	9	**1**
Concept Selection 2 (TRHF Datum)	Normalized Score	0.509	0.607	0.133	0.629	0.783	0.679	0.409	0.417	0.326	0.779
	Rank	6	5	10	**4**	**1**	**3**	8	7	9	**2**
Concept Selection 3 (SMRR Datum)	Normalized Score	0.551	0.666	0.237	0.744	0.794	0.563	0.346	0.358	0.247	0.835
	Rank	6	**4**	10	**3**	**2**	5	8	7	9	**1**
Concept Selection 4 (FSDM Datum)	Normalized Score	0.817	0.711	0.450	0.911	0.817	0.422	0.372	0.450	0.583	0.861
	Rank	**3**	5	7	**1**	**3**	9	10	7	6	**2**
Average	Normalized Score	0.626	0.647	0.233	0.737	0.793	0.557	0.364	0.414	0.371	0.831
	Rank	5	**4**	10	**3**	**2**	6	9	7	8	**1**

After concept evaluation the students involved with the frame design developed a hybrid concept from the top concepts. Overall the students found the process and tool helpful.

H.2 Steering Concept Evaluation

Table H.16 Essential requirements for steering evaluation criteria

Essential Requirements	Features or topics that can be used to evaluate requirements
Ergonomics	
Control	Ability to maintain desired travel path. Includes aspects of restraining speeds (brakes) and directional path (Turning and straight forward motion)
Comfort	Not allowing unnecessary strain/stress on driver. Giving the rider adequate pedaling room. Using an intuitive and easy motion for controlling handlebars
Accessibility	Ease of getting in and out of vehicle. Subsystem is meant to be clear of hinder the rider's ability to accomplish this.
Control Points	Ease of attachment for other components such as brakes
Performance and Structural Integrity	
Turning Radius	How sharply can the vehicle make turns. Factor of wheel base and wheel track. Individual front brakes can decrease turning radius (controls the rotation difference between wheels)
Durability	Ability to withstand fatigue and impulsive forces and overall vehicle dynamics over time.
Stability	How well the vehicle handles at different speeds in motion as well as stationary stability. Is affected by toe in, camber and caster.
Sensitivity	How much the motion of moving the handles affects the turning? Can the sensitivity be adjusted based on the steering configuration? Should not be overly sensitive, but sensitive even for reasonable turning in the handlebars.
Manufacturability	
Components	Includes total number of parts, difference among, and standardization among components, aspects are designed for multifunctional to reduce extra required manufacturing
Ease of Fabrication	Complexity of Design and difficulty to produce parts
Assembly	Minimize assembly task and adding features together, minimize likelihood of failure and stacked error
Cost	Cheapest to produce – based on combination of the above features
Signals and Safety	
Integratability	Must interface well, compatible with other components
Wheel Restrictions	Ability to restrict wheel turning to prevent accidents and failure parts

Table H.17 Steering concept selection using DKSS as a datum

Essential Requirements	DKSS	JSSS	SBOS	UBUS	SWSS
Ergonomics					
Effort	0	1	0	1	1
Comfort	0	-1	-1	1	1
Accessibility	0	1	-1	0	-1
Control Points	0	-1	1	0	0
Score	0	0	-1	2	1
Normalized Score	0.333	0.333	0.000	1.000	0.667
Performance and Structural Integrity					
Turning Radius	0	0	1	1	-1
Durability	0	-1	-1	-1	-1
Stability	0	-1	-1	-1	-1
Sensitivity	0	1	1	1	1
Score	0	-1	0	0	-2
Normalized Score	1.000	0.500	1.000	1.000	0.000
Manufacturability					
Components	0	-1	-1	-1	-1
Ease of Fabrication	0	-1	-1	-1	-1
Assembly	0	-1	-1	-1	-1
Cost	0	-1	-1	-1	-1
Score	0	-4	-4	-4	-4
Normalized Score	1.000	0.000	0.000	0.000	0.000
Signals and Safety					
Integratability	0	1	0	-1	1
Wheel Restrictions	0	1	1	1	1
Score	0	2	1	0	2
Normalized Score	0.000	1.000	0.500	0.000	1.000
"Total Normalized Score"	0.583	0.458	0.375	0.500	0.417
Non-Weighted Rank	1	3	5	2	4

Table H.18 Weighting for different cases for evaluation

	Case					
	1	2	3	4	5	6
Ergonomics	2	1	1	1	4	1.800
Performance and Structural Integrity	1	2	1	1	3	1.600
Manufacturability	1	1	2	1	2	1.400
Signals and Safety	1	1	1	2	1	1.200
Total	5	5	5	5	10	6
					Perceived Weighting	Combined Score

Table H.19 Steering selection results using DKSS datum

Concepts	DKSS	JSSS	SBOS	UBUS	SWSS
Case 1	0.533	0.233	0.200	0.600	0.267
Case 1 Rank	**2**	**4**	5	**1**	**3**
Case 2	0.667	0.467	0.500	0.600	0.333
Case 2 Rank	**1**	**4**	**3**	**2**	5
Case 3	0.667	0.367	0.300	0.400	0.333
Case 3 Rank	**1**	**3**	5	**2**	**4**
Case 4	0.467	0.567	0.400	0.400	0.533
Case 4 Rank	**3**	**1**	**4**	**4**	**2**
Case 5	0.633	0.383	0.350	0.700	0.367
Case 5 Rank	**2**	**3**	5	**1**	**4**
Case 6 (Combined)	0.600	0.433	0.367	0.567	0.400
Case 6 Rank	**1**	**3**	5	**2**	**4**

Table H.20 Steering concept selection using JSSS as a datum

Essential Requirements	DKSS	JSSS	SBOS	UBUS	SWSS
Ergonomics					
Effort	0	0	1	1	1
Comfort	1	0	1	0	1
Accessibility	1	0	-1	-1	-1
Control Points	0	0	1	1	1
Score	2	0	2	1	2
Normalized Score	1.000	0.000	1.000	0.500	1.000
Performance and Structural Integrity					
Turning Radius	0	0	1	0	1
Durability	1	0	0	0	0
Stability	-1	0	0	0	0
Sensitivity	-1	0	1	1	1
Score	-1	0	2	1	2
Normalized Score	0	0.333	1	0.667	1
Manufacturability					
Components	1	0	-1	0	-1
Ease of Fabrication	1	0	-1	0	-1
Assembly	1	0	-1	0	-1
Cost	1	0	-1	-1	-1
Score	4	0	-4	-1	-4
Normalized Score	1.000	0.500	0.000	0.375	0.000
Signals and Safety					
Integratability	-1	0	-1	-1	-1
Wheel Restrictions	-1	0	0	0	0
Score	-2	0	-1	-1	-1
Normalized Score	0.000	1.000	0.500	0.500	0.500
"Total Normalized Score"	0.500	0.458	0.625	0.510	0.625
Non-Weighted Rank	4	5	1	3	1

Table H.21 Steering selection results using JSSS datum

Concepts	DKSS	JSSS	SBOS	UBUS	SWSS
Case 1	0.600	0.167	0.600	0.408	0.600
Case 1 Rank	1	5	1	4	1
Case 2	0.400	0.433	0.700	0.542	0.700
Case 2 Rank	5	4	1	3	1
Case 3	0.600	0.467	0.500	0.483	0.500
Case 3 Rank	1	5	2	4	2
Case 4	0.400	0.567	0.600	0.508	0.600
Case 4 Rank	5	3	1	4	1
Case 5	0.600	0.300	0.750	0.525	0.750
Case 5 Rank	3	5	1	4	1
Case 6 (Combined)	0.533	0.406	0.667	0.515	0.667
Case 6 Rank	3	5	1	4	1

Table H.22 Steering concept selection using UBUS as a datum

Essential Requirements	DKSS	JSSS	SBOS	UBUS	SWSS
Ergonomics					
Effort	0	0	0	0	0
Comfort	0	0	0	0	0
Accessibility	0	-1	-1	0	-1
Control Points	0	-1	0	0	0
Score	0	-2	-1	0	-1
Normalized Score	1.000	0.000	0.500	1.000	0.500
Performance and Structural Integrity					
Turning Radius	-1	0	0	0	0
Durability	1	1	0	0	-1
Stability	0	0	0	0	0
Sensitivity	-1	0	0	0	0
Score	-1	1	0	0	-1
Normalized Score	0.000	1.000	0.500	0.500	0.000
Manufacturability					
Components	1	0	-1	0	-1
Ease of Fabrication	1	0	-1	0	-1
Assembly	1	0	-1	0	-1
Cost	1	0	0	0	0
Score	4	0	-3	0	-3
Normalized Score	1.000	0.429	0.000	0.429	0.000
Signals and Safety					
Integratability	0	1	0	0	0
Wheel Restrictions	-1	0	0	0	0
Score	-1	1	0	0	0
Normalized Score	0.000	1.000	0.500	0.500	0.500
"Total Normalized Score"	0.500	0.607	0.375	0.607	0.250
Non-Weighted Rank	3	1	4	1	5

Table H.23 Steering selection results using UBUS datum

Concepts	DKSS	JSSS	SBOS	UBUS	SWSS
Case 1	0.600	0.286	0.300	0.586	0.200
Case 1 Rank	1	4	3	2	5
Case 2	0.400	0.686	0.400	0.586	0.200
Case 2 Rank	3	1	3	2	5
Case 3	0.600	0.571	0.300	0.571	0.200
Case 3 Rank	1	2	4	2	5
Case 4	0.400	0.686	0.400	0.586	0.300
Case 4 Rank	3	1	3	2	5
Case 6	0.600	0.486	0.400	0.686	0.250
Case 6 Rank	2	3	4	1	5
Case 7 (Combined)	0.533	0.567	0.383	0.633	0.250
Case 7 Rank	3	2	4	1	5

Table H.24 Combined results for complete steering concept selection

		DKSS	JSSS	SBOS	UBUS	SWSS
Concept Selection 1 (DK Datum)	Normalized score	0.600	0.433	0.367	0.567	0.400
	Rank	1	3	5	2	4
Concept Selection 2 (JS Datum)	Normalized score	0.533	0.406	0.667	0.515	0.667
	Rank	3	5	1	4	1
Concept Selection 3 (UBU Datum)	Normalized score	0.533	0.567	0.383	0.633	0.250
	Rank	3	2	4	1	5
Averages	Normalized score	0.556	0.469	0.472	0.572	0.439
	Rank	2	4	3	1	5

The students using the evaluation tool failed to record justifications for their choices. Ultimately the U-bar and direct knuckle designs were close in the evaluation process and the team went with the direct knuckle steering, because of past experience. Additionally the students found using the evaluation tool to help them understanding the pros and cons of the various concepts better.

H.3 Drivetrain Concept Evaluation (Evaluation Criteria Only)

Table H.25 Essential requirements for drivetrain evaluation criteria

Essential Requirements	Features or topics that can be used to evaluate requirements
Performance and Ergonomics	
Efficiency and Effectiveness	The power transfer is efficient and effective. Maximizes the percentage of power supplied by the rider to the rear wheel.
Power Transfer	Comfortable for the rider, offers reasonable pedaling resistance for different terrains, is efficient. Gear range is optimized to maximize to provide easy pedaling resistance for steep uphill climbs and hard pedal resistance for steep downhills and sprints.
Shifting	Shifting works properly for the highest percentage of time. Does not result in the chain derailing or lose of functionality.
Structural Integrity	
Durability	Ability to withstand fatigue and impulsive forces and overall vehicle and rider dynamics over time.
Stability	The system must be stable. Meaning forces apply to system do not effect performance. Previous problems occurred with chain loads causing moments to the idler which become unstable and rotated during use.
Manufacturability	
Components	Includes total number of parts, difference among, and standardization among components, aspects are designed for multifunctional to reduce extra required manufacturing
Ease of Fabrication	Complexity of Design and difficulty to produce parts
Assembly	Minimize assembly task and adding features together, minimize likelihood of failure and stacked error
Feasibility	Practical design, is it a realistic goal to achieve, and within the desired complexity to fabricate
Cost	Cheapest to produce – based on combination of the above features
Signals and Safety	
Integratability	Must interface well, compatible with other components
Moving Parts	Limit the number of possible hazardous moving parts, such as sharp gears, or provide protection from them
Failure	Limit system failures, such as the chain derailing and improper shifting

H.4 Fairing Concept Evaluation (Evaluation Criteria Only)

Table H.26 Essential requirements for drivetrain evaluation criteria

Essential Requirements	Features or topics that can be used to evaluate requirements
Performance and Ergonomics	
Aerodynamics	Shape of the fairing is optimized to provide the best aerodynamic for the vehicle, in effect reduce drag. The drag reduction should be more beneficial to the rider then the weight added.
Environmental Protection	The fairing should protect rider from precipitation and effects of “baking” from the solar radiation. Windshield wipers may also be a necessity for the windshield, on a windshield opening or removal option.
Ventilation	Fairing must have some form of cooling system to help keep the rider at optimal performing temperatures. For colder climates their need to be some form of insulation or heating.
Structural Integrity	
Durability	Ability to withstand fatigue and impulsive forces and overall vehicle and rider dynamics over time.
Stability	The system must be stable. Meaning forces apply to system do not effect performance. Previous problems occurred with chain loads causing moments to the idler which become unstable and rotated during use.
Manufacturability	
Components	Includes total number of parts, difference among, and standardization among components, aspects are designed for multifunctional to reduce extra required manufacturing
Ease of Fabrication	Complexity of Design and difficulty to produce parts
Assembly	Minimize assembly task and adding features together, minimize likelihood of failure and stacked error
Feasibility	Practical design, is it a realistic goal to achieve, and within the desired complexity to fabricate
Cost	Cheapest to produce – based on combination of the above features
Signals and Safety	
Integratability	Must interface well, compatible with other components
Abrasion Resistance	In combination with the RPS the fairing must supply adequate abrasion resistance to protect riders in the event of vehicle rollover
Entering/Exiting	Fairing must allow the rider to safely and easily exit the vehicle, preferably without assistance being required.

APPENDIX I: COMMON ANTHROPOMETRIC DATA

The following anthropometric data is taken directly from a simplified version of Gordon *et al* [29]. The individual(s) who simplified and reformatted the original data are unknown. Thus, I am unable to give credit to them. Elements that pertain to the HPV design from there simplified version of the anthropometric survey, are included in this appendix.

Table I.1 Table of contents for anthropometric data

	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
83.83	**Mean**	33.01	88.74	**Mean**	34.94
4.52	**Std Dev**	1.78	4.71	**Std Dev**	1.85
102.20	**Maximum**	40.24	111.40	**Maximum**	43.86
65.30	**Minimum**	25.71	71.50	**Minimum**	28.15
	Percentiles			**Percentiles**	
73.89	1st	29.09	78.43	1st	30.88
75.02	2nd	29.53	79.71	2nd	31.38
75.73	3rd	29.81	80.48	3rd	31.68
76.69	5th	30.19	81.48	5th	32.08
78.18	10th	30.78	82.98	10th	32.67
79.20	15th	31.18	83.99	15th	33.07
80.01	20th	31.50	84.79	20th	33.38
80.72	25th	31.78	85.49	25th	33.66
81.36	30th	32.03	86.13	30th	33.91
81.96	35th	32.27	86.74	35th	34.15
82.54	40th	32.50	87.32	40th	34.38
83.10	45th	32.72	87.89	45th	34.60
83.66	50th	32.94	88.47	50th	34.83
84.23	55th	33.16	89.06	55th	35.06
84.81	60th	33.39	89.66	60th	35.30
85.42	65th	33.63	90.30	65th	35.55
86.07	70th	33.88	90.99	70th	35.82
86.77	75th	34.16	91.75	75th	36.12
87.57	80th	34.48	92.61	80th	36.46
88.51	85th	34.85	93.62	85th	36.86
89.71	90th	35.32	94.93	90th	37.37
91.50	95th	36.02	96.89	95th	38.14
92.67	97th	36.48	98.15	97th	38.64
93.53	98th	36.82	99.06	98th	39.00
94.86	99th	37.35	100.46	99th	39.55

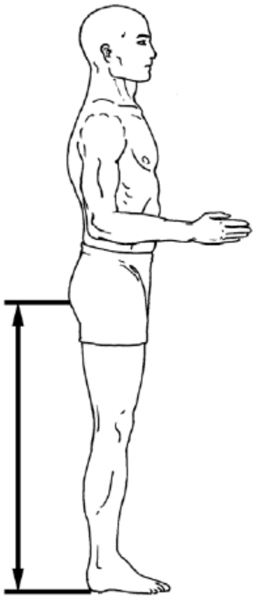


Figure I.1 Buttock height

	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
58.89	**Mean**	23.19	61.64	**Mean**	24.27
2.96	**Std Dev**	1.17	2.99	**Std Dev**	1.18
69.10	**Maximum**	27.20	72.30	**Maximum**	28.46
49.10	**Minimum**	19.33	50.60	**Minimum**	19.92
	Percentiles			**Percentiles**	
52.18	1st	20.54	55.07	1st	21.68
53.03	2nd	20.88	55.81	2nd	21.97
53.54	3rd	21.08	56.28	3rd	22.16
54.21	5th	21.34	56.90	5th	22.40
55.20	10th	21.73	57.87	10th	22.78
55.87	15th	22.00	58.54	15th	23.05
56.39	20th	22.20	59.08	20th	23.26
56.85	25th	22.38	59.55	25th	23.45
57.27	30th	22.55	59.98	30th	23.62
27.66	35th	22.70	60.39	35th	23.77
58.04	40th	22.85	60.78	40th	23.93
58.41	45th	23.00	61.16	45th	24.08
58.78	50th	23.14	61.54	50th	24.23
59.15	55th	23.29	61.93	55th	24.38
59.54	60th	23.44	62.32	60th	24.54
59.95	65th	23.60	62.73	65th	24.70
60.38	70th	23.77	63.17	70th	24.87
60.85	75th	23.96	63.65	75th	25.06
61.39	80th	24.17	64.19	80th	25.27
62.01	85th	24.41	64.81	85th	25.52
62.81	90th	24.73	65.60	90th	25.83
63.98	95th	25.19	66.74	95th	26.28
64.72	97th	25.48	67.45	97th	26.56
65.24	98th	25.69	67.95	98th	26.75
66.02	99th	25.99	68.69	99th	27.04

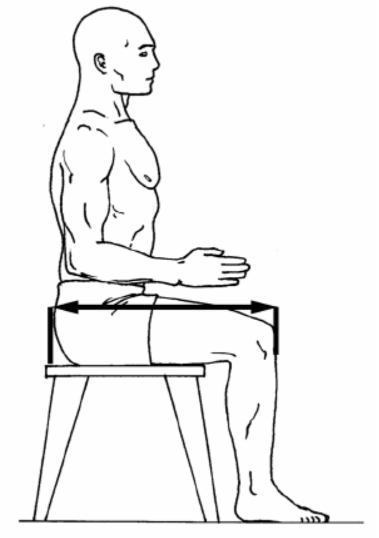


Figure I.2 Buttock-knee length

	FEMALE **N = 2208**			**MALE** **N = 1774**	
Centimeters		**Inches**	**Centimeters**		**Inches**
48.17	**Mean**	18.96	50.04	**Mean**	1970
2.66	**Std Dev**	1.05	2.66	**Std Dev**	1.05
57.80	**Maximum**	22.76	59.70	**Maximum**	23.50
39.40	**Minimum**	15.51	40.10	**Minimum**	15.79
	Percentiles			**Percentiles**	
42.10	1st	16.57	44.13	1st	17.37
42.91	2nd	16.89	44.81	2nd	17.64
43.39	3rd	17.08	45.24	3rd	17.81
44.00	5th	17.32	45.81	5th	18.04
44.89	10th	17.67	46.70	10th	18.39
45.47	15th	17.90	47.30	15th	18.62
45.93	20th	18.08	47.79	20th	18.81
46.34	25th	18.24	48.21	25th	18.98
46.71	30th	18.39	48.59	30th	19.13
47.05	35th	18.52	48.95	35th	19.27
47.39	40th	18.66	49.29	40th	19.41
47.72	45th	18.79	49.63	45th	19.54
48.05	50th	18.92	49.96	50th	19.67
48.39	55th	19.05	50.30	55th	19.80
48.73	60th	19.19	50.65	60th	19.94
49.10	65th	19.33	51.01	65th	20.08
49.49	70th	19.49	51.39	70th	20.23
49.93	75th	19.66	51.81	75th	20.40
50.42	80th	19.85	52.28	80th	20.58
50.99	85th	20.07	52.83	85th	20.80
51.72	90th	20.36	53.53	90th	21.07
52.77	95th	20.78	54.55	95th	21.48
53.43	97th	21.03	55.21	97th	21.74
53.88	98th	21.21	55.68	98th	21.92
54.54	99th	21.47	56.40	99th	22.21

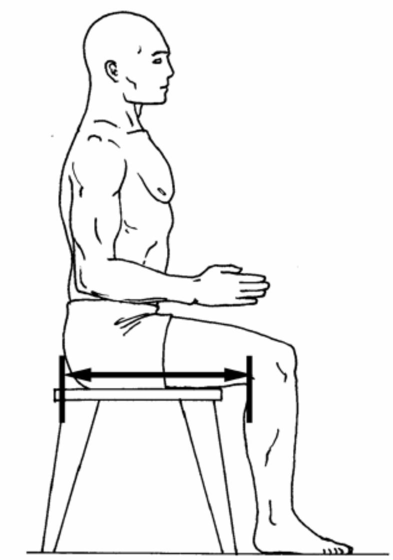


Figure I.3 Buttock-popliteal length

	FEMALE **N = 2208**			**MALE** **N = 1774**	
Centimeters		**Inches**	**Centimeters**		**Inches**
22.05	**Mean**	8.68	23.06	**Mean**	9.08
2.68	**Std Dev**	1.05	2.72	**Std Dev**	1.07
30.20	**Maximum**	11.89	31.10	**Maximum**	12.24
12.40	**Minimum**	4.88	14.00	**Minimum**	5.51
	Percentiles			**Percentiles**	
15.80	1st	6.22	16.75	1st	6.60
16.49	2nd	6.49	17.35	2nd	6.83
16.94	3rd	6.67	17.78	3rd	7.00
17.57	5th	6.92	18.41	5th	7.25
18.56	10th	7.31	19.44	10th	7.65
19.24	15th	7.57	20.17	15th	7.94
19.77	20th	7.87	20.74	20th	8.17
20.24	25th	7.97	21.24	25th	8.36
20.65	30th	8.13	21.69	30th	8.54
21.03	35th	8.28	22.09	35th	8.70
21.39	40th	8.42	22.47	40th	8.85
21.74	45th	8.56	22.83	45th	8.99
22.08	50th	8.69	23.19	50th	9.13
22.42	55th	8.83	23.53	55th	9.27
22.77	60th	8.96	23.88	60th	9.40
23.12	65th	9.10	24.23	65th	9.54
23.49	70th	8.25	24.59	70th	9.68
23.89	75th	9.41	24.98	75th	9.83
24.33	80th	9.58	25.40	80th	10.00
24.84	85th	9.78	25.88	85th	10.19
25.49	90th	10.03	26.48	90th	10.43
26.44	95th	10.41	27.37	95th	10.78
27.06	97th	10.65	27.96	97th	11.01
27.52	98th	10.83	28.41	98th	11.19
28.24	99th	11.12	29.16	99th	11.48

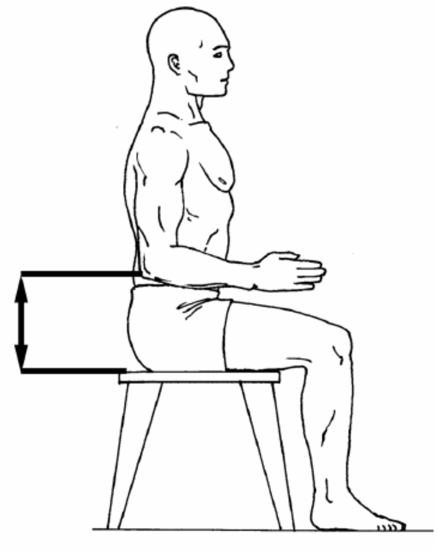


Figure I.4 Elbow rest height, sitting

	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
32.88	**Mean**	12.94	36.00	**Mean**	14.17
1.77	**Std Dev**	.70	1.79	**Std Dev**	.70
41.30	**Maximum**	16.26	43.60	**Maximum**	17.17
23.70	**Minimum**	9.33	29.30	**Minimum**	11.54
	Percentiles			**Percentiles**	
29.93	1st	11.39	32.26	1st	12.70
29.35	2nd	11.56	32.64	2nd	12.85
29.63	3rd	11.67	32.89	3rd	12.95
30.02	5th	11.82	33.23	5th	13.08
30.63	10th	12.06	33.78	10th	13.30
31.04	15th	12.22	34.16	15th	13.45
31.37	20th	12.35	34.47	20th	13.57
31.66	25th	12.47	34.75	25th	13.68
31.92	30th	12.57	35.00	30th	13.78
32.17	35th	12.66	35.24	35th	13.87
32.40	40th	12.75	35.47	40th	13.97
32.62	45th	12.84	35.70	45th	14.05
32.84	50th	12.93	35.92	50th	14.14
33.06	55th	13.02	36.15	55th	14.23
33.29	60th	13.10	36.39	60th	14.33
33.52	65th	13.20	36.63	65th	14.42
33.77	70th	13.29	36.89	70th	14.52
34.04	75th	13.40	37.18	75th	14.64
34.34	80th	13.52	37.50	80th	14.76
34.69	85th	13.66	37.87	85th	14.91
35.15	90th	13.84	38.35	90th	15.10
35.84	95th	14.11	39.06	95th	15.38
36.29	97th	14.29	39.51	97th	15.55
36.64	98th	14.42	39.83	98th	15.68
37.20	99th	14.64	40.33	99th	15.88

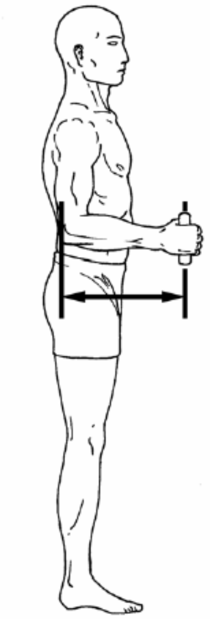


Figure I.5 Elbow-center of grip length

	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
73.87	**Mean**	29.08	79.20	**Mean**	31.18
3.32	**Std Dev**	1.31	3.42	**Std Dev**	1.35
86.40	**Maximum**	34.02	90.30	**Maximum**	35.55
64.00	**Minimum**	25.20	67.30	**Minimum**	26.50
	Percentiles			**Percentiles**	
66.40	1st	26.14	71.18	1st	28.02
67.21	2nd	26.46	72.11	2nd	28.39
67.74	3rd	26.67	72.70	3rd	28.62
68.46	5th	26.95	73.50	5th	28.94
69.60	10th	27.40	74.76	10th	29.43
70.38	15th	27.71	75.61	15th	29.77
71.01	20th	27.96	76.29	20th	30.04
71.56	25th	28.17	76.88	25th	30.27
72.06	30th	28.37	77.40	30th	30.47
72.52	35th	28.55	77.88	35th	30.66
72.96	40th	28.72	78.34	40th	30.84
73.39	45th	28.89	78.79	45th	31.02
73.82	50th	29.06	79.23	50th	31.19
74.25	55th	29.23	79.66	55th	31.36
74.68	60th	29.40	80.10	60th	31.54
75.13	65th	29.58	80.56	65th	31.72
75.61	70th	29.77	81.04	70th	31.90
76.13	75th	29.97	81.55	75th	32.11
73.71	80th	30.20	82.13	80th	32.33
77.37	85th	30.46	82.78	85th	32.59
78.21	90th	30.79	83.61	90th	32.92
79.43	95th	31.27	84.80	95th	33.39
80.20	97th	31.57	85.56	97th	33.68
81.59	99th	32.12	86.93	99th	34.23
80.75	98th	31.79	86.10	98th	33.90

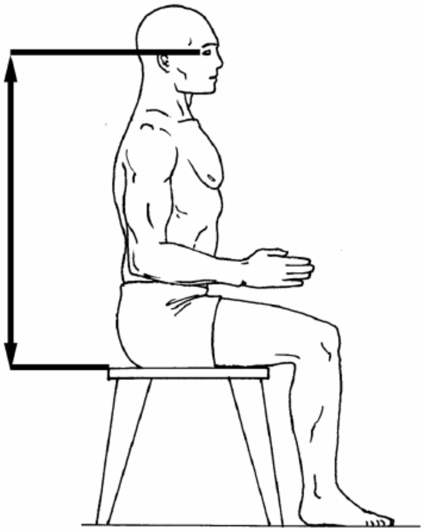


Figure I.6 Eye height, sitting

	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
151.61	**Mean**	59.69	163.39	**Mean**	64.32
6.25	**Std Dev**	2.46	6.57	**Std Dev**	2.59
175.30	**Maximum**	69.02	191.20	**Maximum**	75.28
132.50	**Minimum**	52.17	138.10	**Minimum**	54.37
	Percentiles			**Percentiles**	
137.39	1st	54.09	148.40	1st	58.43
139.07	2nd	54.75	150.22	2nd	59.14
140.11	3rd	55.16	151.33	3rd	59.14
141.52	5th	55.72	152.82	5th	59.58
143.67	10th	56.56	155.08	10th	60.17
145.13	15th	57.14	156.60	15th	61.05
146.29	20th	57.59	157.82	20th	61.65
147.30	25th	57.99	158.88	25th	62.13
148.21	30th	58.35	159.84	30th	62.55
149.06	35th	58.68	160.73	35th	62.93
149.87	40th	59.00	161.59	40th	63.62
150.66	45th	59.32	162.42	45th	63.95
151.45	50th	59.63	163.26	50th	64.28
152.24	55th	59.94	164.10	55th	64.61
153.05	60th	60.26	164.96	60th	64.94
153.90	65th	60.59	165.85	65th	65.30
154.79	70th	60.94	166.79	70th	65.67
155.77	75th	61.33	167.82	75th	66.07
156.86	80th	61.76	168.97	80th	66.52
158.14	85th	62.26	170.29	85th	67.04
159.75	90th	62.90	171.29	90th	67.69
162.13	95th	63.83	174.29	95th	68.62
163.35	97th	64.43	175.73	97th	69.18
164.75	98th	64.86	176.72	98th	69.57
166.43	99th	65.52	178.15	99th	70.14

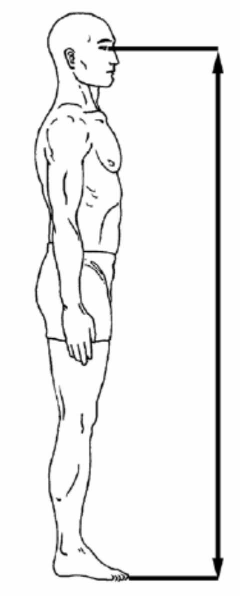


Figure I.7 Eye height, standing

	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
46.85	**Mean**	18.44	54.61	**Mean**	21.50
3.47	**Std Dev**	1.36	4.36	**Std Dev**	1.72
60.90	**Maximum**	23.98	72.52	**Maximum**	28.54
37.30	**Minimum**	14.69	39.90	**Minimum**	15.71
	Percentiles			**Percentiles**	
39.42	1st	15.52	45.12	1st	17.76
40.24	2nd	15.84	46.17	2nd	18.18
40.76	3rd	16.05	46.84	3rd	18.44
41.47	5th	16.33	47.74	5th	18.80
42.58	10th	16.76	49.16	10th	19.35
43.33	15th	17.06	50.13	15th	19.74
43.94	20th	17.30	50.91	20th	20.04
44.47	25th	17.51	51.59	25th	20.31
44.94	30th	17.69	52.21	30th	20.56
45.39	35th	17.87	52.79	35th	20.79
45.82	40th	18.04	53.35	40th	21.00
46.24	45th	18.20	53.90	45th	21.22
46.66	50th	18.37	54.45	50th	21.44
47.08	55th	18.54	55.00	55th	21.65
47.52	60th	18.71	55.56	60th	21.88
47.98	65th	18.89	56.16	65th	22.11
48.47	70th	19.08	56.79	70th	22.36
49.01	75th	19.30	57.47	75th	22.63
49.63	80th	19.54	58.25	80th	22.93
50.37	85th	19.83	59.16	85th	23.29
51.33	90th	20.21	60.32	90th	23.75
52.84	95th	20.80	62.06	95th	24.43
53.87	97th	21.21	63.18	97th	24.87
54.66	98th	21.52	64.00	98th	25.20
55.95	99th	22.03	65.27	99th	25.70

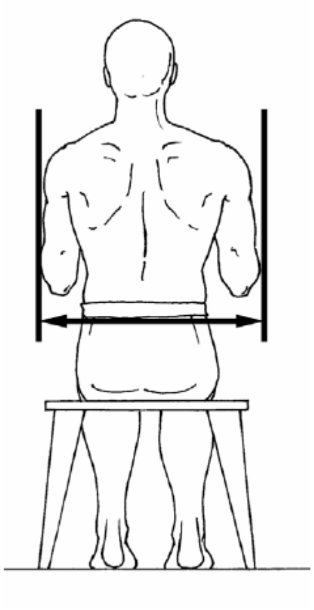


Figure I.8 Forearm-forearm breadth

	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
68.61	**Mean**	27.01	75.07	**Mean**	29.55
3.39	**Std Dev**	1.33	3.68	**Std Dev**	1.45
83.20	**Maximum**	32.76	92.10	**Maximum**	36.26
57.50	**Minimum**	22.64	62.60	**Minimum**	24.65
	Percentiles			**Percentiles**	
61.51	1st	24.22	67.26	1st	26.48
62.12	2nd	24.46	68.04	2nd	26.79
62.55	3rd	24.63	68.55	3rd	26.99
63.19	5th	24.88	69.28	5th	27.28
64.26	10th	25.30	70.45	10th	27.74
65.03	15th	25.60	71.27	15th	28.06
65.66	20th	25.85	71.93	20th	28.32
66.22	25th	26.07	72.52	25th	28.55
66.72	30th	26.27	73.05	30th	28.76
67.19	35th	26.45	73.54	35th	28.95
67.64	40th	26.63	74.02	40th	29.14
68.08	45th	26.80	74.49	45th	29.33
68.51	50th	26.97	74.95	50th	29.51
68.95	55th	27.15	75.42	55th	29.69
69.40	60th	27.32	75.90	60th	29.88
69.86	65th	27.50	76.40	65th	30.08
70.34	70th	27.69	76.92	70th	30.29
70.87	75th	27.90	77.50	75th	30.51
71.46	80th	28.14	78.15	80th	30.77
72.15	85th	28.41	78.91	85th	31.07
73.03	90th	28.75	79.87	90th	31.45
74.36	95th	29.27	81.31	95th	32.01
75.24	97th	29.62	82.25	97th	32.38
75.90	98th	29.88	82.94	98th	32.65
76.97	99th	30.30	84.03	99th	33.08

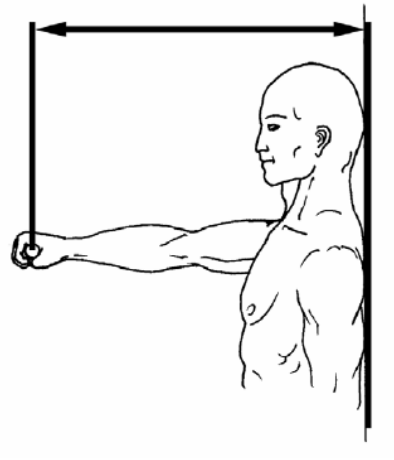


Figure I.9 Functional grip reach

	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
74.56	**Mean**	29.35	81.82	**Mean**	32.21
3.61	**Std Dev**	1.42	3.91	**Std Dev**	1.54
92.40	**Maximum**	36.38	98.60	**Maximum**	38.82
62.60	**Minimum**	24.65	68.70	**Minimum**	27.05
	Percentiles			**Percentiles**	
66.55	1st	26.20	72.88	1st	28.69
67.40	2nd	26.54	73.88	2nd	29.09
67.96	3rd	26.76	74.53	3rd	29.34
68.73	5th	27.06	75.43	5th	29.70
69.96	10th	27.54	76.83	10th	30.25
70.80	15th	27.87	77.79	15th	30.63
71.48	20th	28.14	78.54	20th	30.92
72.07	25th	28.37	79.19	25th	31.18
72.60	30th	28.58	79.77	30th	31.41
73.09	35th	28.78	80.30	35th	31.62
73.56	40th	28.96	80.81	40th	31.82
74.02	45th	29.14	81.30	45th	32.01
74.48	50th	29.32	81.78	50th	32.20
74.94	55th	29.50	82.27	55th	32.39
75.40	60th	29.69	82.76	60th	32.58
75.89	65th	29.88	83.27	65th	32.78
76.40	70th	30.08	83.80	70th	32.99
76.96	75th	30.30	84.39	75th	33.22
77.59	80th	30.55	85.05	80th	33.49
78.33	85th	30.84	85.83	85th	33.79
79.28	90th	31.21	86.84	90th	34.19
80.70	95th	31.77	88.41	95th	34.81
81.65	97th	32.15	89.50	97th	35.24
82.36	98th	32.42	90.33	98th	35.56
83.50	99th	32.87	91.73	99th	36.11

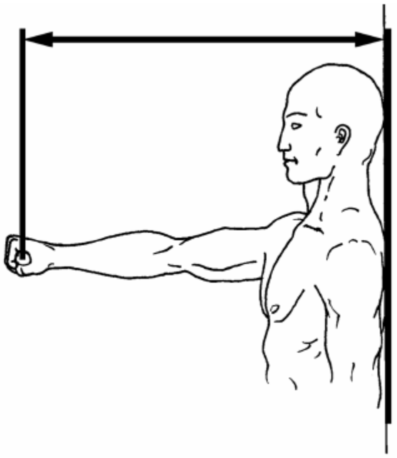
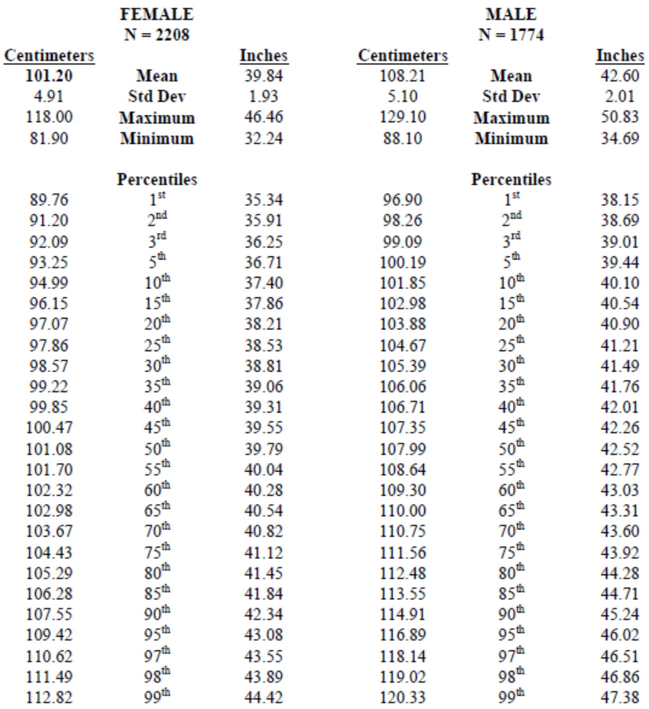


Figure I.10 Function grip reach, extended



	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
101.20	**Mean**	39.84	108.21	**Mean**	42.60
4.91	**Std Dev**	1.93	5.10	**Std Dev**	2.01
118.00	**Maximum**	46.46	129.10	**Maximum**	50.83
81.90	**Minimum**	32.24	88.10	**Minimum**	34.69
	Percentiles			**Percentiles**	
89.76	1st	35.34	96.90	1st	38.15
91.20	2nd	35.91	98.26	2nd	38.69
92.09	3rd	36.25	99.09	3rd	39.01
93.25	5th	36.71	100.19	5th	39.44
94.99	10th	37.40	101.85	10th	40.10
96.15	15th	37.86	102.98	15th	40.54
97.07	20th	38.21	103.88	20th	40.90
97.86	25th	38.53	104.67	25th	41.21
98.57	30th	38.81	105.39	30th	41.49
99.22	35th	39.06	106.06	35th	41.76
99.85	40th	39.31	106.71	40th	42.01
100.47	45th	39.55	107.35	45th	42.26
101.08	50th	39.79	107.99	50th	42.52
101.70	55th	40.04	108.64	55th	42.77
102.32	60th	40.28	109.30	60th	43.03
102.98	65th	40.54	110.00	65th	43.31
103.67	70th	40.82	110.75	70th	43.60
104.43	75th	41.12	111.56	75th	43.92
105.29	80th	41.45	112.48	80th	44.28
106.28	85th	41.84	113.55	85th	44.71
107.55	90th	42.34	114.91	90th	45.24
109.42	95th	43.08	116.89	95th	46.02
110.62	97th	43.55	118.14	97th	46.51
111.49	98th	43.89	119.02	98th	46.86
112.82	99th	44.42	120.33	99th	47.38

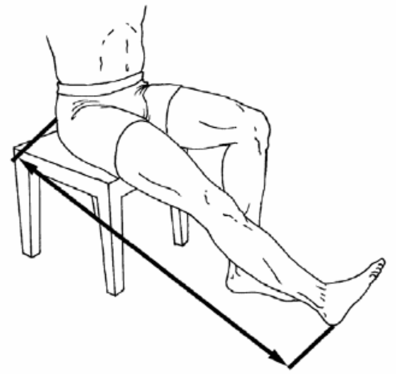
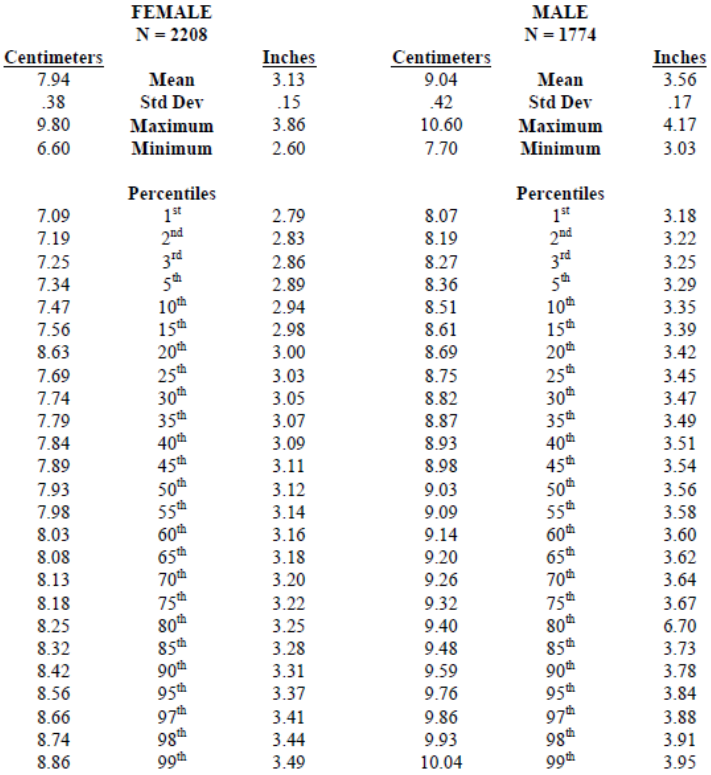


Figure I.11 Functional leg length, seated



	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
7.94	**Mean**	3.13	9.04	**Mean**	3.56
.38	**Std Dev**	.15	.42	**Std Dev**	.17
9.80	**Maximum**	3.86	10.60	**Maximum**	4.17
6.60	**Minimum**	2.60	7.70	**Minimum**	3.03
	Percentiles			**Percentiles**	
7.09	1st	2.79	8.07	1st	3.18
7.19	2nd	2.83	8.19	2nd	3.22
7.25	3rd	2.86	8.27	3rd	3.25
7.34	5th	2.89	8.36	5th	3.29
7.47	10th	2.94	8.51	10th	3.35
7.56	15th	2.98	8.61	15th	3.39
8.63	20th	3.00	8.69	20th	3.42
7.69	25th	3.03	8.75	25th	3.45
7.74	30th	3.05	8.82	30th	3.47
7.79	35th	3.07	8.87	35th	3.49
7.84	40th	3.09	8.93	40th	3.51
7.89	45th	3.11	8.98	45th	3.54
7.93	50th	3.12	9.03	50th	3.56
7.98	55th	3.14	9.09	55th	3.58
8.03	60th	3.16	9.14	60th	3.60
8.08	65th	3.18	9.20	65th	3.62
8.13	70th	3.20	9.26	70th	3.64
8.18	75th	3.22	9.32	75th	3.67
8.25	80th	3.25	9.40	80th	6.70
8.32	85th	3.28	9.48	85th	3.73
8.42	90th	3.31	9.59	90th	3.78
8.56	95th	3.37	9.76	95th	3.84
8.66	97th	3.41	9.86	97th	3.88
8.74	98th	3.44	9.93	98th	3.91
8.86	99th	3.49	10.04	99th	3.95

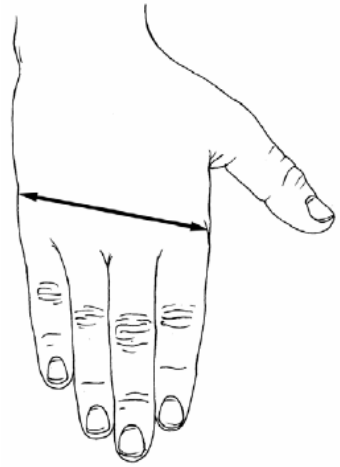


Figure I.12 Hand breadth

	FEMALE **N = 2208**			**MALE** **N = 1774**	
Centimeters		**Inches**	**Centimeters**		**Inches**
18.62	**Mean**	7.33	21.38	**Mean**	8.42
.85	**Std Dev**	.33	.97	**Std Dev**	.38
23.00	**Maximum**	9.06	24.70	**Maximum**	9.72
15.80	**Minimum**	6.22	18.20	**Minimum**	7.17
	Percentiles			**Percentiles**	
16.73	1st	6.59	19.16	1st	7.54
16.93	2nd	6.67	19.45	2nd	7.66
17.07	3rd	6.72	19.62	3rd	7.72
17.25	5th	6.79	19.85	5th	7.81
17.55	10th	6.91	20.18	10th	7.94
17.75	15th	6.99	20.40	15th	8.03
17.91	20th	7.05	20.57	20th	8.10
18.04	25th	7.10	20.72	25th	8.16
18.17	30th	7.15	20.86	30th	8.21
18.28	35th	7.20	20.98	35th	8.26
18.39	40th	7.24	21.11	40th	8.31
18.50	45th	7.28	21.22	45th	8.36
18.60	50th	7.32	21.34	50th	8.40
18.70	55th	7.36	21.46	55th	8.45
18.81	60th	7.41	21.59	60th	8.50
18.92	65th	7.45	21.72	65th	8.55
19.04	70th	7.49	21.86	70th	8.61
19.16	75th	7.54	22.01	75th	8.67
19.30	80th	7.60	22.18	80th	8.73
19.47	85th	7.67	22.38	85th	8.81
19.69	90th	7.75	22.64	90th	8.92
20.03	95th	7.88	23.03	95th	9.07
20.25	97th	7.97	23.28	97th	9.17
20.43	98th	8.04	23.46	98th	9.24
20.72	99th	8.16	23.74	99th	9.35

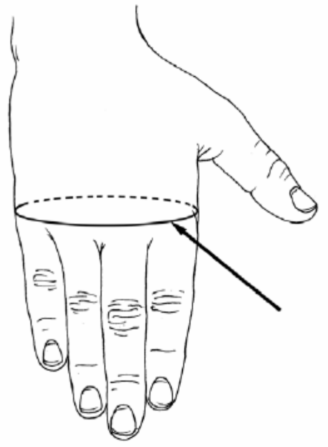


Figure I.13 Hand circumference

	FEMALE **N = 2208**			**MALE** **N = 1774**	
Centimeters		**Inches**	**Centimeters**		**Inches**
18.05	**Mean**	7.10	19.38	**Mean**	7.63
.97	**Std Dev**	.38	.98	**Std Dev**	.39
21.50	**Maximum**	8.46	23.30	**Maximum**	9.17
14.90	**Minimum**	5.87	16.00	**Minimum**	6.30
	Percentiles			**Percentiles**	
15.89	1st	6.26	17.28	1st	6.80
16.13	2nd	6.35	17.52	2nd	6.90
16.29	3rd	6.41	17.67	3rd	6.96
16.50	5th	6.50	17.87	5th	7.04
16.83	10th	6.63	18.18	10th	7.16
17.06	15th	6.72	18.39	15th	7.24
17.24	20th	6.79	18.56	20th	7.31
17.39	25th	6.85	18.71	25th	7.37
17.53	30th	6.90	18.85	30th	7.42
17.66	35th	6.95	18.97	35th	7.47
17.78	40th	7.00	19.09	40th	7.52
17.90	45th	7.05	19.21	45th	7.56
18.02	50th	7.09	19.33	50th	7.61
18.14	55th	7.14	19.45	55th	7.66
18.26	60th	7.19	19.57	60th	7.70
18.39	65th	7.24	19.70	65th	7.75
18.52	70th	7.29	19.84	70th	7.81
18.67	75th	7.35	19.99	75th	7.87
18.84	80th	7.42	20.16	80th	7.94
19.04	85th	7.49	20.37	85th	8.02
19.29	90th	7.60	20.64	90th	8.13
19.69	95th	7.75	21.06	95th	8.29
19.96	97th	7.86	21.34	97th	8.40
20.16	98th	7.94	21.55	98th	8.49
20.50	99th	8.07	21.90	99th	8.62

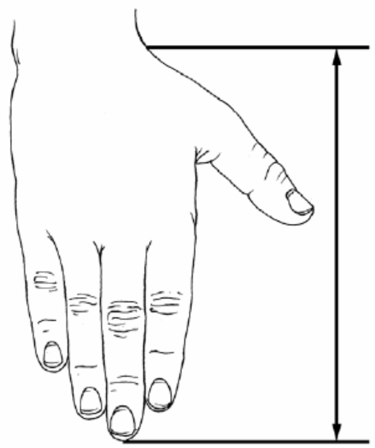
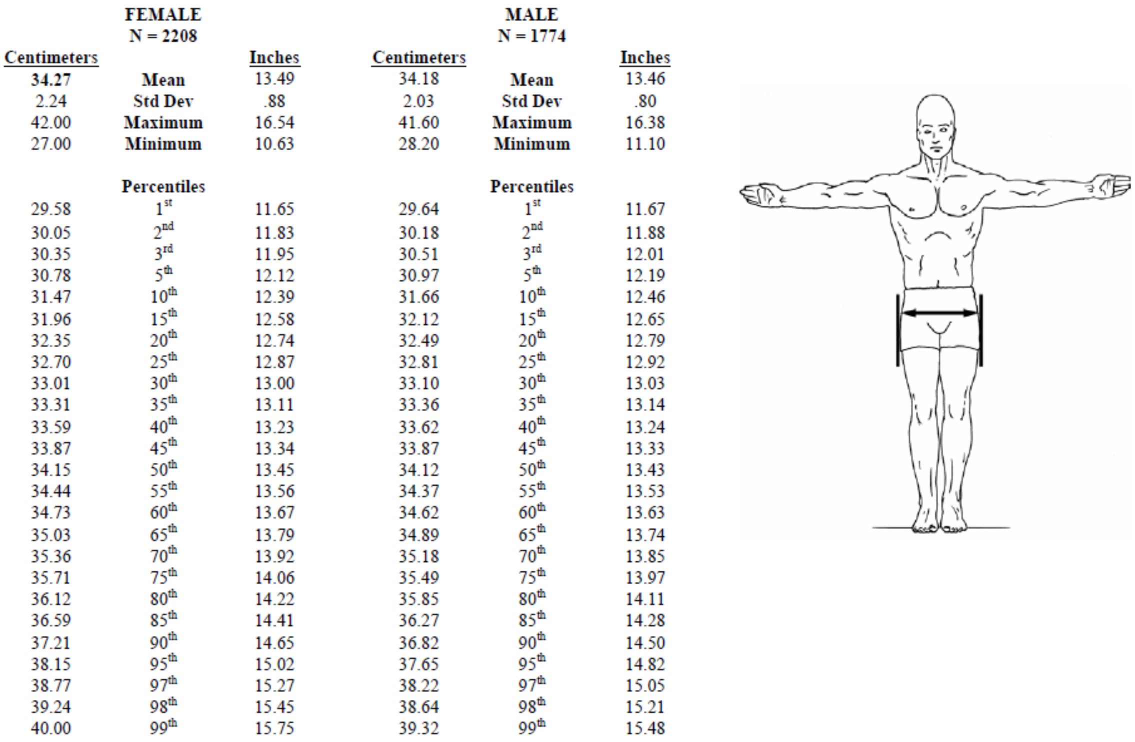
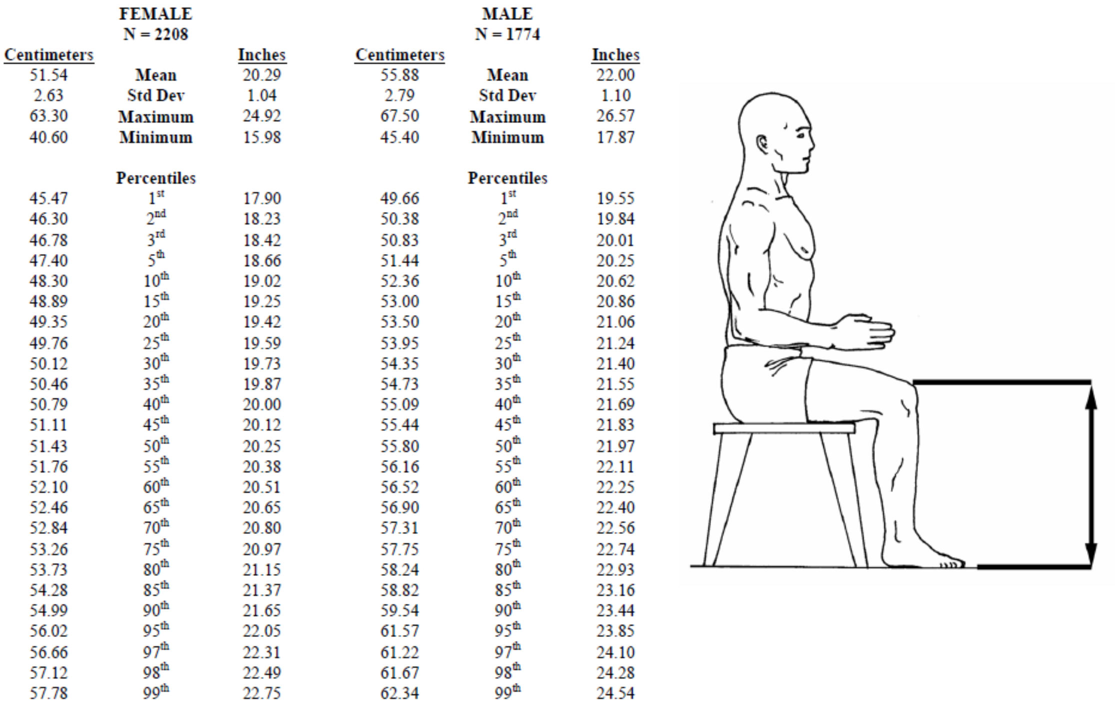


Figure I.14 Hand length



	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
34.27	**Mean**	13.49	34.18	**Mean**	13.46
2.24	**Std Dev**	.88	2.03	**Std Dev**	.80
42.00	**Maximum**	16.54	41.60	**Maximum**	16.38
27.00	**Minimum**	10.63	28.20	**Minimum**	11.10
	Percentiles			**Percentiles**	
29.58	1st	11.65	29.64	1st	11.67
30.05	2nd	11.83	30.18	2nd	11.88
30.35	3rd	11.95	30.51	3rd	12.01
30.78	5th	12.12	30.97	5th	12.19
31.47	10th	12.39	31.66	10th	12.46
31.96	15th	12.58	32.12	15th	12.65
32.35	20th	12.74	32.49	20th	12.79
32.70	25th	12.87	32.81	25th	12.92
33.01	30th	13.00	33.10	30th	13.03
33.31	35th	13.11	33.36	35th	13.14
33.59	40th	13.23	33.62	40th	13.24
33.87	45th	13.34	33.87	45th	13.33
34.15	50th	13.45	34.12	50th	13.43
34.44	55th	13.56	34.37	55th	13.53
34.73	60th	13.67	34.62	60th	13.63
35.03	65th	13.79	34.89	65th	13.74
35.36	70th	13.92	35.18	70th	13.85
35.71	75th	14.06	35.49	75th	13.97
36.12	80th	14.22	35.85	80th	14.11
36.59	85th	14.41	36.27	85th	14.28
37.21	90th	14.65	36.82	90th	14.50
38.15	95th	15.02	37.65	95th	14.82
38.77	97th	15.27	38.22	97th	15.05
39.24	98th	15.45	38.64	98th	15.21
40.00	99th	15.75	39.32	99th	15.48

Figure I.15 Hip breadth



	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
51.54	**Mean**	20.29	55.88	**Mean**	22.00
2.63	**Std Dev**	1.04	2.79	**Std Dev**	1.10
63.30	**Maximum**	24.92	67.50	**Maximum**	26.57
40.60	**Minimum**	15.98	45.40	**Minimum**	17.87
	Percentiles			**Percentiles**	
45.47	1st	17.90	49.66	1st	19.55
46.30	2nd	18.23	50.38	2nd	19.84
46.78	3rd	18.42	50.83	3rd	20.01
47.40	5th	18.66	51.44	5th	20.25
48.30	10th	19.02	52.36	10th	20.62
48.89	15th	19.25	53.00	15th	20.86
49.35	20th	19.42	53.50	20th	21.06
49.76	25th	19.59	53.95	25th	21.24
50.12	30th	19.73	54.35	30th	21.40
50.46	35th	19.87	54.73	35th	21.55
50.79	40th	20.00	55.09	40th	21.69
51.11	45th	20.12	55.44	45th	21.83
51.43	50th	20.25	55.80	50th	21.97
51.76	55th	20.38	56.16	55th	22.11
52.10	60th	20.51	56.52	60th	22.25
52.46	65th	20.65	56.90	65th	22.40
52.84	70th	20.80	57.31	70th	22.56
53.26	75th	20.97	57.75	75th	22.74
53.73	80th	21.15	58.24	80th	22.93
54.28	85th	21.37	58.82	85th	23.16
54.99	90th	21.65	59.54	90th	23.44
56.02	95th	22.05	61.57	95th	23.85
56.66	97th	22.31	61.22	97th	24.10
57.12	98th	22.49	61.67	98th	24.28
57.78	99th	22.75	62.34	99th	24.54

Figure I.16 Knee height, sitting

	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
24.34	**Mean**	9.58	26.99	**Mean**	10.62
1.55	**Std Dev**	.61	1.57	**Std Dev**	.62
31.20	**Maximum**	12.28	32.50	**Maximum**	12.80
15.70	**Minimum**	6.18	21.20	**Minimum**	8.35
	Percentiles			**Percentiles**	
20.97	1st	8.26	23.67	1st	9.32
21.32	2nd	8.39	24.01	2nd	9.45
21.55	3rd	8.49	24.23	3rd	9.54
21.87	5th	8.61	24.54	5th	9.66
22.39	10th	8.81	25.03	10th	9.85
22.74	15th	8.95	25.37	15th	9.99
23.03	20th	9.07	25.65	20th	10.10
23.28	25th	9.16	25.89	25th	10.19
23.50	30th	9.25	26.11	30th	10.28
23.71	35th	9.33	26.32	35th	10.36
23.91	40th	9.41	26.52	40th	10.44
24.10	45th	9.49	26.72	45th	10.52
24.30	50th	9.57	26.92	50th	10.60
24.49	55th	9.64	27.12	55th	10.68
24.69	60th	9.72	27.32	60th	10.76
24.89	65th	9.80	27.53	65th	10.84
25.11	70th	9.89	27.76	70th	10.93
25.35	75th	9.98	28.01	75th	11.03
25.62	80th	10.09	28.29	80th	11.14
25.93	85th	10.21	28.62	85th	11.27
26.33	90th	10.37	29.05	90th	11.44
26.94	95th	10.61	29.69	95th	11.69
27.35	97th	10.77	30.11	97th	11.85
27.65	98th	10.89	30.42	98th	11.98
28.14	99th	11.08	30.92	99th	12.17

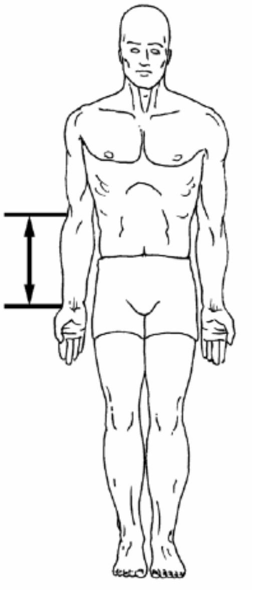


Figure I.17 Lower arm

	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
45.87	**Mean**	18.06	50.48	**Mean**	19.88
2.61	**Std Dev**	1.03	2.76	**Std Dev**	1.09
58.40	**Maximum**	22.99	62.00	**Maximum**	24.41
35.80	**Minimum**	14.09	40.60	**Minimum**	15.98
	Percentiles			**Percentiles**	
39.94	1st	15.73	44.30	1st	17.44
40.64	2nd	16.00	45.05	2nd	17.74
41.07	3rd	16.17	45.50	3rd	17.91
41.67	5th	16.40	46.10	5th	18.15
42.58	10th	16.76	47.01	10th	18.51
43.19	15th	17.00	47.63	15th	18.75
43.68	20th	17.20	48.13	20th	18.95
44.10	25th	17.36	48.56	25th	19.12
44.48	30th	17.51	48.96	30th	19.27
44.83	35th	17.65	49.33	35th	19.42
45.16	40th	17.78	49.69	40th	19.56
45.48	45th	17.91	50.04	45th	19.70
45.81	50th	18.03	50.39	50th	19.84
46.13	55th	18.16	50.75	55th	19.98
46.46	60th	18.29	51.11	60th	20.12
46.81	65th	18.43	51.49	65th	20.27
47.17	70th	18.57	51.90	70th	20.43
47.57	75th	18.73	52.34	75th	20.61
48.02	80th	18.91	52.84	80th	20.80
48.55	85th	19.11	53.41	85th	21.03
49.23	90th	19.38	54.13	90th	21.31
50.25	95th	19.78	55.16	95th	21.72
50.94	97th	20.05	55.78	97th	21.96
51.45	98th	20.26	56.21	98th	22.13
52.27	99th	20.58	56.81	99th	22.37

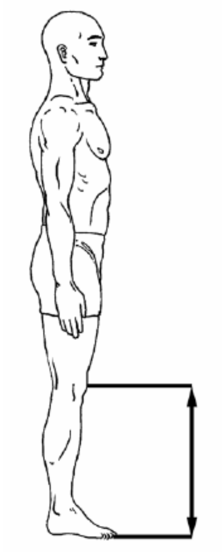


Figure I.18 Lower leg

	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
38.94	**Mean**	15.33	43.41	**Mean**	17.09
2.37	**Std Dev**	.93	2.49	**Std Dev**	.98
50.00	**Maximum**	19.69	54.70	**Maximum**	21.54
29.90	**Minimum**	11.77	33.80	**Minimum**	13.31
	Percentiles			**Percentiles**	
33.67	1st	13.25	37.83	1st	14.89
34.24	2nd	13.48	38.49	2nd	15.15
34.61	3rd	13.63	38.90	3rd	15.32
35.13	5th	13.83	39.46	5th	15.53
35.93	10th	14.14	40.30	10th	15.86
36.48	15th	14.36	40.86	15th	16.09
36.92	20th	14.53	41.31	20th	16.26
37.30	25th	14.39	41.70	25th	16.42
37.65	30th	14.82	42.06	30th	16.56
37.98	35th	14.95	42.39	35th	16.69
38.29	40th	15.07	42.70	40th	16.81
38.59	45th	15.19	43.01	45th	16.93
38.89	50th	15.31	43.32	50th	17.06
39.19	55th	15.43	43.63	55th	17.18
39.50	60th	15.55	43.95	60th	17.30
39.82	65th	15.68	44.28	65th	17.43
40.16	70th	15.81	44.64	70th	17.57
40.53	75th	15.96	45.03	75th	17.73
40.94	80th	16.12	45.47	80th	17.90
41.42	85th	16.31	45.98	85th	18.10
42.04	90th	16.55	46.64	90th	18.36
42.94	95th	16.91	47.63	95th	18.75
43.53	97th	17.14	48.28	97th	19.01
43.96	98th	17.31	48.75	98th	19.19
44.63	99th	17.57	49.49	99th	19.48

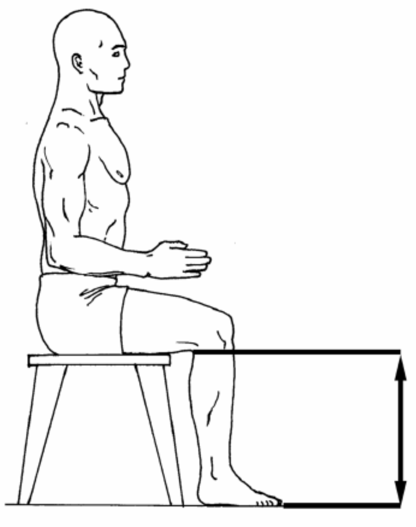


Figure I.19 Popliteal height

	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
133.36	**Mean**	52.50	144.25	**Mean**	56.79
5.79	**Std Dev**	2.28	6.20	**Std Dev**	2.44
156.5	**Maximum**	61.61	170.4	**Maximum**	67.09
113.9	**Minimum**	44.84	118.2	**Minimum**	46.54
	Percentiles			**Percentiles**	
119.82	1st	47.17	129.86	1st	51.13
121.63	2nd	47.89	131.62	2nd	51.82
122.70	3rd	48.31	132.71	3rd	52.25
124.09	5th	48.85	134.16	5th	52.82
126.12	10th	49.65	136.35	10th	53.68
127.45	15th	50.18	137.83	15th	54.26
128.49	20th	50.59	139.00	20th	54.72
129.40	25th	50.95	140.02	25th	55.13
130.22	30th	51.27	140.93	30th	55.49
130.99	35th	51.57	141.78	35th	55.82
131.72	40th	51.86	142.60	40th	56.14
132.44	45th	52.14	143.39	45th	56.45
133.16	50th	52.43	144.18	50th	56.76
133.90	55th	52.72	144.97	55th	57.07
134.65	60th	53.01	145.77	60th	57.39
135.43	65th	53.32	146.61	65th	57.72
136.27	70th	53.65	147.50	70th	58.07
137.19	75th	54.01	148.46	75th	58.45
138.23	80th	54.42	149.53	80th	58.87
139.44	85th	54.90	150.77	85th	59.36
140.97	90th	55.50	152.32	90th	59397
143.20	95th	56.38	154.56	95th	60.85
144.59	97th	56.93	155.95	97th	61.40
145.57	98th	57.31	156.93	98th	61.79
146.99	99th	57.87	158.38	99th	62.35

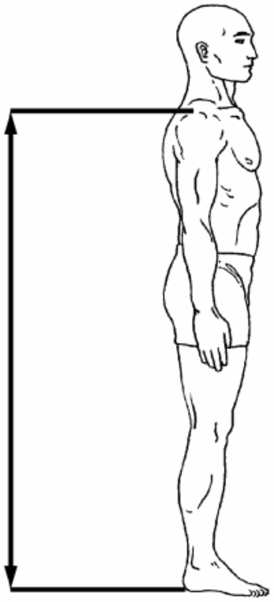


Figure I.20 Shoulder height

	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
55.55	**Mean**	21.87	59.78	**Mean**	23.53
2.86	**Std Dev**	1.13	2.96	**Std Dev**	1.16
66.40	**Maximum**	26.14	69.50	**Maximum**	27.36
46.40	**Minimum**	18.27	50.10	**Minimum**	19.72
	Percentiles			**Percentiles**	
49.24	1st	19.38	52.52	1st	20.68
49.88	2nd	19.64	53.49	2nd	21.06
50.31	3rd	19.81	54.08	3rd	21.29
50.91	5th	20.04	54.85	5th	21.59
51.87	10th	20.42	55.98	10th	22.04
52.54	15th	20.69	56.73	15th	22.33
53.09	20th	20.90	57.31	20th	22.56
53.56	25th	21.09	57.81	25th	22.76
53.99	30th	21.26	58.25	30th	22.93
54.39	35th	21.41	58.66	35th	23.10
54.77	40th	21.56	59.05	40th	23.25
55.14	45th	21.71	59.43	45th	23.40
55.51	50th	21.85	59.80	50th	23.54
55.88	55th	22.00	60.17	55th	23.69
56.25	60th	22.15	60.55	60th	23.84
56.64	65th	22.30	60.94	65th	23.99
57.05	70th	22.46	61.35	70th	24.15
57.50	75th	22.64	61.79	75th	24.33
57.99	80th	22.83	62.29	80th	24.52
58.57	85th	23.06	62.86	85th	24.75
59.29	90th	23.34	63.58	90th	25.03
60.36	95th	23.76	64.63	95th	25.44
61.05	97th	24.03	65.28	97th	25.70
61.55	98th	24.23	65.75	98th	25.89
62.33	99th	24.54	66.45	99th	26.16

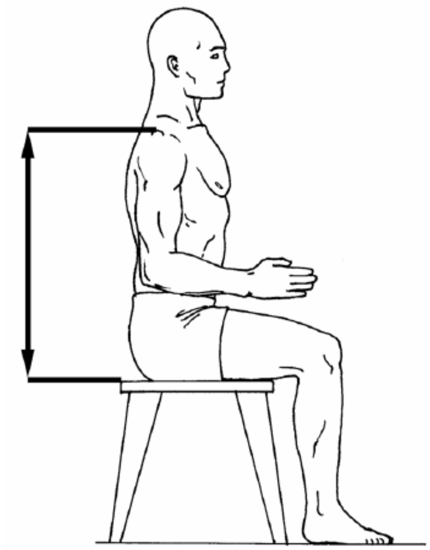


Figure I.21 Shoulder height, sitting

	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
33.58	**Mean**	13.22	36.90	**Mean**	14.53
1.74	**Std Dev**	.68	1.79	**Std Dev**	.71
40.10	**Maximum**	15.79	44.60	**Maximum**	17.56
28.20	**Minimum**	11.10	29.70	**Minimum**	11.69
	Percentiles			**Percentiles**	
29.62	1st	11.66	32.88	1st	12.94
30.08	2nd	11.84	33.33	2nd	13.12
30.37	3rd	11.96	33.62	3rd	13.24
30.76	5th	12.11	34.02	5th	13.39
31.36	10th	12.35	34.64	10th	13.64
31.77	15th	12.51	35.06	15th	13.80
32.09	20th	12.64	35.40	20th	13.94
32.38	25th	12.75	35.69	25th	14.05
32.63	30th	12.85	35.95	30th	14.15
32.87	35th	12.94	36.20	35th	14.25
33.10	40th	13.03	36.43	40th	14.34
33.32	45th	13.12	36.66	45th	14.43
33.54	50th	13.20	36.88	50th	14.52
33.76	55th	13.29	37.11	55th	14.61
33.98	60th	13.38	37.34	60th	14.70
34.22	65th	13.47	37.58	65th	14.79
34.47	70th	13.57	37.83	70th	14.89
34.74	75th	13.68	38.10	75th	15.00
35.05	80th	13.80	38.41	80th	15.12
35.40	85th	13.94	38.76	85th	15.26
35.85	90th	14.11	39.21	90th	15.44
36.51	95th	14.37	39.88	95th	15.70
36.92	97th	14.54	40.31	97th	15.87
37.23	98th	14.66	40.63	98th	16.00
37.69	99th	14.84	41.13	99th	16.19

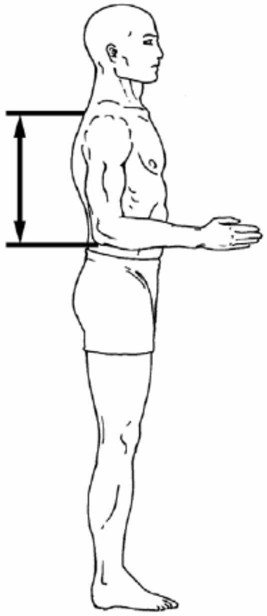


Figure I.22 Shoulder-elbow length

	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
35.15	**Mean**	13.84	38.37	**Mean**	15.11
2.28	**Std Dev**	.90	2.56	**Std Dev**	1.01
44.20	**Maximum**	17.40	48.30	**Maximum**	19.02
27.80	**Minimum**	10.94	30.50	**Minimum**	12.01
	Percentiles			**Percentiles**	
30.15	1st	11.87	32.65	1st	12.85
30.69	2nd	12.08	33.29	2nd	13.11
31.04	3rd	12.22	33.70	3rd	13.27
31.53	5th	12.41	34.27	5th	13.49
32.28	10th	12.71	35.15	10th	13.84
32.80	15th	12.97	35.74	15th	14.07
33.21	20th	13.07	36.22	20th	14.26
33.57	25th	13.22	36.63	25th	14.42
33.90	30th	13.35	37.00	30th	14.57
34.21	35th	13.47	37.34	35th	14.70
34.50	40th	13.58	37.64	40th	14.83
34.79	45th	13.70	37.99	45th	14.95
35.07	50th	13.81	38.30	50th	15.08
35.36	55th	13.92	38.62	55th	15.20
35.65	60th	14.04	38.94	60th	15.33
35.96	65th	14.16	39.28	65th	15.46
36.29	70th	14.29	39.63	70th	15.60
36.65	75th	14.43	40.02	75th	15.76
37.05	80th	14.59	40.47	80th	15.93
37.52	85th	14.77	40.99	85th	16.14
38.13	90th	15.01	41.67	90th	16.40
39.06	95th	15.38	42.72	95th	16.82
39.67	97th	15.62	43.43	97th	17.10
40.12	98th	15.80	43.98	98th	17.31
40.85	99th	16.08	44.88	99th	17.67

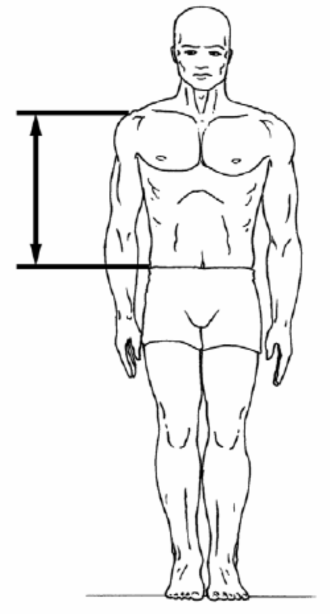


Figure I.23 Shoulder-waist length (omphalion)

	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
85.20	**Mean**	33.54	91.39	**Mean**	35.98
3.49	**Std Dev**	1.37	3.56	**Std Dev**	1.40
97.10	**Maximum**	38.23	103.20	**Maximum**	40.63
74.80	**Minimum**	29.45	80.80	**Minimum**	31.81
	Percentiles			**Percentiles**	
77.48	1st	30.50	82.79	1st	32.59
78.27	2nd	30.81	83.88	2nd	33.02
78.79	3rd	31.02	84.55	3rd	33.29
79.53	5th	31.31	85.45	5th	33.67
80.70	10th	31.77	86.79	10th	34.17
81.52	15th	32.09	87.68	15th	34.52
82.18	20th	32.35	88.38	20th	34.80
82.76	25th	32.58	88.99	25th	35.03
83.28	30th	32.79	89.53	30th	35.25
83.77	35th	32.98	90.03	35th	35.44
84.23	40th	33.16	90.51	40th	35.63
84.69	45th	33.34	90.97	45th	35.81
85.14	50th	33.52	91.42	50th	35.99
85.59	55th	33.70	91.88	55th	36.17
86.05	60th	33.88	92.34	60th	36.35
86.52	65th	34.06	92.82	65th	36.54
87.02	70th	34.26	93.32	70th	36.47
87.57	75th	34.48	93.86	75th	36.95
88.17	80th	34.71	94.46	80th	37.19
88.87	85th	34.99	95.14	85th	37.46
89.75	90th	35.33	95.99	90th	37.79
91.02	95th	35.84	97.19	95th	38.26
91.83	97th	36.15	97.91	97th	38.55
92.42	98th	36.38	98.42	98th	38.75
93.31	99th	36.74	99.14	99th	39.03

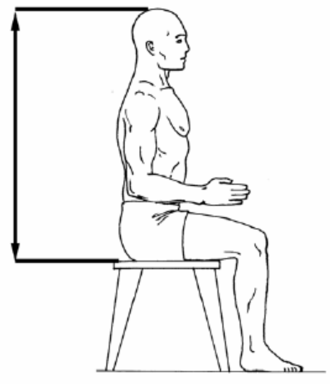


Figure I.24 Sitting Height

FEMALE N = 2208			MALE N = 1774		
Centimeters		Inches	Centimeters		Inches
167.19	**Mean**	65.82	182.31	**Mean**	71.77
8.13	**Std Dev**	3.20	8.19	**Std Dev**	3.23
196.80	**Maximum**	77.48	215.90	**Maximum**	85.00
135.60	**Minimum**	53.39	147.40	**Minimum**	58.03
	Percentiles			**Percentiles**	
148.81	1st	58.89	164.79	1st	64.88
151.02	2nd	59.46	166.53	2nd	65.56
152.38	3rd	59.99	167.68	3rd	66.02
154.21	5th	60.71	169.31	5th	66.66
157.00	10th	61.81	171.94	10th	67.69
158.88	15th	62.55	173.78	15th	68.42
160.37	20th	63.14	175.28	20th	69.01
161.67	25th	63.65	176.60	25th	69.53
162.85	30th	64.11	177.80	30th	70.00
163.94	35th	64.54	178.92	35th	70.44
164.98	40th	64.95	179.99	40th	70.86
166.00	45th	65.36	181.04	45th	71.28
167.02	50th	65.76	182.09	50th	71.69
168.04	55th	66.16	183.14	55th	72.10
169.09	60th	66.57	184.21	60th	72.52
170.18	65th	67.00	185.32	65th	72.96
171.33	70th	67.45	186.50	70th	73.42
172.60	75th	67.95	187.77	75th	73.93
174.02	80th	68.51	189.21	80th	74.49
175.67	85th	69.16	190.86	85th	75.14
177.76	90th	69.99	192.96	90th	75.97
180.86	95th	71.20	196.03	95th	77.18
182.84	97th	71.98	197.99	97th	77.95
184.27	98th	72.55	199.42	98th	78.51
186.45	99th	73.41	201.62	99th	79.38

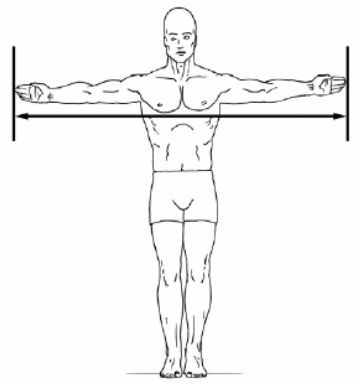


Figure I.25 Span

FEMALE N = 2208			MALE N = 1774		
Centimeters		Inches	Centimeters		Inches
162.94	**Mean**	64.15	175.58	**Mean**	69.13
6.36	**Std Dev**	2.50	6.68	**Std Dev**	2.63
187.00	**Maximum**	73.62	204.20	**Maximum**	80.39
142.80	**Minimum**	56.22	149.70	**Minimum**	58.94
	Percentiles			**Percentiles**	
148.32	1st	58.39	160.27	1st	63.10
150.18	2nd	59.13	162.05	2nd	63.80
151.31	3rd	59.57	163.17	3rd	64.24
152.78	5th	60.15	164.69	5th	64.84
154.97	10th	61.01	167.03	10th	65.76
156.43	15th	61.59	168.62	15th	66.39
157.58	20th	62.04	169.86	20th	66.88
158.58	25th	62.43	173.99	25th	67.32
159.48	30th	62.79	171.98	30th	67.71
160.32	35th	63.12	172.90	35th	68.70
161.14	40th	63.44	173.78	40th	68.42
161.93	45th	63.75	174.64	45th	68.76
162.72	50th	64.06	175.49	50th	69.09
163.53	55th	64.38	176.34	55th	69.43
164.35	60th	64.70	177.21	60th	69.77
165.21	65th	65.04	178.11	65th	70.12
166.13	70th	65.40	179.06	70th	70.50
167.13	75th	65.80	180.09	75th	70.90
168.27	80th	66.25	181.24	80th	71.35
169.59	85th	66.77	182.57	85th	71.88
171.27	90th	67.43	184.23	90th	72.53
173.73	95th	68.40	186.65	95th	73.48
175.28	97th	69.01	188.16	97th	74.08
176.39	98th	69.44	189.24	98th	74.50
178.04	99th	70.09	190.87	99th	75.14

Figure I.26 Statue

	FEMALE **N = 2208**			**MALE** **N = 1774**	
Centimeters		Inches	Centimeters		Inches
31.19	**Mean**	12.28	34.08	**Mean**	13.42
1.67	**Std Dev**	.66	1.72	**Std Dev**	.68
37.00	**Maximum**	14.57	41.50	**Maximum**	16.34
26.20	**Minimum**	10.31	27.10	**Minimum**	10.67
	Percentiles			**Percentiles**	
27.37	1st	10.77	30.23	1st	11.90
27.83	2nd	10.95	30.66	2nd	12.07
28.11	3rd	11.07	30.94	3rd	12.18
28.49	5th	11.22	31.32	5th	12.33
29.07	10th	11.44	31.91	10th	12.56
29.46	15th	11.60	32.31	15th	12.72
29.77	20th	11.72	32.63	20th	12.85
30.04	25th	11.83	32.91	25th	12.96
30.28	30th	11.92	33.16	30th	13.06
30.50	35th	12.01	33.40	35th	13.15
30.72	40th	12.09	33.62	40th	13.24
30.93	45th	12.18	33.83	45th	13.32
31.14	50th	12.26	34.05	50th	13.41
31.35	55th	12.34	34.27	55th	13.49
31.57	60th	12.43	34.49	60th	13.58
31.79	65th	12.52	34.72	65th	13.67
32.03	70th	12.61	34.96	70th	13.76
32.29	75th	12.71	35.22	75th	13.87
32.59	80th	12.83	35.52	80th	13.98
32.93	85th	12.96	35.86	85th	14.12
33.37	90th	13.14	36.30	90th	14.29
34.02	95th	13.39	36.95	95th	14.55
34.44	97th	13.56	37.38	97th	14.72
34.74	98th	13.68	37.69	98th	14.84
35.21	99th	13.86	38.18	99th	15.03

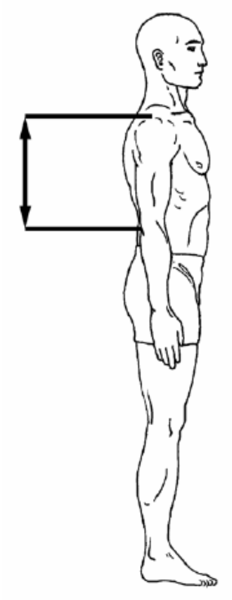


Figure I.27 Upper arm length

	FEMALE **N = 2208**			**MALE** **N = 1774**	
Centimeters		Inches	Centimeters		Inches
60.95	**Mean**	24.00	66.57	**Mean**	26.21
3.27	**Std Dev**	1.29	3.33	**Std Dev**	1.31
73.50	**Maximum**	28.94	81.40	**Maximum**	32.05
49.20	**Minimum**	19.37	54.10	**Minimum**	21.30
	Percentiles			**Percentiles**	
35.55	1st	21.08	59.08	1st	23.26
54.42	2nd	21.43	59.95	2nd	23.60
54.97	3rd	21.64	60.50	3rd	23.82
55.71	5th	21.93	62.23	5th	24.11
56.84	10th	22.38	62.36	10th	24.55
57.61	15th	22.68	63.13	15th	24.85
58.21	20th	22.92	63.74	20th	25.09
58.74	25th	23.13	64.28	25th	25.31
59.21	30th	23.31	64.76	30th	25.50
59.65	35th	23.48	65.21	35th	25.67
60.07	40th	23.65	65.65	40th	25.84
60.48	45th	23.81	66.07	45th	26.01
60.88	50th	23.97	66.49	50th	26.18
61.29	55th	24.13	66.92	55th	26.35
61.70	60th	24.29	67.35	60th	26.52
62.14	65th	24.46	67.81	65th	26.70
62.60	70th	24.64	68.29	70th	26.89
63.10	75th	24.84	68.81	75th	27.09
63.66	80th	25.06	69.40	80th	27.32
64.32	85th	25.32	70.09	85th	27.59
65.16	90th	25.65	70.96	90th	27.94
66.42	95th	26.15	72.23	95th	28.44
67.25	97th	26.48	73.04	97th	28.75
67.86	98th	26.72	73.61	98th	28.98
68.82	99th	27.09	74.49	99th	29.33

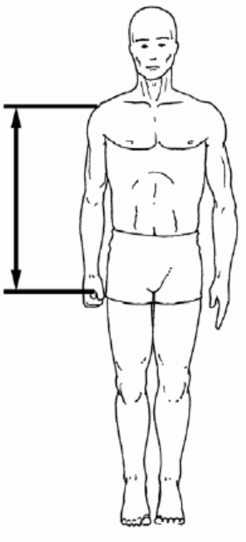


Figure I.28 Vertical grip reach down

	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
121.23	Mean	47.73	130.98	Mean	51.57
5.13	Std Dev	2.02	5.45	Std Dev	2.15
138.60	Maximum	54.57	155.10	Maximum	61.06
103.00	Minimum	40.55	106.40	Minimum	41.89
	Percentiles			Percentiles	
109.24	1st	43.01	117.75	1st	46.36
110.60	2nd	43.54	119.64	2nd	47.10
111.48	3rd	43.89	120.74	3rd	47.53
112.69	5th	44.36	122.14	5th	48.09
114.57	10th	45.11	124.15	10th	48.88
115.86	15th	45.61	125.45	15th	49.39
116.87	20th	46.01	126.46	20th	49.79
117.76	25th	46.36	127.34	25th	50.13
118.54	30th	46.67	128.12	30th	50.44
119.27	35th	46.96	128.84	35th	50.73
119.96	40th	47.23	129.54	40th	51.00
120.62	45th	47.49	130.22	45th	51.27
121.28	50th	47.75	130.90	50th	51.54
121.93	55th	48.01	131.59	55th	51.81
122.59	60th	48.27	132.29	60th	52.08
123.27	65th	48.53	133.02	65th	52.37
123.99	70th	48.81	133.80	70th	52.68
124.75	75th	49.12	134.64	75th	53.01
125.61	80th	49.45	135.60	80th	53.38
126.59	85th	49.84	136.70	85th	53.82
127.82	90th	50.32	138.08	90th	54.36
129.61	95th	51.03	140.05	95th	55.14
130.76	97th	51.48	141.25	97th	55.61
131.60	98th	51.81	142.06	98th	55.93
132.90	99th	52.32	143.20	99th	56.38

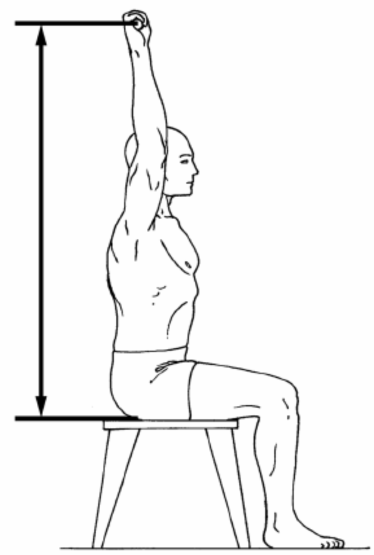


Figure I.29 Vertical Grip reach, sitting

	FEMALE N = 2208			MALE N = 1774	
Centimeters		Inches	Centimeters		Inches
105.65	Mean	41.60	112.71	Mean	44.37
5.17	Std Dev	2.04	5.20	Std Dev	2.05
123.40	Maximum	48.58	134.80	Maximum	53.07
86.30	Minimum	33.98	91.70	Minimum	36.10
	Percentiles			Percentiles	
94.14	1st	37.06	100.91	1st	39.73
95.39	2nd	37.56	102.28	2nd	40.27
96.20	3rd	37.88	103.15	3rd	40.61
97.32	5th	38.32	104.31	5th	41.07
99.09	10th	39.01	106.11	10th	41.78
100.30	15th	39.49	107.33	15th	42.26
101.26	20th	39.87	108.30	20th	42.64
102.10	25th	40.20	109.15	25th	42.97
102.86	30th	40.50	109.91	30th	43.27
103.56	35th	40.77	110.62	35th	43.55
104.23	40th	41.04	111.29	40th	43.82
104.88	45th	41.29	111.95	45th	44.07
105.53	50th	41.55	112.60	50th	44.33
106.18	55th	41.80	113.26	55th	44.59
106.84	60th	42.06	113.92	60th	44.85
107.52	65th	42.33	114.62	65th	45.13
108.25	70th	42.62	115.35	70th	45.41
109.04	75th	42.93	116.15	75th	45.73
109.93	80th	43.28	117.05	80th	46.08
110.97	85th	43.69	118.08	85th	46.49
112.31	90th	44.22	119.40	90th	47.01
1143.33	95th	45.01	121.34	95th	47.77
115.67	97th	45.54	122.58	97th	48.26
116.68	98th	45.94	123.48	98th	48.61
118.30	99th	46.58	124.86	99th	49.16

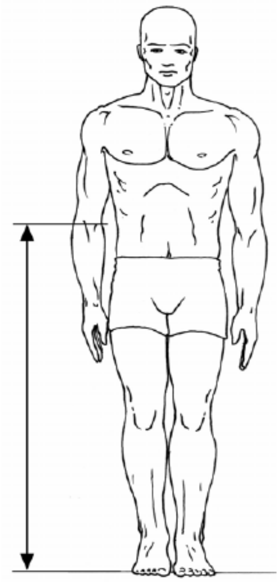


Figure I.30 Waist height (Natural indentation)

	FEMALE **N = 2208**			**MALE** **N = 1774**	
Centimeters		**Inches**	**Centimeters**		**Inches**
27.95	**Mean**	11.01	28.73	**Mean**	11.31
2.14	**Std Dev**	.84	1.66	**Std Dev**	.65
36.00	**Maximum**	14.17	34.70	**Maximum**	13.66
20.08	**Minimum**	8.19	23.10	**Minimum**	9.09
	Percentiles			**Percentiles**	
22.81	1st	8.98	24.79	1st	9.76
23.48	2nd	9.24	35.31	2nd	9.96
23.88	3rd	9.40	25.63	3rd	10.09
24.42	5th	9.61	26.04	5th	10.25
25.22	10th	9.93	26.66	10th	10.50
25.75	15th	10.14	27.06	15th	10.65
26.16	20th	10.30	27.37	20th	10.78
26.52	25th	10.44	27.64	25th	10.88
26.84	30th	10.57	27.88	30th	10.98
27.14	35th	10.69	28.10	35th	11.06
27.42	40th	10.80	28.30	40th	11.14
27.70	45th	10.90	28.51	45th	11.22
27.97	50th	11.01	28.70	50th	11.30
28.24	55th	11.12	28.90	55th	11.38
28.51	60th	11.23	29.11	60th	11.46
28.80	65th	11.34	29.32	65th	11.54
29.10	70th	11.46	29.55	70th	11.63
29.42	75th	11.58	29.79	75th	11.73
29.78	80th	11.73	30.07	80th	11.84
30.20	85th	11.89	30.41	85th	11.97
30.72	90th	12.09	30.84	90th	12.14
31.46	95th	12.39	31.58	95th	12.40
31.92	97th	12.57	31.95	97th	12.58
32.25	98th	12.70	32.29	98th	12.71
32.73	99th	12.89	32.85	99th	12.93

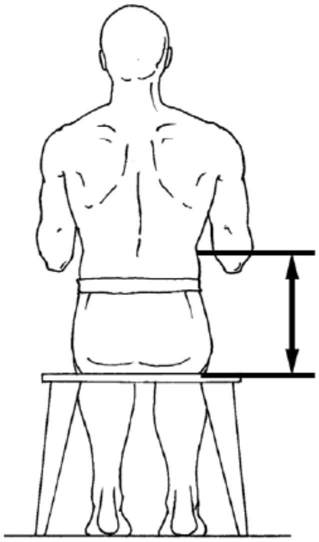


Figure I.31 Waist height sitting (natural indentation)

	FEMALE **N = 2208**			**MALE** **N = 1774**	
Centimeters		**Inches**	**Centimeters**		**Inches**
47.13	**Mean**	18.55	45.98	**Mean**	18.10
3.44	**Std Dev**	1.36	.52	**Std Dev**	1.39
57.20	**Maximum**	22.52	55.90	**Maximum**	22.01
35.50	**Minimum**	13.98	34.30	**Minimum**	13.50
	Percentiles			**Percentiles**	
39.46	1st	15.53	37.13	1st	14.62
40.09	2nd	15.78	38.19	2nd	15.04
40.57	3rd	15.97	38.88	3rd	15.31
41.29	5th	16.25	39.84	5th	15.68
42.52	10th	16.74	41.32	10th	16.27
43.40	15th	17.09	42.30	15th	16.66
44.12	20th	17.37	43.07	20th	16.96
44.75	25th	17.62	43.72	25th	17.21
45.31	30th	17.84	44.29	30th	17.44
45.83	35th	18.04	44.81	35th	17.64
46.32	40th	18.24	45.29	40th	17.83
46.79	45th	18.42	45.74	45th	18.01
47.25	50th	18.60	46.19	50th	18.18
47.71	55th	18.78	46.62	55th	18.35
48.16	60th	18.96	47.05	60th	18.52
48.62	65th	19.14	47.49	65th	18.70
49.10	70th	19.33	47.94	70th	18.88
49.61	75th	19.53	48.43	75th	19.07
50.16	80th	19.75	48.96	80th	19.28
50.79	85th	19.99	49.57	85th	19.52
51.56	90th	20.30	50.34	90th	19.82
52.66	95th	20.73	51.50	95th	20.27
53.37	97th	21.01	52.27	97th	20.58
53.89	98th	21.22	52.87	98th	20.82
54.72	99th	21.54	53.88	99th	21.21

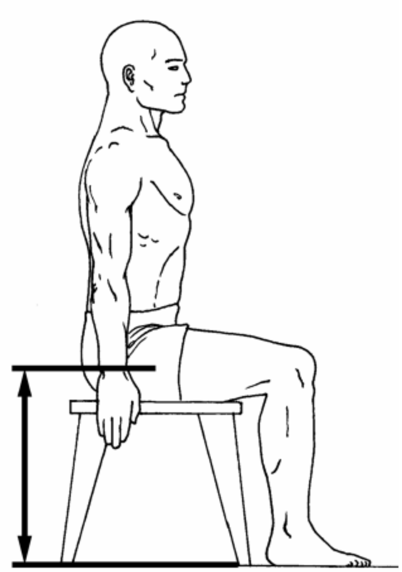
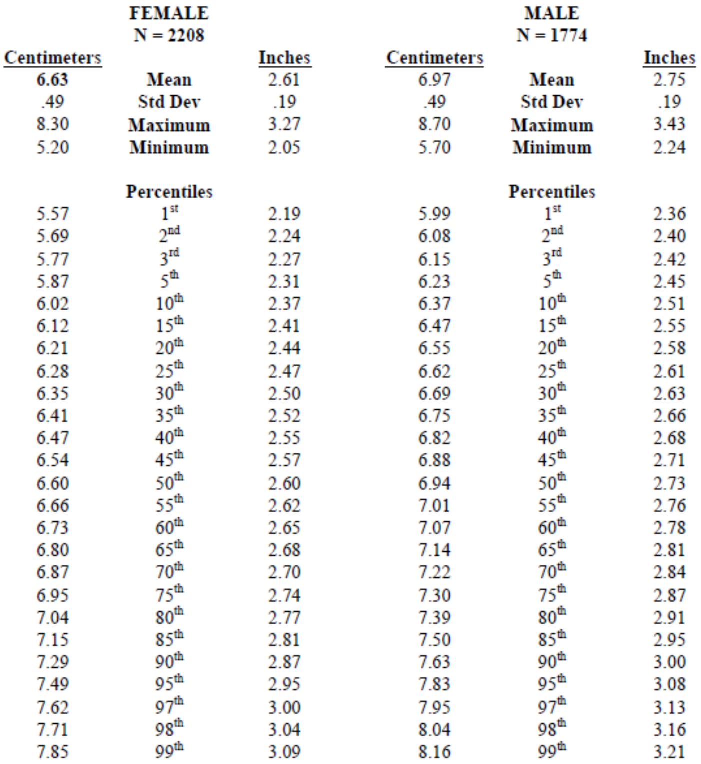


Figure I.32 Wrist height, sitting



Centimeters	FEMALE N = 2208	Inches	Centimeters	MALE N = 1774	Inches
6.63	**Mean**	2.61	6.97	**Mean**	2.75
.49	**Std Dev**	.19	.49	**Std Dev**	.19
8.30	**Maximum**	3.27	8.70	**Maximum**	3.43
5.20	**Minimum**	2.05	5.70	**Minimum**	2.24
	Percentiles			**Percentiles**	
5.57	1st	2.19	5.99	1st	2.36
5.69	2nd	2.24	6.08	2nd	2.40
5.77	3rd	2.27	6.15	3rd	2.42
5.87	5th	2.31	6.23	5th	2.45
6.02	10th	2.37	6.37	10th	2.51
6.12	15th	2.41	6.47	15th	2.55
6.21	20th	2.44	6.55	20th	2.58
6.28	25th	2.47	6.62	25th	2.61
6.35	30th	2.50	6.69	30th	2.63
6.41	35th	2.52	6.75	35th	2.66
6.47	40th	2.55	6.82	40th	2.68
6.54	45th	2.57	6.88	45th	2.71
6.60	50th	2.60	6.94	50th	2.73
6.66	55th	2.62	7.01	55th	2.76
6.73	60th	2.65	7.07	60th	2.78
6.80	65th	2.68	7.14	65th	2.81
6.87	70th	2.70	7.22	70th	2.84
6.95	75th	2.74	7.30	75th	2.87
7.04	80th	2.77	7.39	80th	2.91
7.15	85th	2.81	7.50	85th	2.95
7.29	90th	2.87	7.63	90th	3.00
7.49	95th	2.95	7.83	95th	3.08
7.62	97th	3.00	7.95	97th	3.13
7.71	98th	3.04	8.04	98th	3.16
7.85	99th	3.09	8.16	99th	3.21

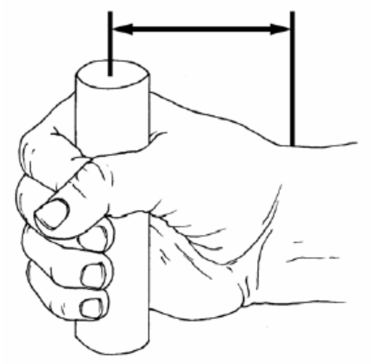
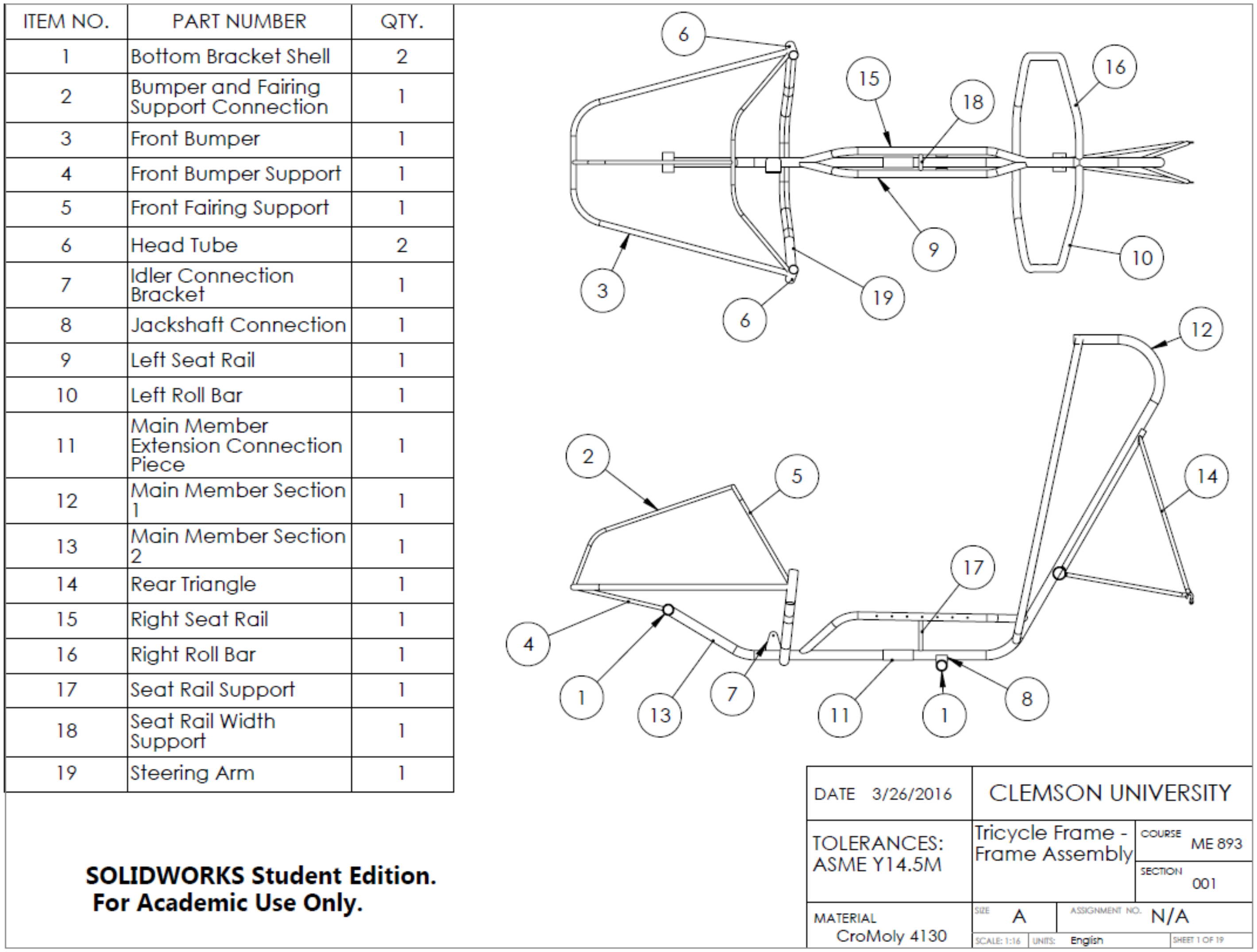


Figure I.33 Wrist-center of grip length



ITEM NO.	PART NUMBER	QTY.
1	Bottom Bracket Shell	2
2	Bumper and Fairing Support Connection	1
3	Front Bumper	1
4	Front Bumper Support	1
5	Front Fairing Support	1
6	Head Tube	2
7	Idler Connection Bracket	1
8	Jackshaft Connection	1
9	Left Seat Rail	1
10	Left Roll Bar	1
11	Main Member Extension Connection Piece	1
12	Main Member Section 1	1
13	Main Member Section 2	1
14	Rear Triangle	1
15	Right Seat Rail	1
16	Right Roll Bar	1
17	Seat Rail Support	1
18	Seat Rail Width Support	1
19	Steering Arm	1

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DATE 3/26/2016
CLEMSON UNIVERSITY
TOLERANCES: ASME Y14.5M
Tricycle Frame - Frame Assembly
COURSE ME 893
SECTION 001
MATERIAL CroMoly 4130
SIZE A
ASSIGNMENT NO. N/A
SCALE: 1:16
UNITS: English
SHEET 1 OF 19

Figure J.1 Frame Assembly drawing (BOM and callouts)

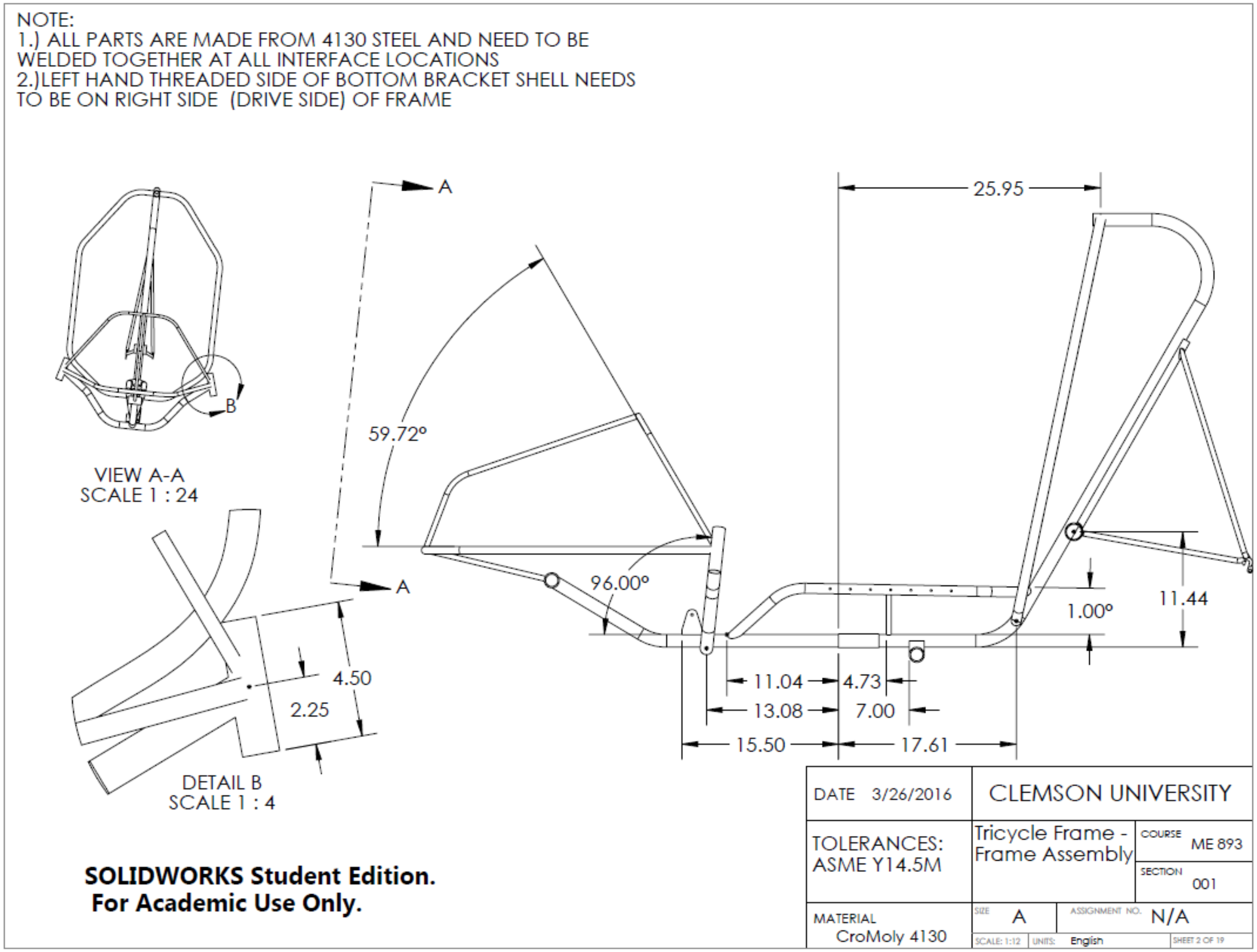


Figure J.2 Frame assembly drawing (dimensioning)

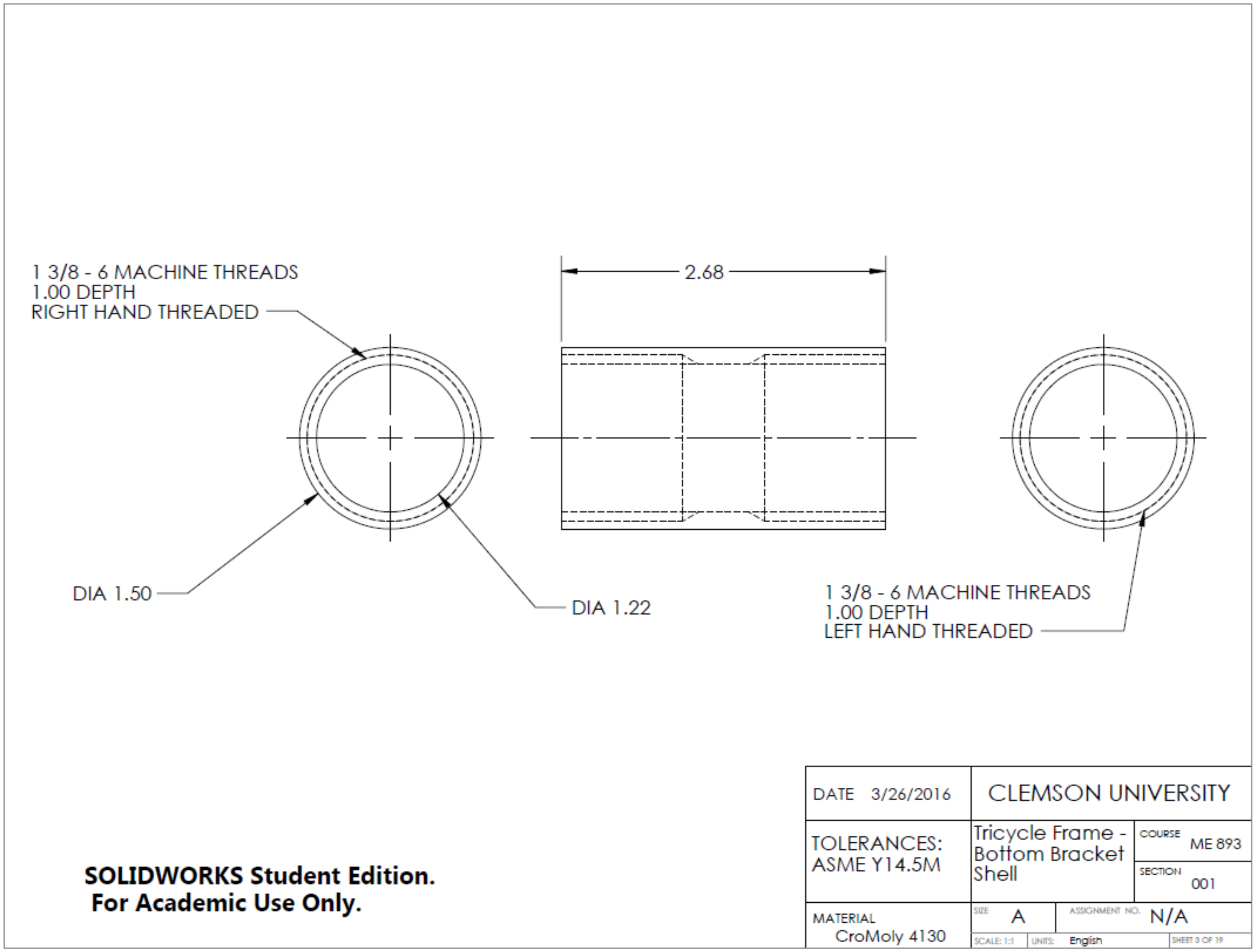


Figure J.3 Bottom bracket shell drawing

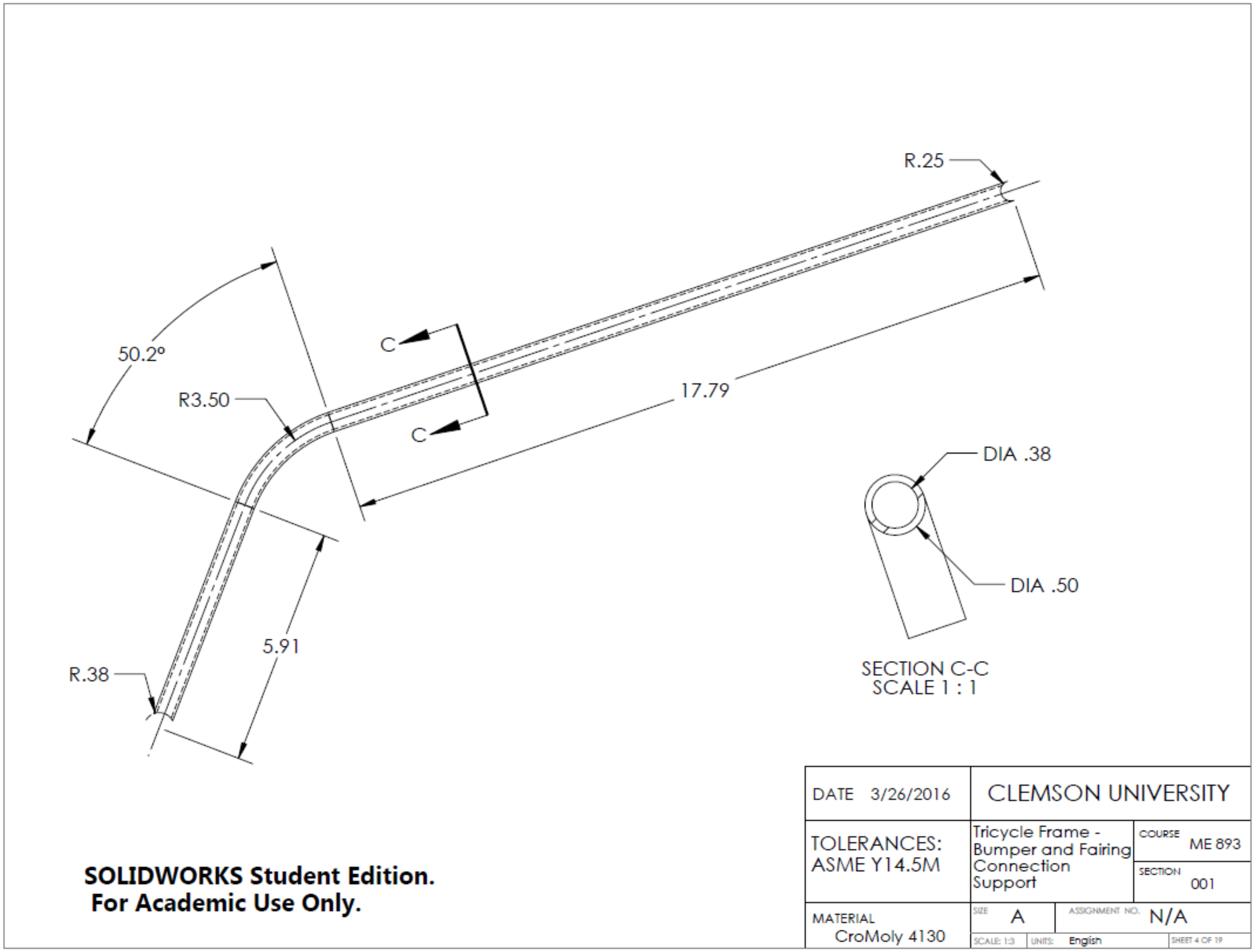


Figure J.4 Bumper and fairing support connection drawing

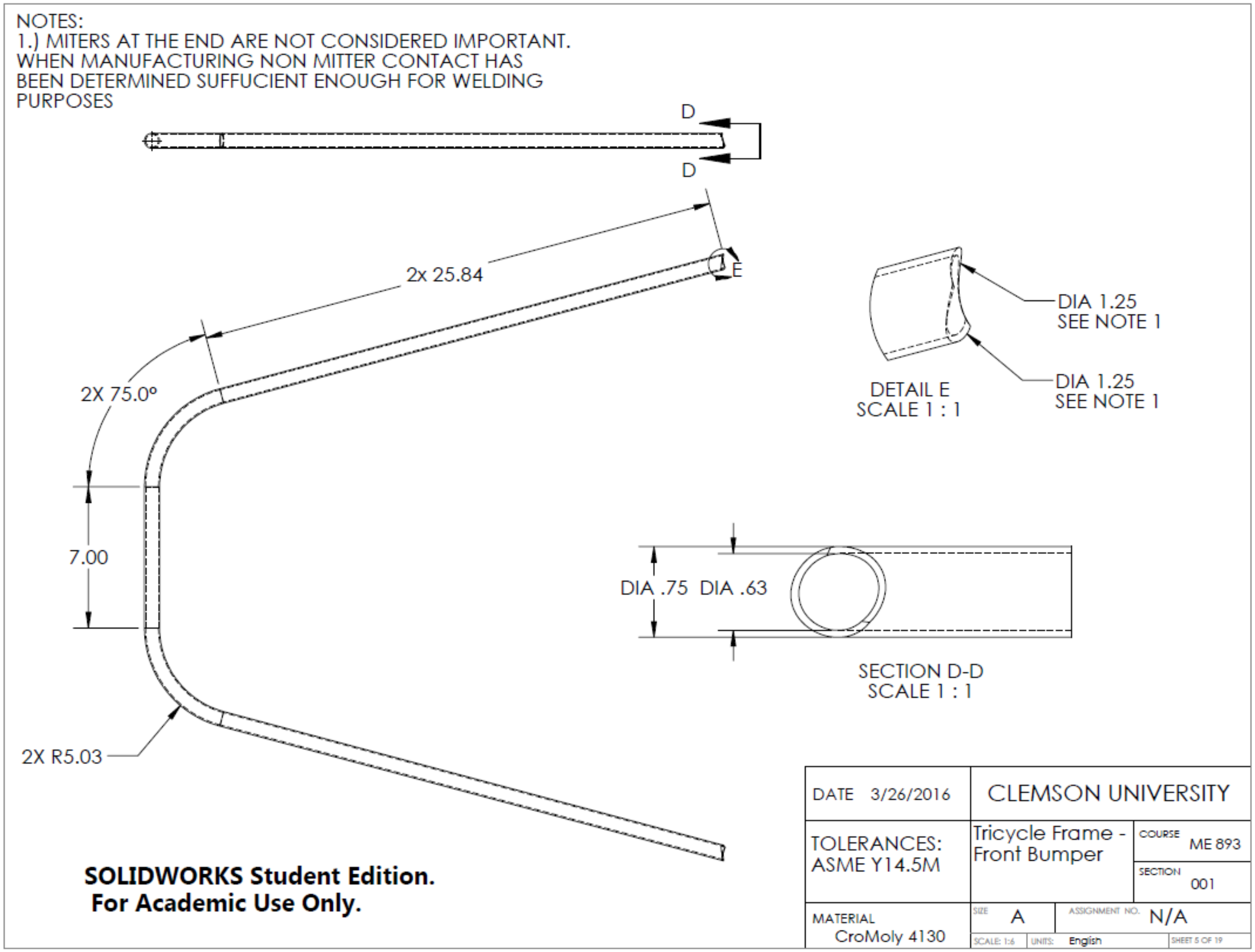


Figure J.5 Front bumper drawing

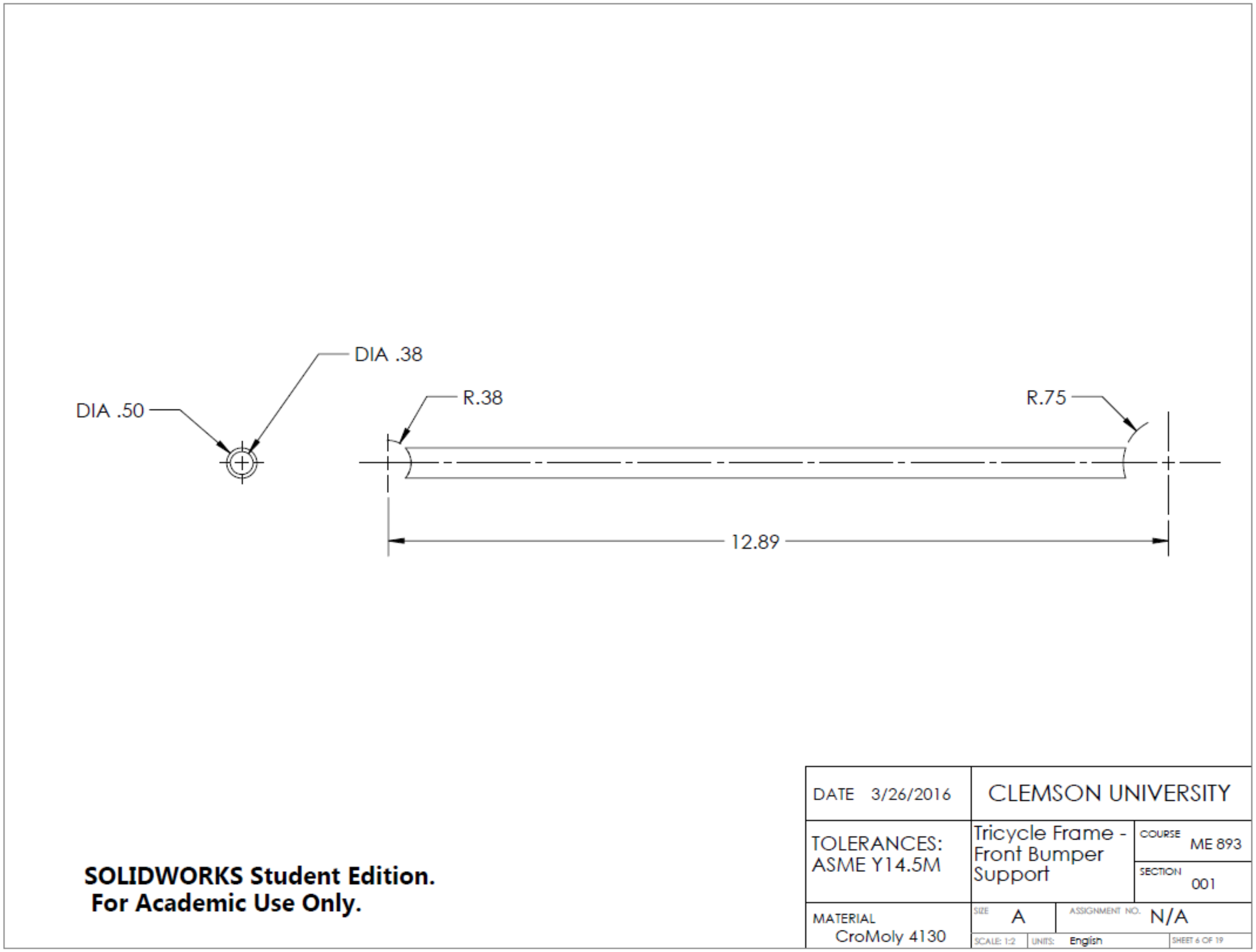


Figure J.6 Front bumper support drawing

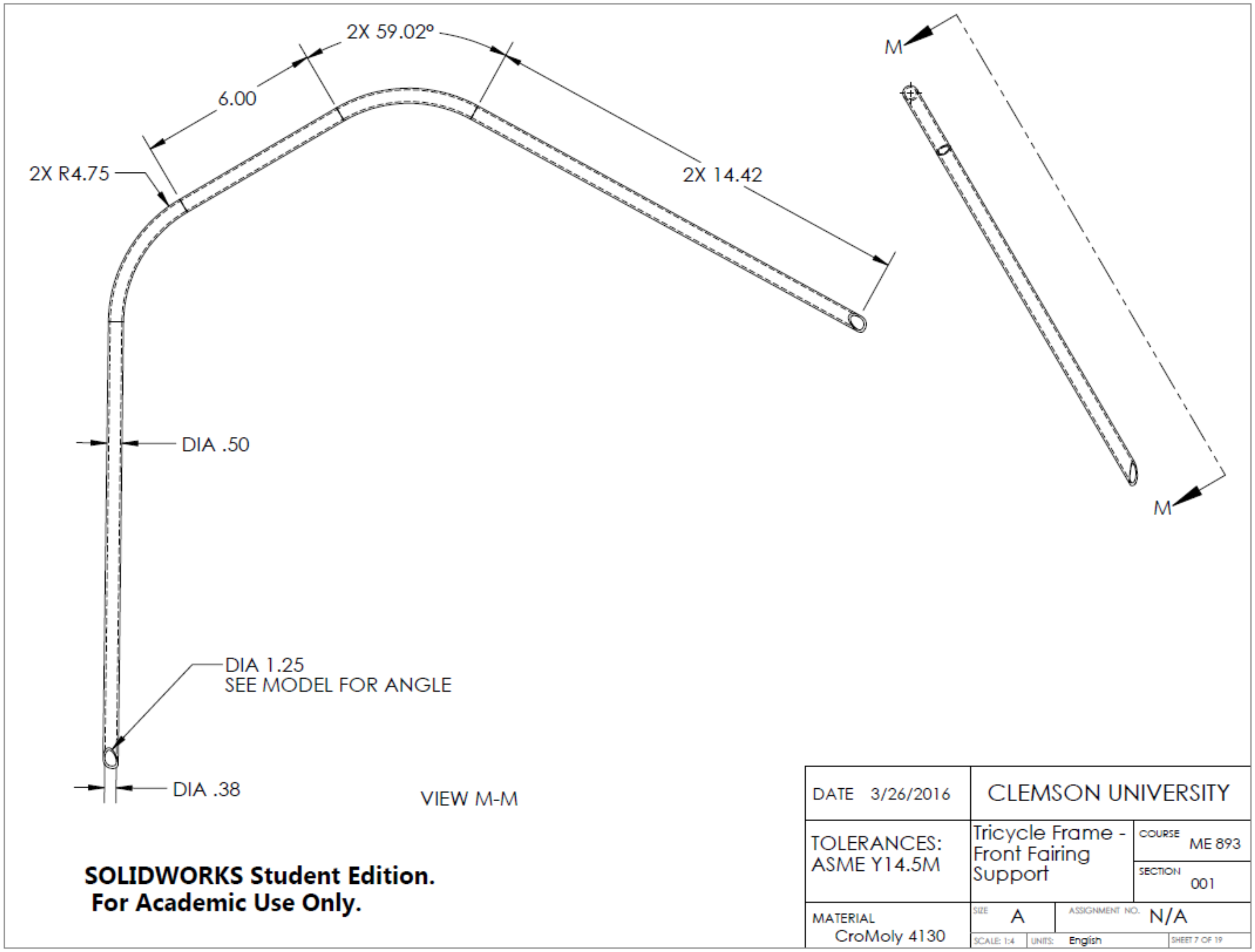


Figure J.7 Front fairing support drawing

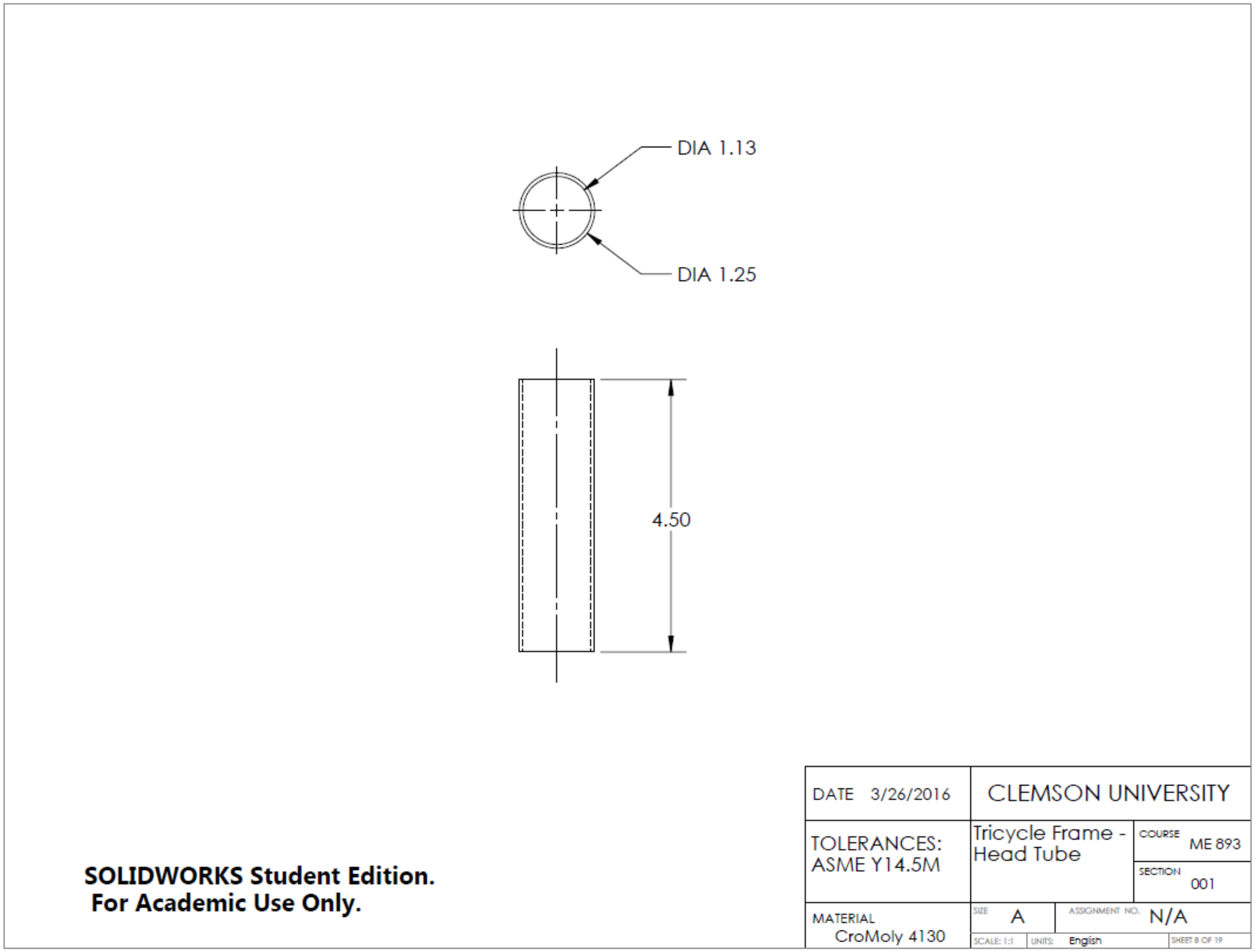


Figure J.8 Head tube drawing

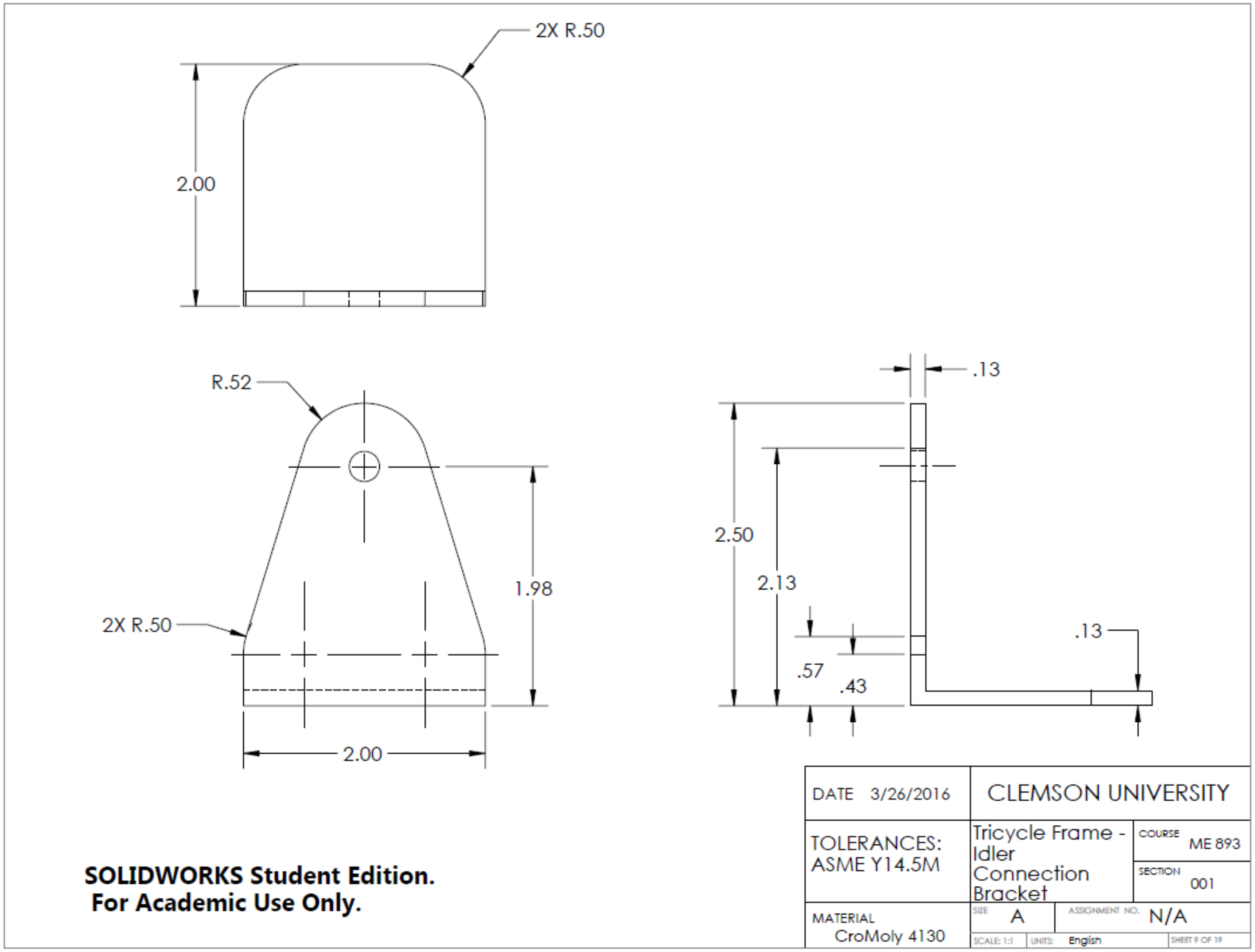


Figure J.9 Idler connection bracket drawing

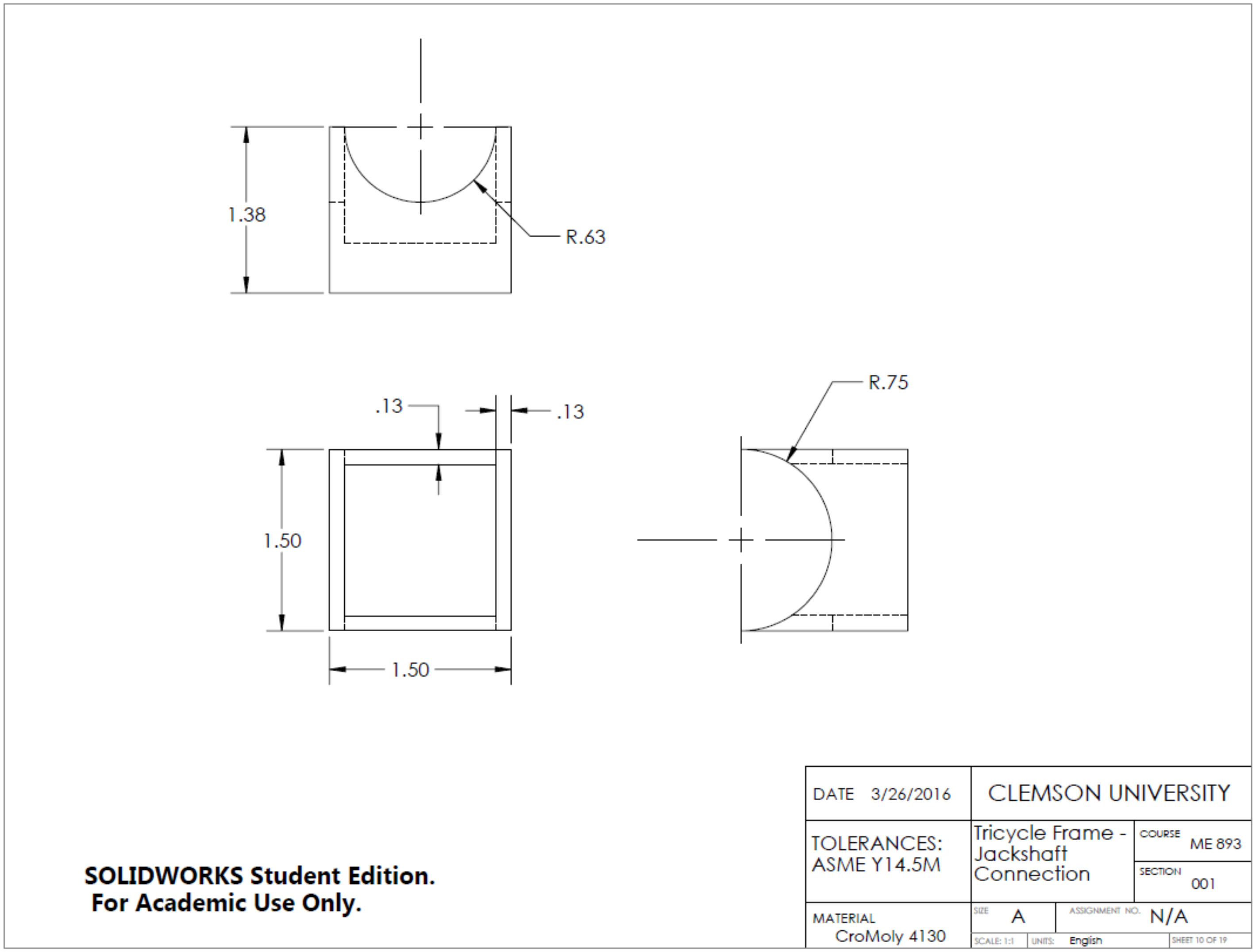


Figure J.10 Jackshaft connection drawing

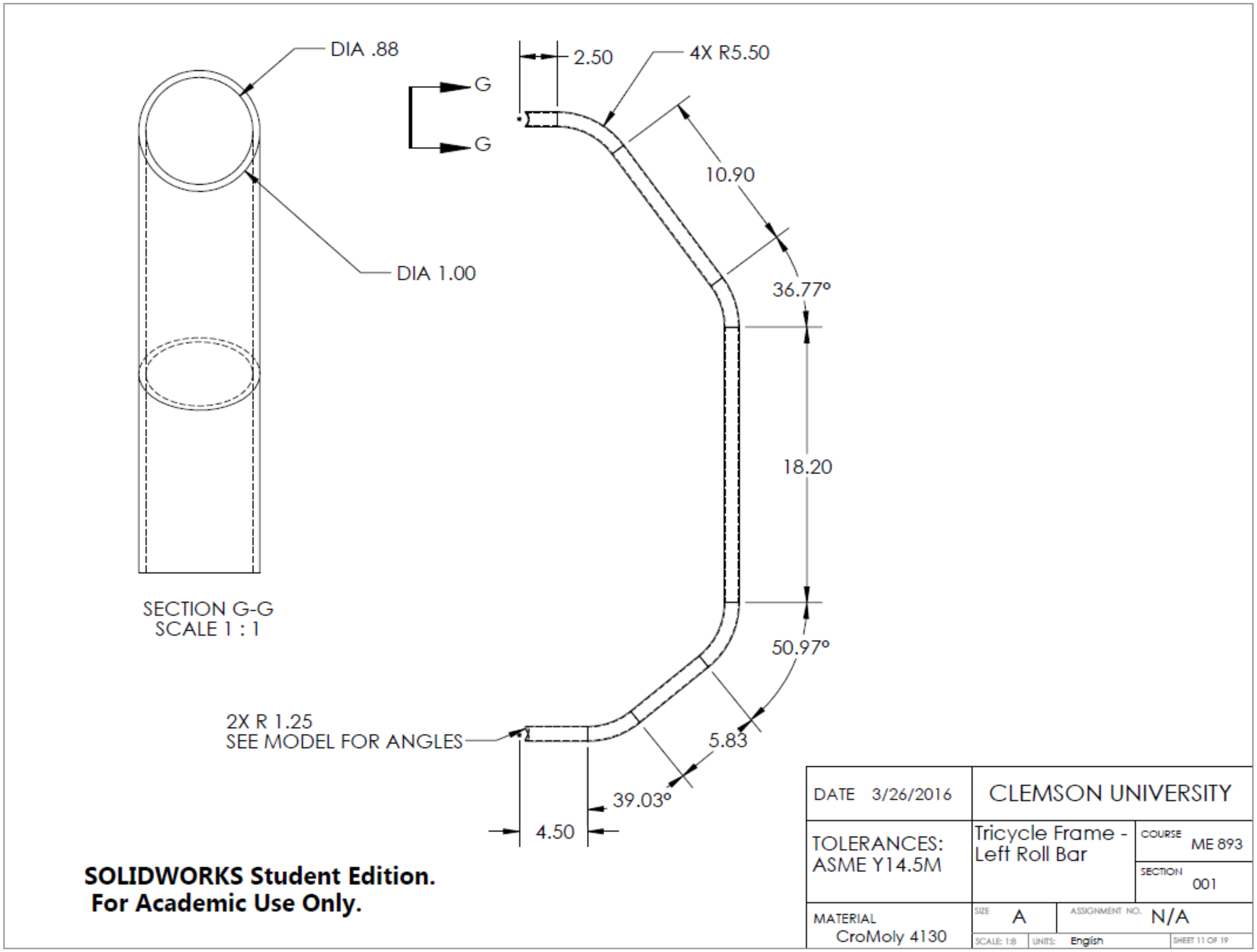


Figure J.11 Left roll bar drawing

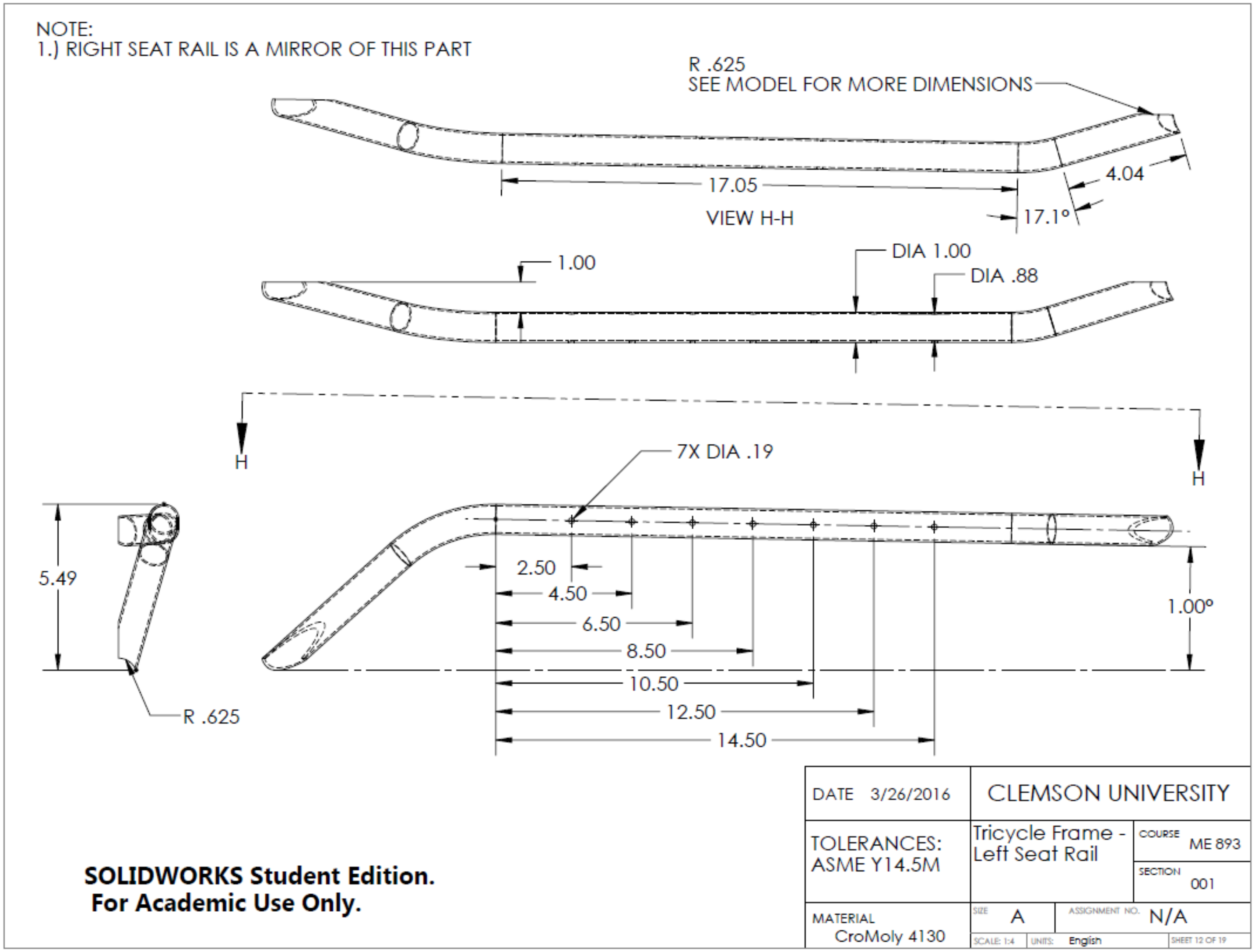


Figure J.12 Left seat rail drawing

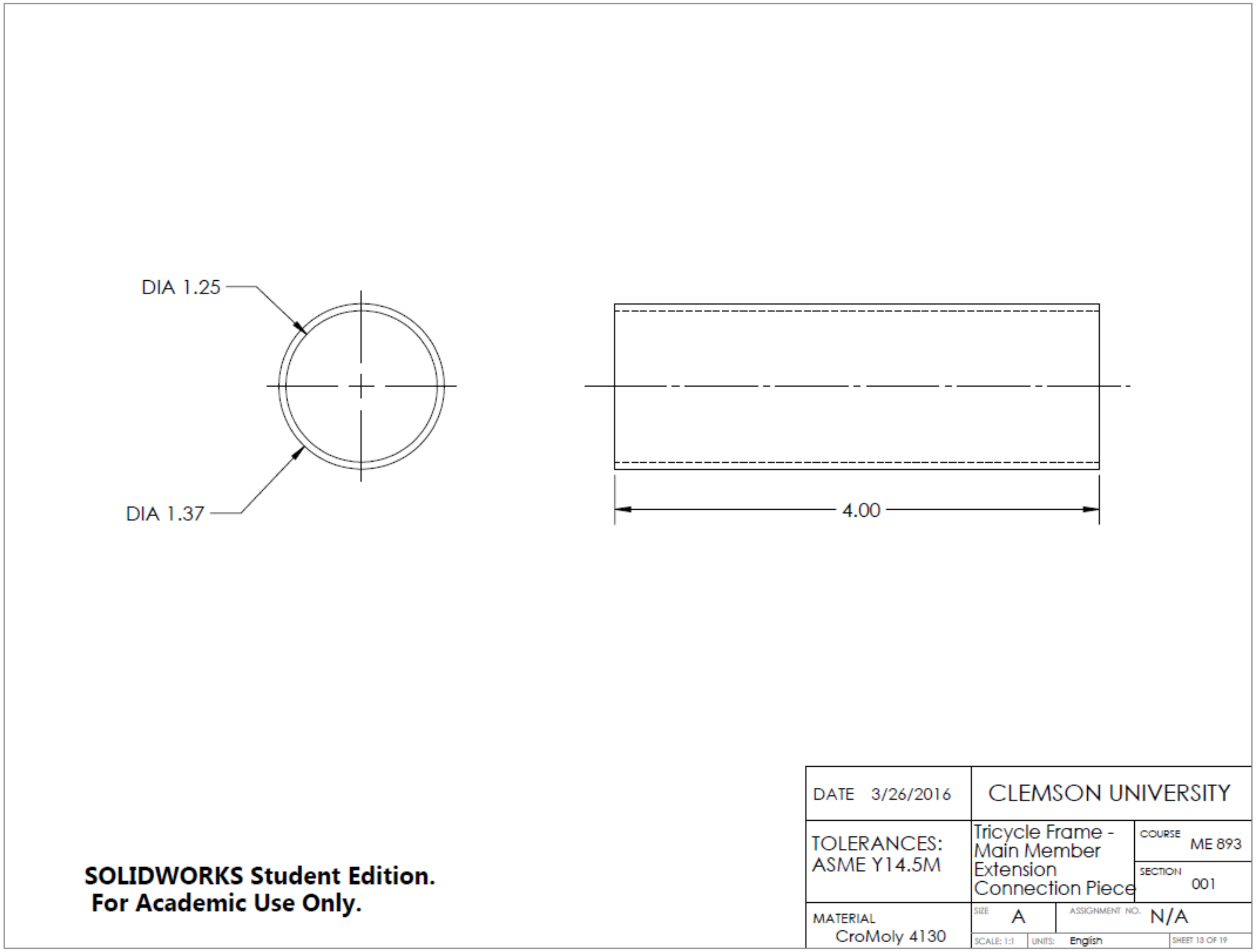


Figure J.13 Main member extension connection piece drawing

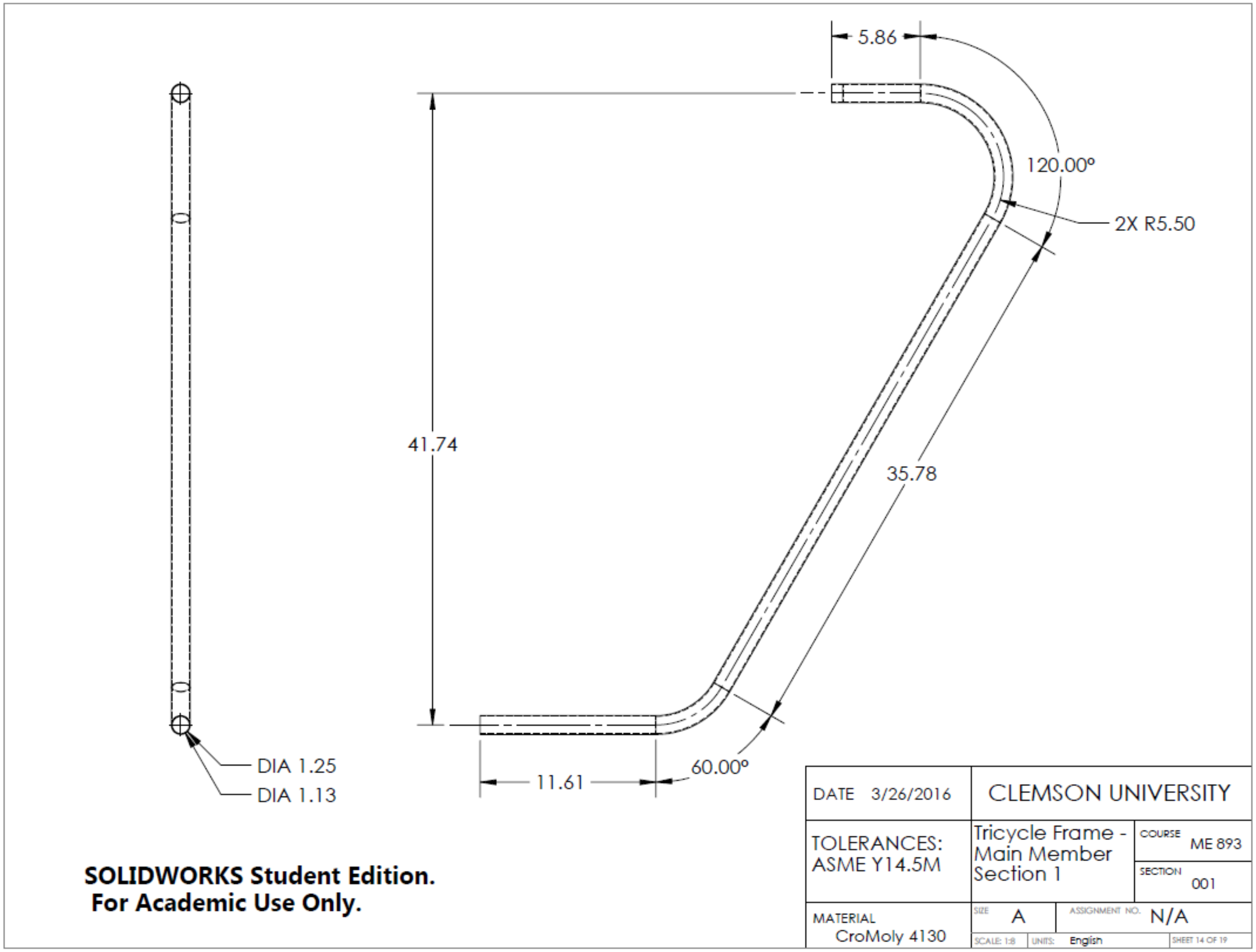


Figure J.14 Main member section 1 drawing

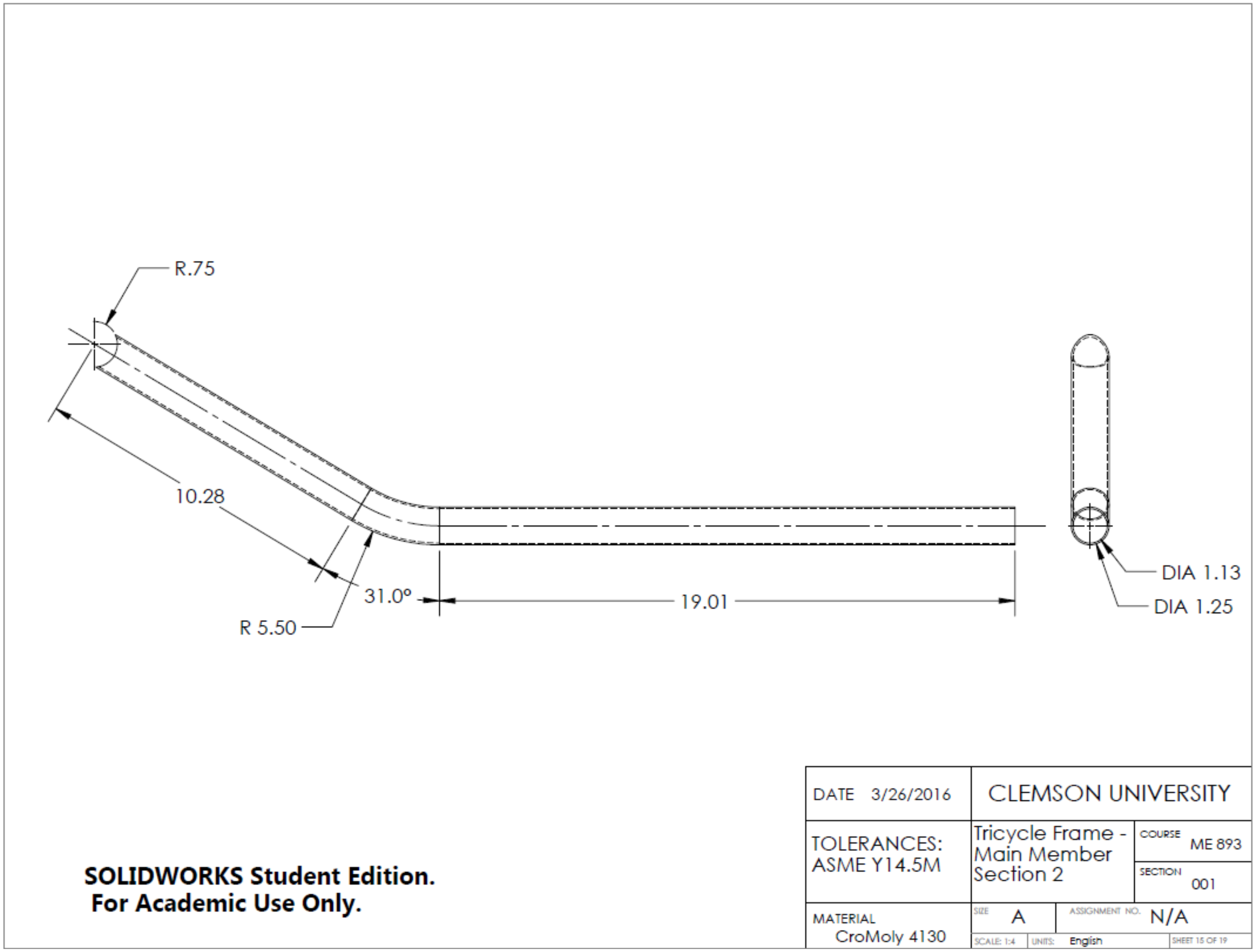


Figure J.15 Main member section 2 drawing

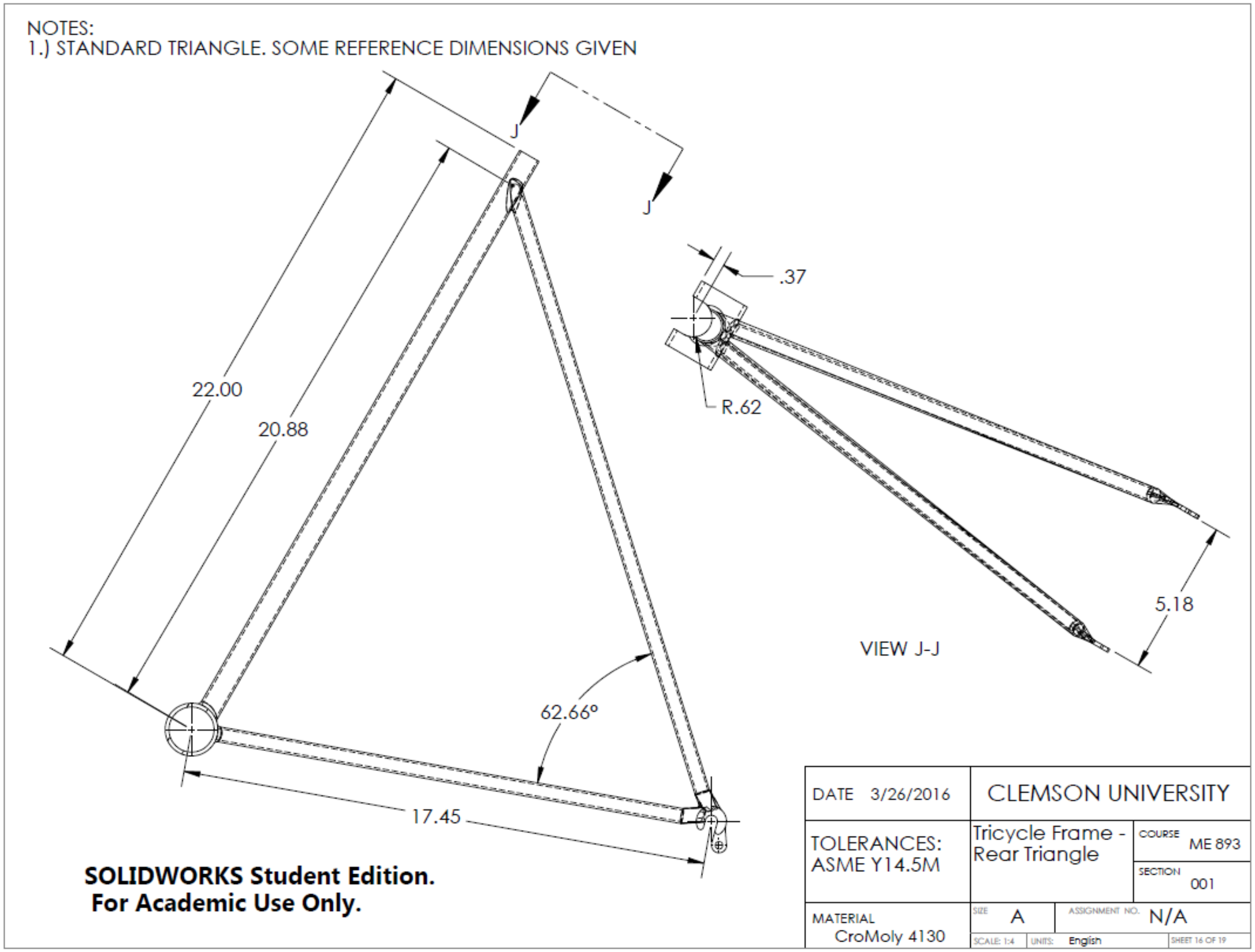


Figure J.16 Rear triangle drawing

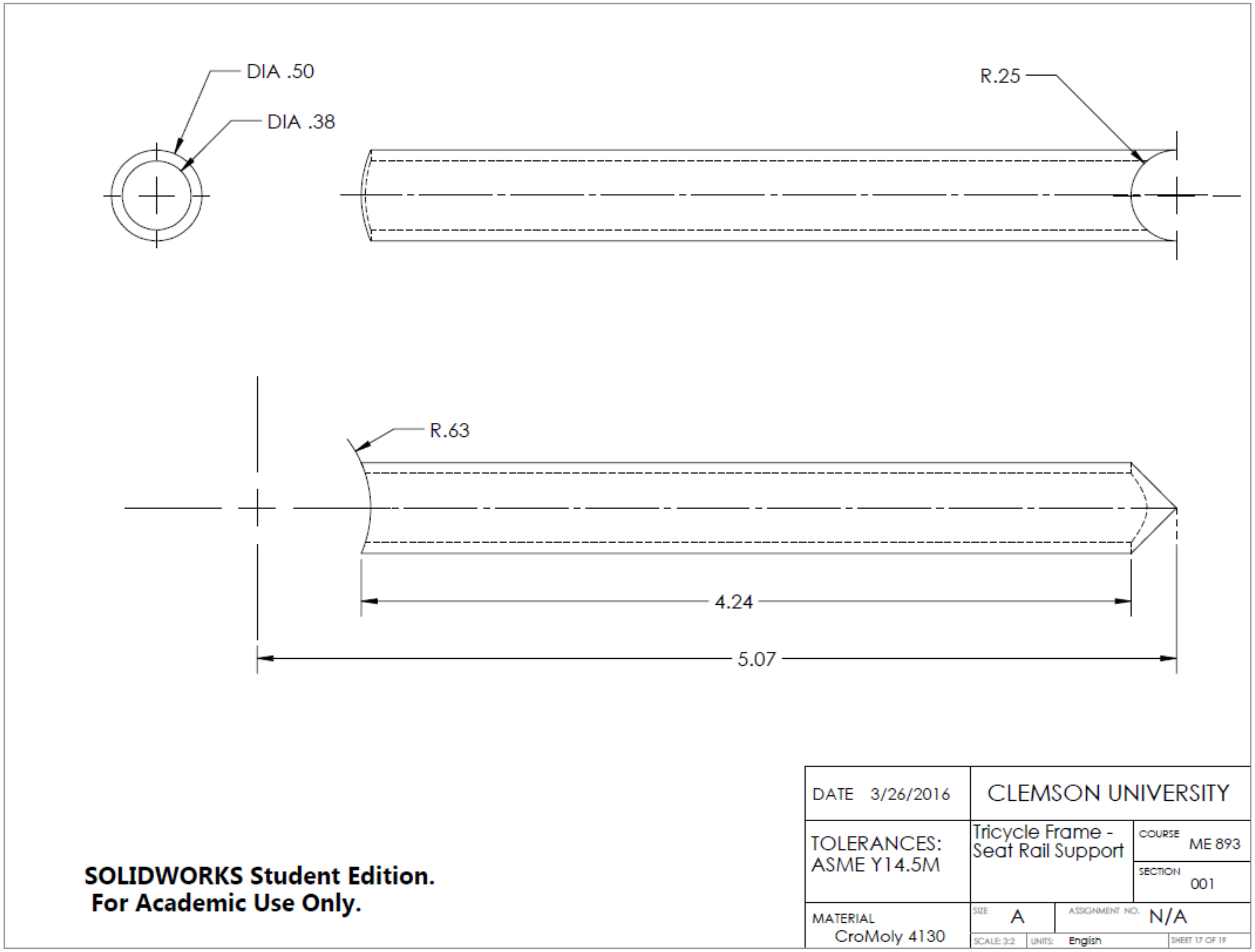


Figure J.17 Seat Rail Support drawing

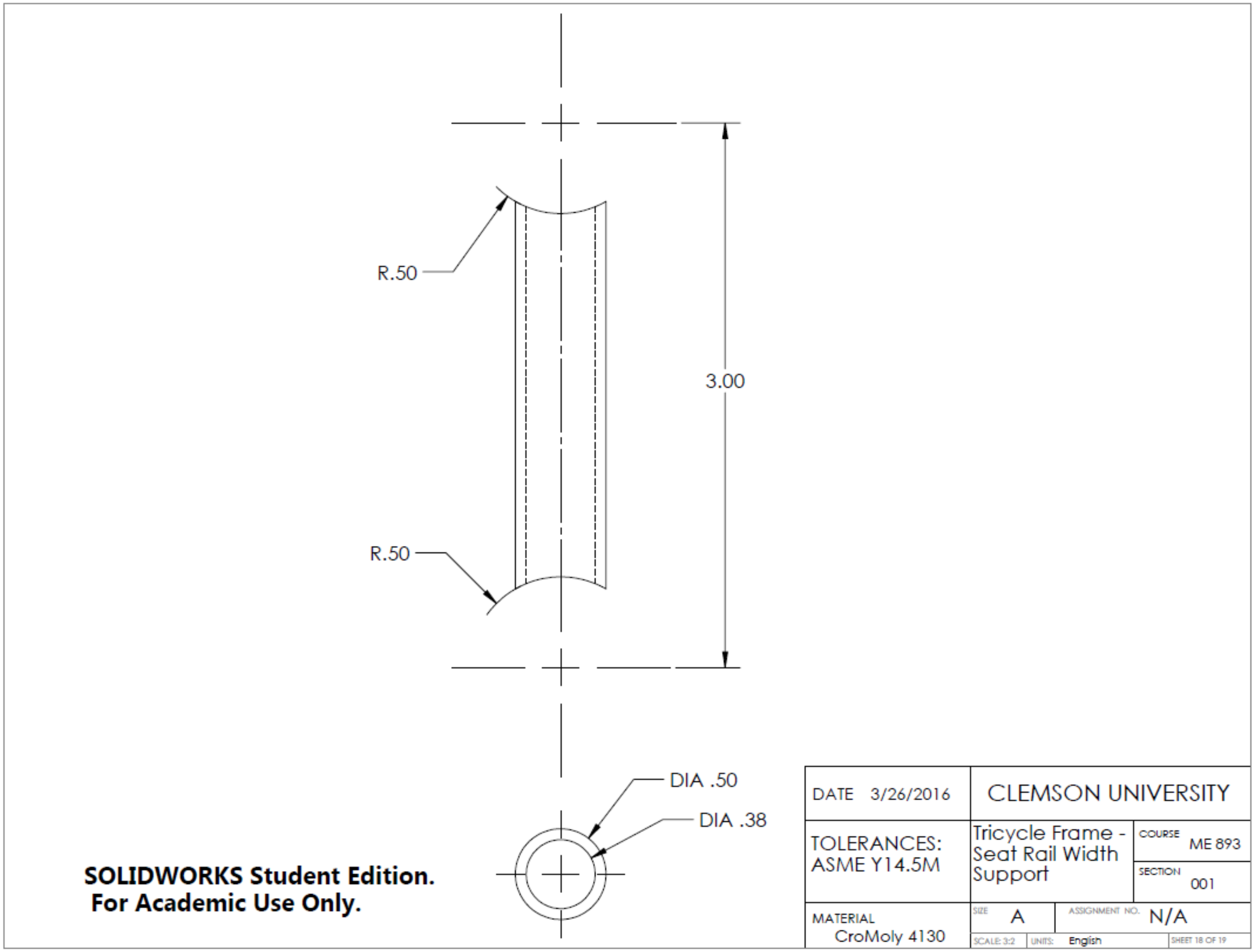


Figure J.18 Seat rail width support drawing

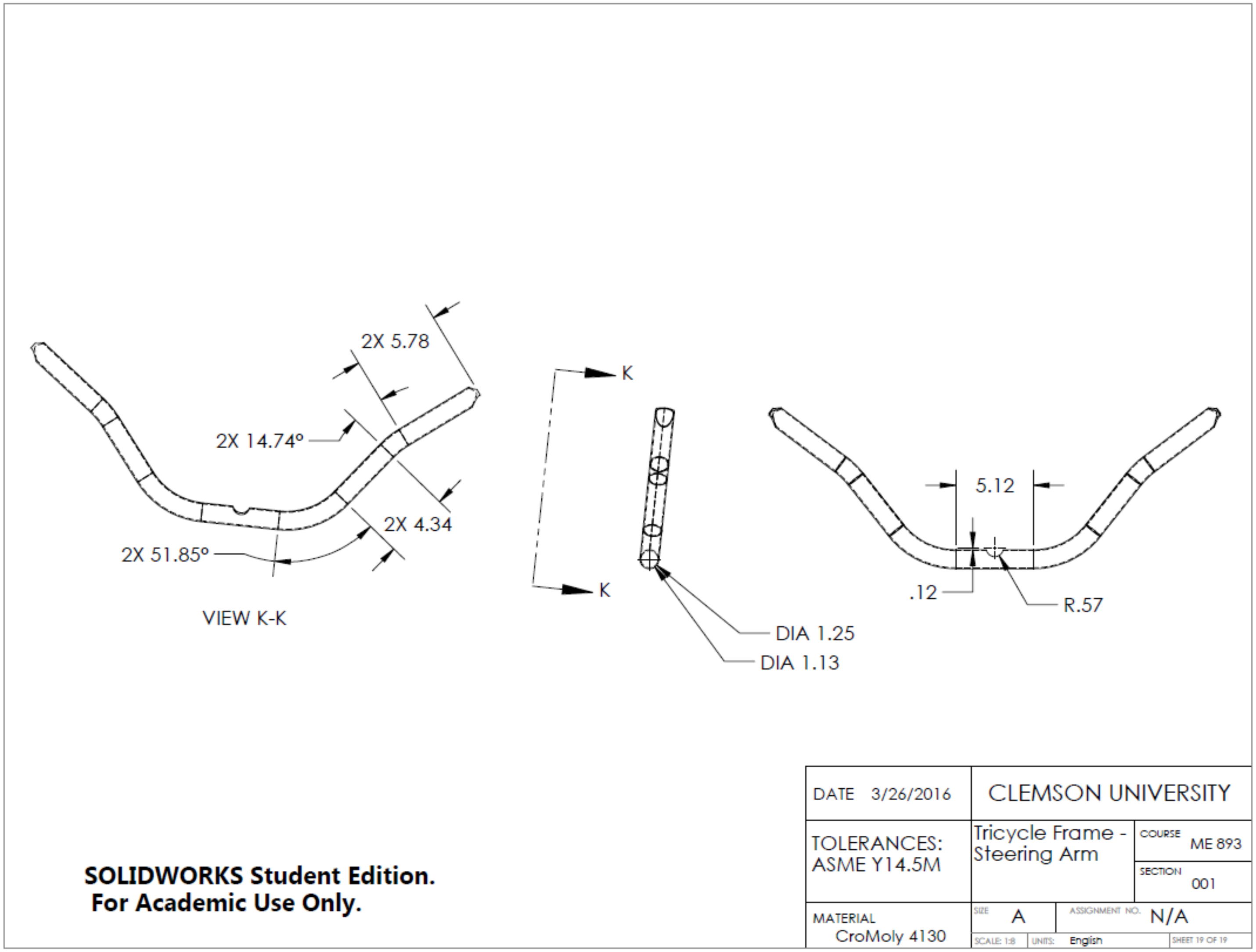


Figure J.19 Steering arm drawing

APPENDIX K: SURVEY RESULTS

In other to provide full details of the survey conduct the entire survey, combined results, and individual results are provided here. To protect the identity of the users and schools involved non-Clemson school involved in the survey are label as such. The number of year the non-Clemson schools have been involved in HPV design was estimated using the earliest event scoring for that school in HPVC events. To select students for the survey all school team leaders involved in the HPVC 2016 east competition we asked if they complete the survey, as well as past and current actively involved members of the Clemson HPV team.

K.1 Survey

The following is the survey that was provided to the participants involved.

Title: HPV Guidebook Usefulness Survey

Description: You have been selected to participate in a survey regarding the usefulness of a guidebook referencing human power vehicle (HPV) design. Before completing the survey please read the following, which outlines elements discussed in the guidebook.

The objective of the guidebook is to outline useful elements for systems engineering and the traditional design process. In doing so a combined design process is outlined and discussed in the contents of human powered vehicles. Some elements of the guidebook include are a summary of the traditional design process, summary of the systems engineering design process, human powered vehicle competition (HPVC) related information, project planning, conceptual design, embodiment design, embodiment considerations specific to HPVs, detailed design, prototyping and testing, and possible design changes. The following outlines elements in each of the design stages that are discussed in the guidelines.

Project Planning

- Group formation (System/subsystem creation, leaders and other group members)
- Project planning (Creating a project plan, allocating resources, establish meetings and design reviews)
- Communication (File management, information sharing, and meetings)
- Problem Development (Goal setting, Obtaining customer needs, requirement generation)

Conceptual Design

- Different concepting methods
- Example concepting methods results
- Aspects of concepting at different system levels
- Concept evaluation tools and results

Embodiment Design

- Modeling to determine the form, fit, and function (CAD modeling, prototypes, anthropometric data, and using standards)
- System interface management
- Specific HPV guidelines (Frame, steering, drive train, and fairing aspects. Details about common configurations, manufacturing techniques, use of standard parts, and functionality requirements)

Detailed Design

- Documenting/completing design analysis for requirement verification (FEA, CFD, energy recovery, power requirements, basic physics calculations)
- Design for X (material selection, of the shelf components, manufacturing, assembly and installation, safety, and maintenance and repair)
- Documenting part and assembly drawings (Including tolerances)

Prototyping and Testing

- Prototyping and purpose
- Testing (Different areas to test on, system level testing, creating testing documentation, requirement verification)
- Design changes and success in failures

Question 1: What school are you from?
Answer: Short answer

Question 2: What class are you in?
Answers: Freshmen, Sophomore, Junior, Senior, Graduate

Question 3: What is your major?
Answers: Aerospace engineering, civil engineering, mechanical engineering, other

Question 4: How long have you participated in HPVC?
Answers: First year, Two Years, Three Years, More than three years

Question 5: On average how many students are actively involved on the design team?
Answers: 1 to 3, 4 to 6, 7 to 10, 10 to 15, more than 15

Question 6: Does your design team currently use a design process?
Answers: Yes, no, other

Question 7: When designing a HPV is the HPV system divided into subsystems? If yes please describe to what extent this is done.
Answers: Yes, no, + optional short answer for yes

Question 8: If the system is divided into different subsystems, are requirements generated for the system as a whole, the individual subsystems, or both?
Answers: The system as whole, subsystems only, both the subsystems and the system, no requirement are typically generated, other

Question 9: How do you currently form groups?
Answers: Volunteer basis, Based on student experience, assigned groups, there is no group formation, because it is one large group, other

Question 10: Do you currently have a management hierarchy? If so how does the management relate to the different subsystems, please describe
Answers: Yes and it corresponding directly with our subsystem configuration, Yes and it does not correlate to the different the different subsystem configurations, No everyone works together on all aspects, other

Question 11: Please check all of the standard concept development methods your design team uses
Answers: Brainstorming, brainwriting, morphological analysis, 6-3-5 method, C-sketch, gallery method, design catalogs, TRIZ, biological mimicry, function structures, function tress, none of the above, other

Question 12: Please check all of the standard concept evaluation methods your design team uses
Answers: Decision matrices, pair wise comparisons, weighted analysis, no formal methods, other

Question 13: How well do you understand the functionality of different HPV subsystems (i.e. frame, steering, drive train, fairing, etc.)?
Answers: Scale 1 through 5 (1-Not at all to 5-Complete understanding)

Question 14: How well do you understand the connectivity and interfaces between different HPV subsystems (i.e. frame, steering, drive train, fairing, etc.)?
Answers: Scale 1 through 5 (1-Not at all to 5-Complete understanding)

Question 15: How well do you plan for vehicle fabrication?
Answers: Scale 1 through 5 (1- No or basic model with rough dimensions to 5- Have a model, part drawings, assembly drawings, manufacturing plans, and documentation)

Question 16: How much prototyping is completed before the competition?
Answers: Scale 1 through 5 (1- Little to no testing occurs to 5- Every requirement is tested and verified)

Question 17: How adequate do you think the testing conducted before the competition is?

Answers: Scale 1 through 5 (1- More testing should be completed to 5- The testing completed is more than necessary)

Question 18: When testing, is testing documentation created beforehand?
Answers: Yes for all testing that occurs, yes for important testing that occurs, yes for some testing that occurs, no, other

Question 19: After testing how often are changes made to the design?
Answers: Scale 1 through 5 (1Changes never occur even if they need to to 5-Testing always results in design changes)

Question 20: Do you have difficultly finishing the vehicle before the competition?
Answers: Yes, no, other

Question 21: Do you create a project plan, such as a Gantt chart, at the beginning of the design process?
Answers: Yes, no, other

Question 22: If a project plan is created how well is it followed?
Answers: Scale 1 through 5 (1-Project plan is made then neglected to 5-Project plan is made and all tasks are finished on time or beforehand)

Question 23: How much would your design team benefit from the proposed guidelines?
Answers: Scale 1 through 5 (1-No benefit to final design or team to 5-Extreme benefit to team and final design)

Question 24: What areas would the team and/or design benefit from the proposed guidelines? Check all that apply
Answers: System level concepts, project planning, conceptual development and evaluation, embodiment design, detailed design and documentation, prototype and testing, understanding HPV specific information, none of the above, other

Question 25: If given the guidebook, what is the likelihood it would be used?
Answers: Scale 1 through 5 (1-The guidebook would never be used to 5-The guidebook would be used on a daily or weekly basis.

K.2 Combined Survey Results

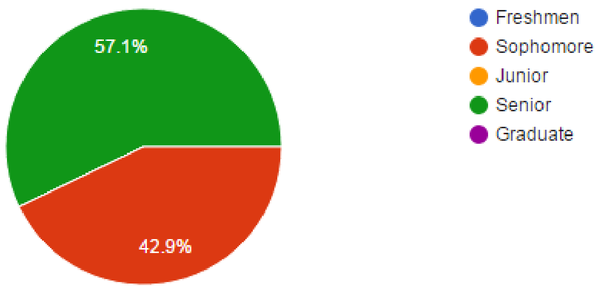


Figure K.1 Survey Results: What class are you in?

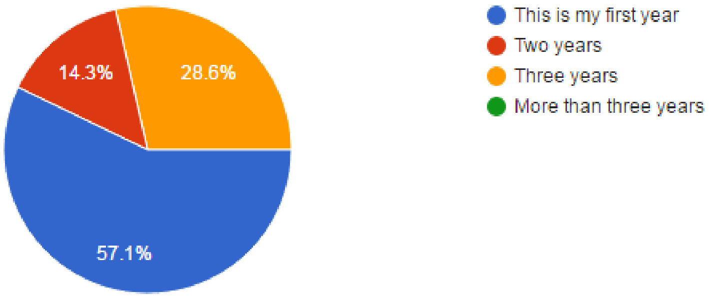


Figure K.2 Survey results: How long have you participated in HPV?

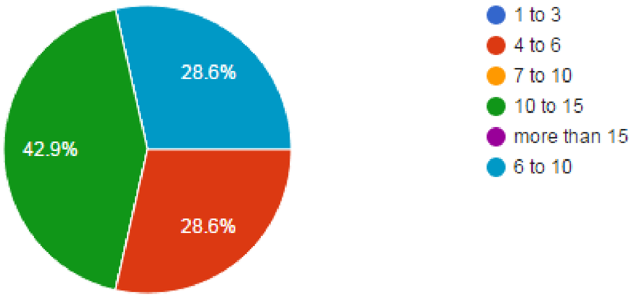


Figure K.3 Survey results: On average how many students are actively involved on the design team?

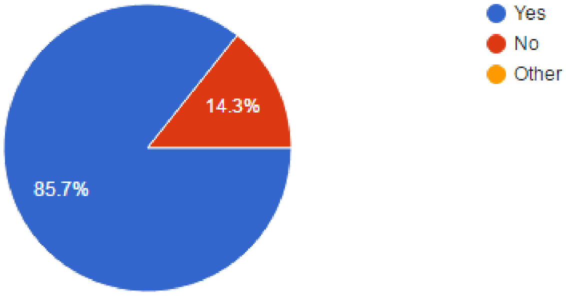


Figure K.4 Survey results: Does your team currently use a design process

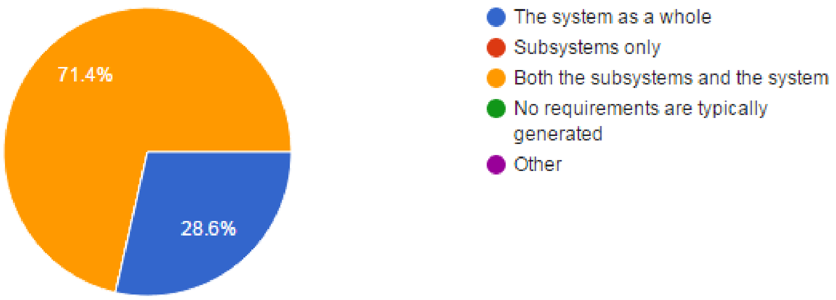


Figure K.5 Survey results: If the system is divided into different subsystems, are requirements generated for the system as a whole, the individual subsystems, or both?

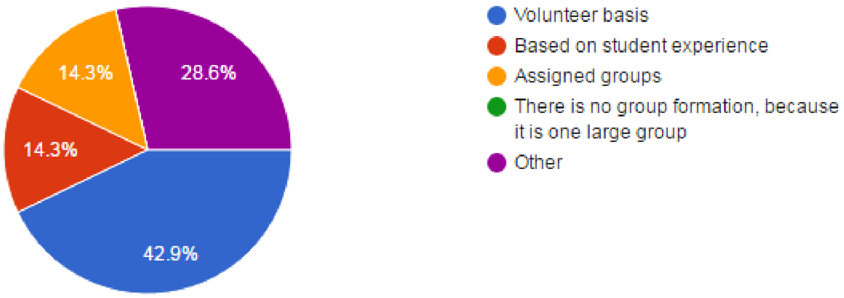


Figure K.6 Survey results: How do you currently form groups

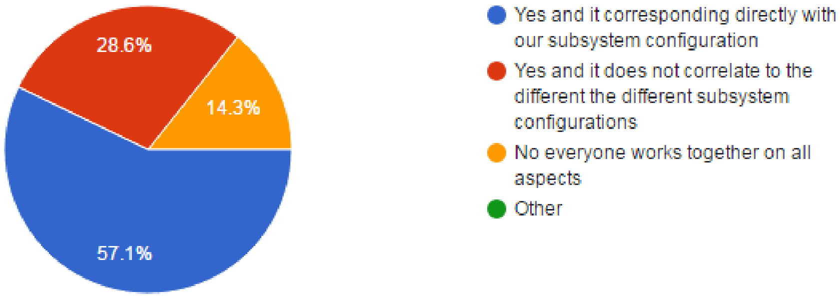


Figure K.7 Survey results: Do you currently have a management hierarchy? If so how does the management relate to the different subsystems?

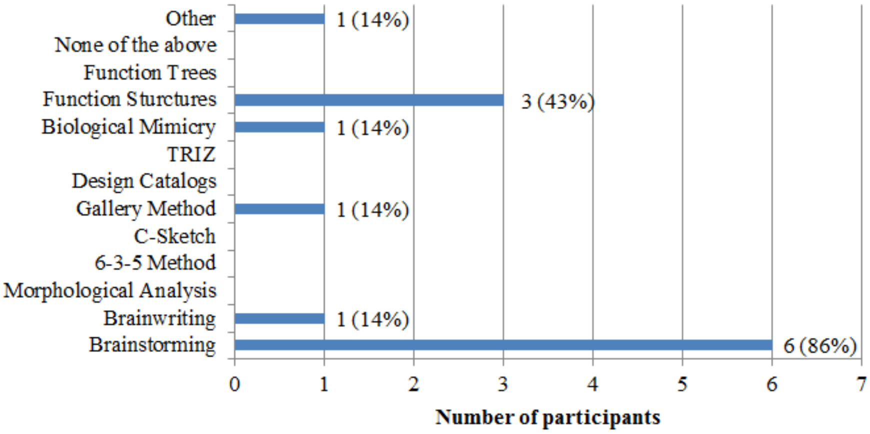


Figure K.8 Survey results: Standard concept development methods your teams use

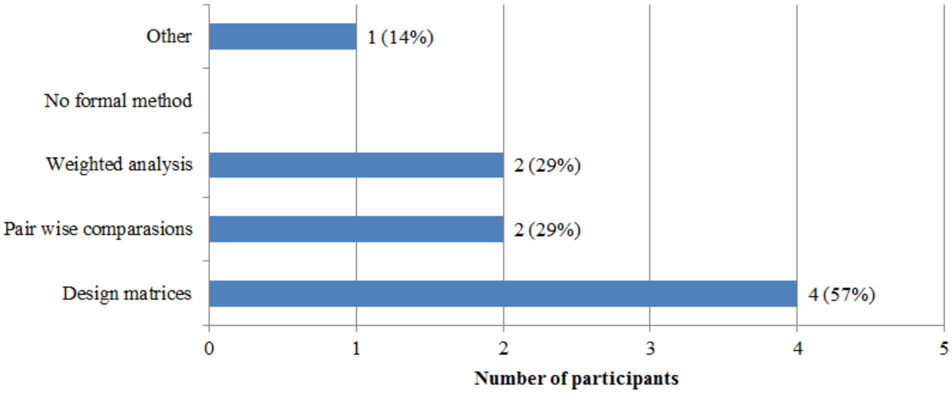


Figure K.9 Survey results: Standard concept evaluation methods your teams use

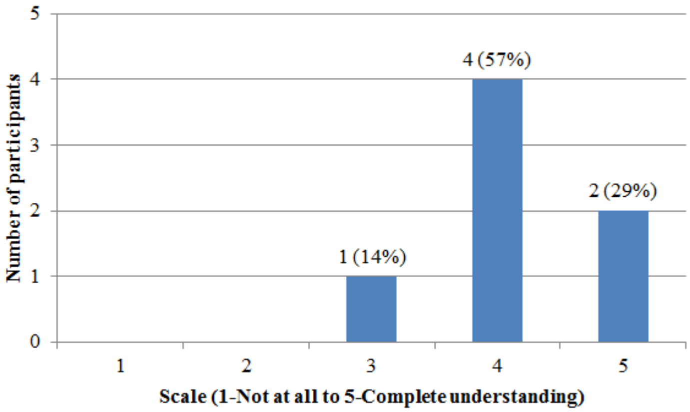


Figure K.10 Survey results: How well do you understand the functionality of different HPV subsystems (i.e frame, steering, drivetrain, fairing. etc.)?

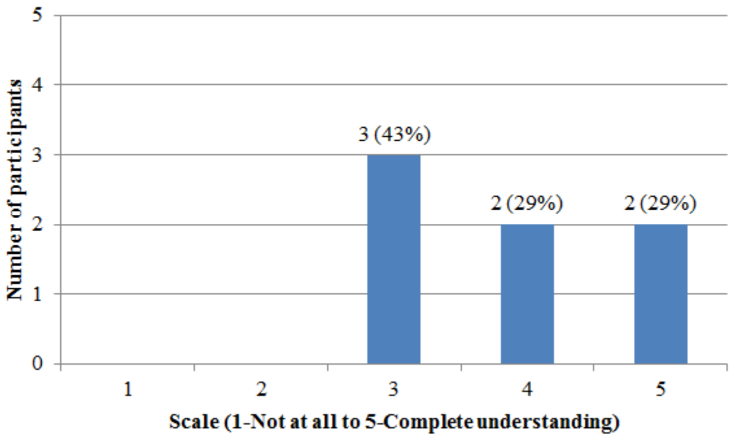


Figure K.11 Survey results: How well do you understand the connectivity and interfaces between different HPV subsystems (i.e frame, steering, drivetrain, fairing. etc.)?

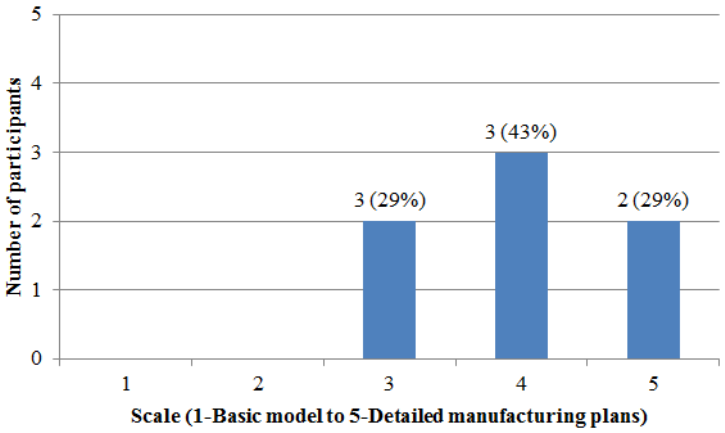


Figure K.12 Survey results: How well do you plan for vehicle fabrication?

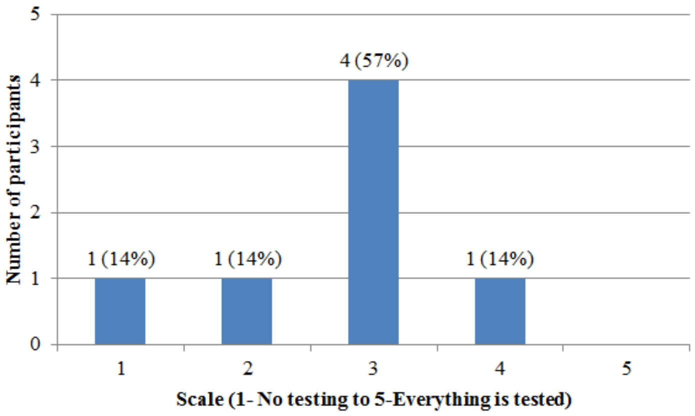


Figure K.13 Survey results: How much prototyping is completed before the competition?

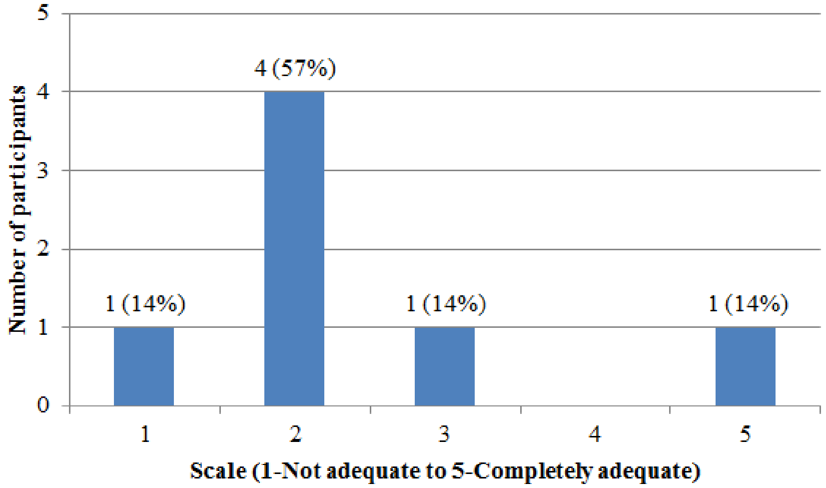


Figure K.14 Survey results: How adequate is testing conducted before the competition?

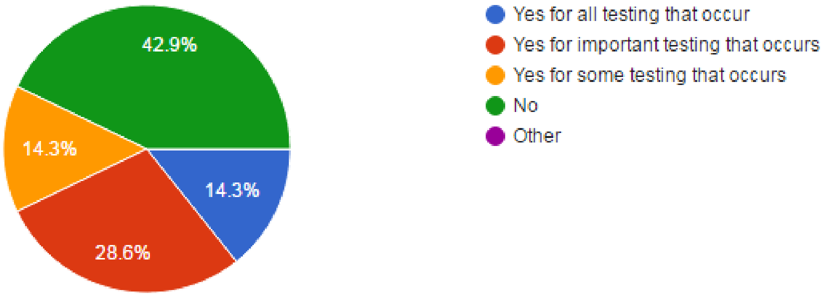


Figure K.15 Survey results: When testing, is testing documentation created beforehand?

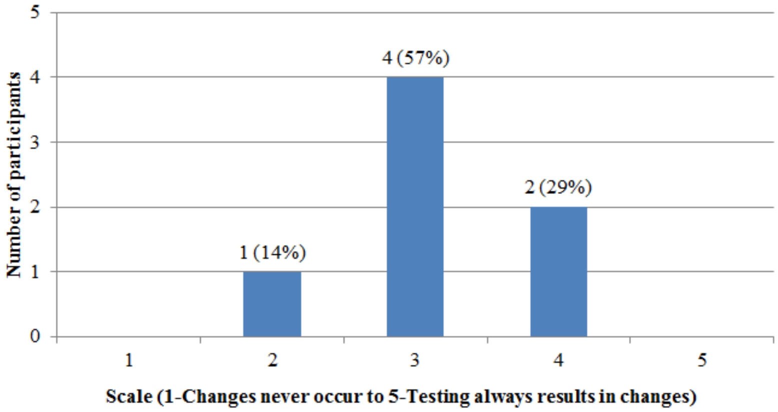


Figure K.16 Survey results: After testing how often are changes made to the design?

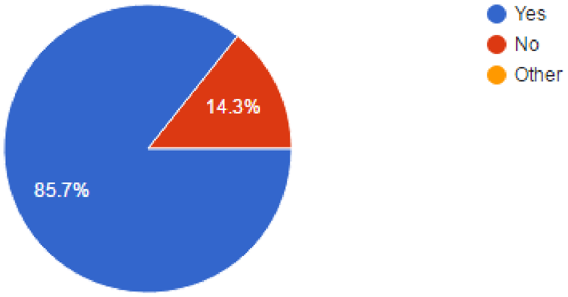


Figure K.17 Survey results: Do you have difficulty finishing the vehicle before the competition?

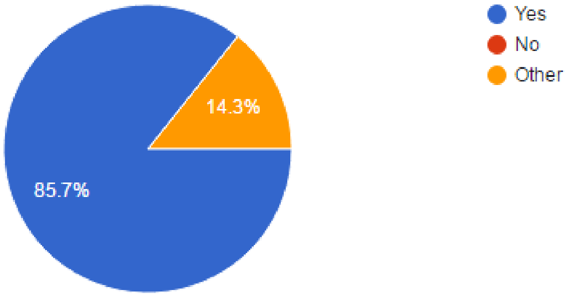


Figure K.18 Survey results: Do you create a project plan, such as a Gantt chart, at the beginning of the design process?

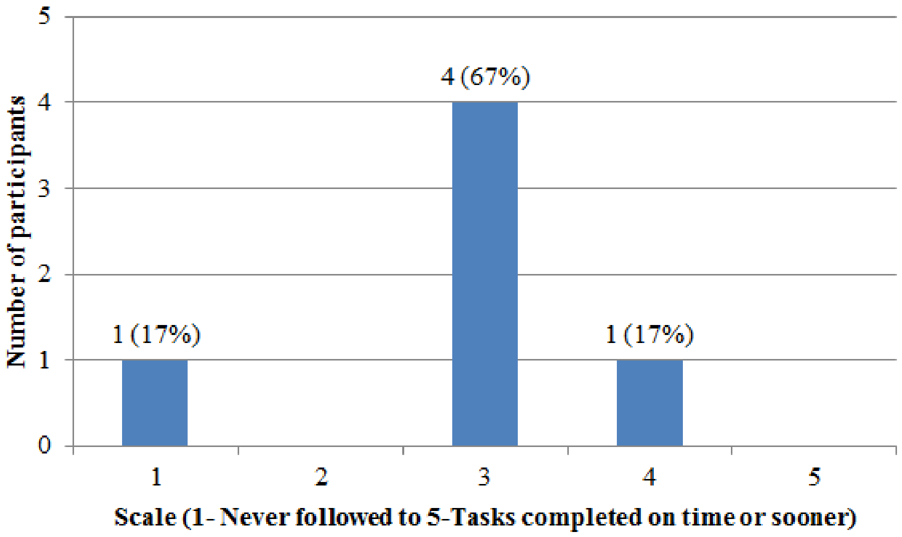


Figure K.19 Survey results: If a project plan is created how well is it followed?

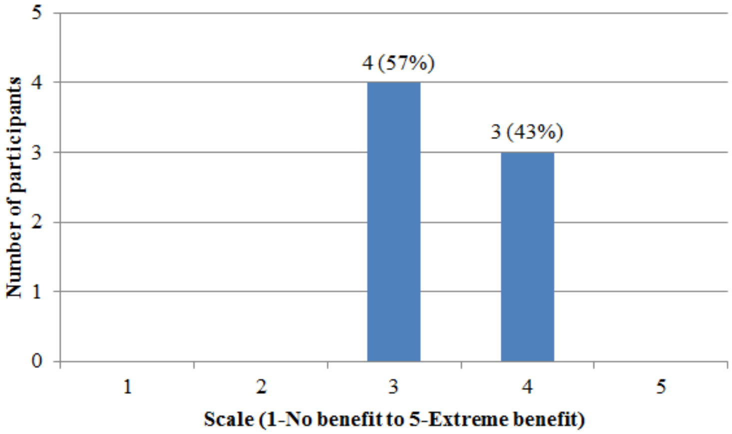


Figure K.20 Survey results: How much would your team benefit from the proposed guidelines?

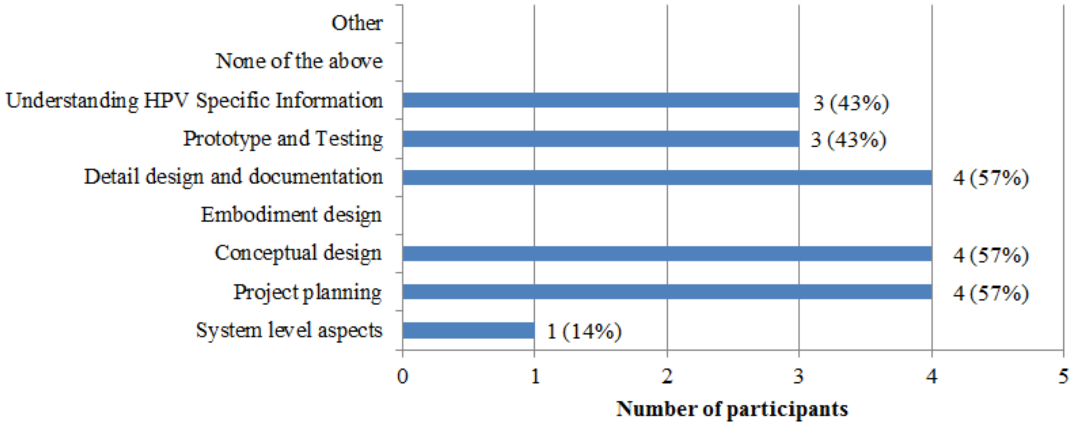


Figure K.21 Survey results: Areas the team and/or design benefit from the proposed guidelines

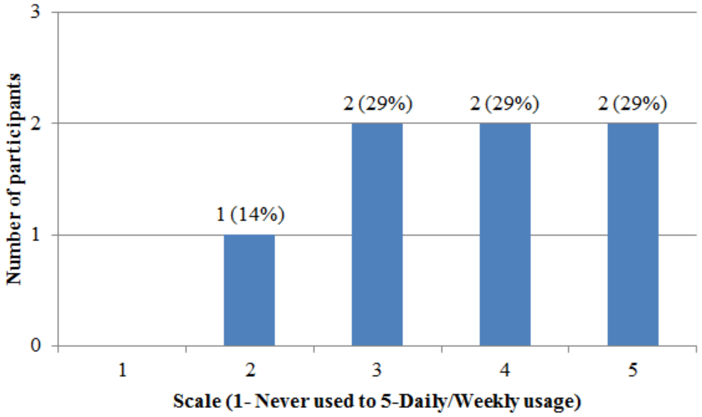


Figure K.22 Survey results: If given the guidebook, what is the likelihood it would be used?

K.3 Individual Survey Results

Table K.1 Individual survey results

What school are you from?	Non-Clemson	Clemson University	Clemson University	Non-Clemson	Clemson University	Non-Clemson	Non-Clemson
Years of schools involvement (Researched)	About 10 years	2nd Year	2nd Year	4th Year	2nd Year	5th Year	1st Year
What class are you in?	Sophomore	Senior	Sophomore	Senior	Sophomore	Senior	Senior
What is your major?	Mechanical Engineering	Mechanical Engineering	Mechanical Engineering	Mechanical Engineering	Mechanical Engineering	Mechanical Engineering	Mechanical Engineering
How long have you participated in HPVC?	Two years	First year	First year	Three years	First year	Three years	First year
On average how many students are actively involved on the design team	10 to 15	10 to 15	4 to 6	10 to 15	6 to 10	6 to 10	4 to 6
Does your design team currently use a design process?	Yes	Yes	Yes	Yes	Yes	No	Yes
When designing a HPV is the HPV system divided into subsystems? If yes please describe to what extent this is done.	Yes	Yes (Fairing, Steering, Drive Train, Structure)	Yes	Yes	Yes	Yes	Yes

Table K.1 (Cont.)

What school are you from?	Non-Clemson	Clemson University	Clemson University	Non-Clemson	Clemson University	Non-Clemson	Non-Clemson
If the system is divided into different subsystems, how are requirements generated?	Both the subsystems and the system	Both the subsystems and the system	The system as a whole	Both the subsystems and the system	Both the subsystems and the system	Both the subsystems and the system	The system as a whole
How do you currently form groups?	Volunteer basis	Preference considered, then groups are assigned	Assigned groups	Volunteer basis	Volunteer basis	Volunteer first, then assigned	Based on student experience
Do you currently have a management hierarchy? If so how does the management relate to the different subsystems, please describe	Yes and it does not correlate to the different the different subsystem configurations	Yes and it corresponding directly with our subsystem configuration	Yes and it corresponding directly with our subsystem configuration	Yes and it corresponding directly with our subsystem configuration	Yes and it corresponding directly with our subsystem configuration	No everyone works together on all aspects	Yes and it does not correlate to the different the different subsystem configurations
Check all of the standard concept development methods your design team uses	Brainstorming, Brainwriting	Was not heavily involved in early design. Came in late.	Brainstorming, Function Structures	Brainstorming, Gallery Method, Biological Mimicry, Function Structures	Brainstorming	Brainstorming, Function Structures	Brainstorming

Table K.1 (Cont.)

What school are you from?	Non-Clemson	Clemson University	Clemson University	Non-Clemson	Clemson University	Non-Clemson	Non-Clemson
Check all of the standard evaluation methods your design team uses	Decision matrices	CFD	Decision matrices	Pair wise comparisons, Weight analysis	Decision matrices	Pair wise comparisons	Decision matrices, Weight analysis
How well do you understand the connectivity between different subsystems?	4	4	4	4	5	5	3
How well do you plan for vehicle fabrication?	3	3	4	4	5	5	3
How much prototyping is completed before the competition?	4	4	5	3	5	4	3
How adequate do you think the testing conducted before the competition is?	4	1	3	3	3	2	3

Table K.1 (Cont.)

What school are you from?	Non-Clemson	Clemson University	Clemson University	Non-Clemson	Clemson University	Non-Clemson	Non-Clemson
How adequate do you think the testing conducted before the competition is?	4	1	3	3	3	2	3
When testing, is testing documentation created beforehand?	3	1	5	2	2	2	2
After testing how often are changes to the design made?	No	No	Yes for important testing that occurs	Yes for some testing that occurs	Yes for important testing that occurs	No	Yes for all testing that occur
Do you have difficultly finishing the vehicle before the competition?	4	4	3	3	3	3	2
Do you create a project plan, such as a Gantt chart, at the beginning of the design process?	Yes	Yes	No	Yes	Yes	Yes	Yes

Table K.1 (Cont.)

What school are you from?	Non-Clemson	Clemson University	Clemson University	Non-Clemson	Clemson University	Non-Clemson	Non-Clemson
If a project plan is created how well is it followed?	Yes	Unknown	Yes	Yes	Yes	Yes	Yes
How much would your design team benefit from the proposed guidelines?	3		4	3	3	3	1
What areas would the team and/or design benefit from the proposed guidelines? Check all that apply	3	3	3	4	4	4	3
If given the guidebook what is likelihood it would be used?	Conceptual development and evaluation, Detailed design and documentation	Detailed design and documentation, Prototype and testing	Understanding HPV specific information	Project planning, Conceptual development and evaluation, Detailed design and documentation, Prototype and testing	Project planning, Detailed design and documentation, Understanding HPV specific information	Project planning, Conceptual development and evaluation	System level aspects, Project planning, Conceptual development and evaluation, Prototype and testing, Understanding HPV specific information

APPENDIX L: DESIGN REPORT EXAMPLES

Is this section design report examples are given for the Clemson University HPV submission in the 2015 and 2016 competitions. These are given for three main reasons. First the design reports outline an example of how the product could be summarized for the ASME HPVC. Thus, it provides an example for writing style, report structure, and required information. To examine how well these design report met that criteria the scoring rubric for each respective year is given as well. Help evaluate how well the report is made. For the 2015 HPVC submission the report combined with a later presentation scored a value of 61.83/100 yielding a design rank of 13 out of 33 [9]. The 2015 innovation report was ranked 20th out of the 33 HPV submissions. The evaluation of the 2016 report has not been evaluated yet, but it is expected to be much higher based on help with it meets the scoring criteria in comparison.

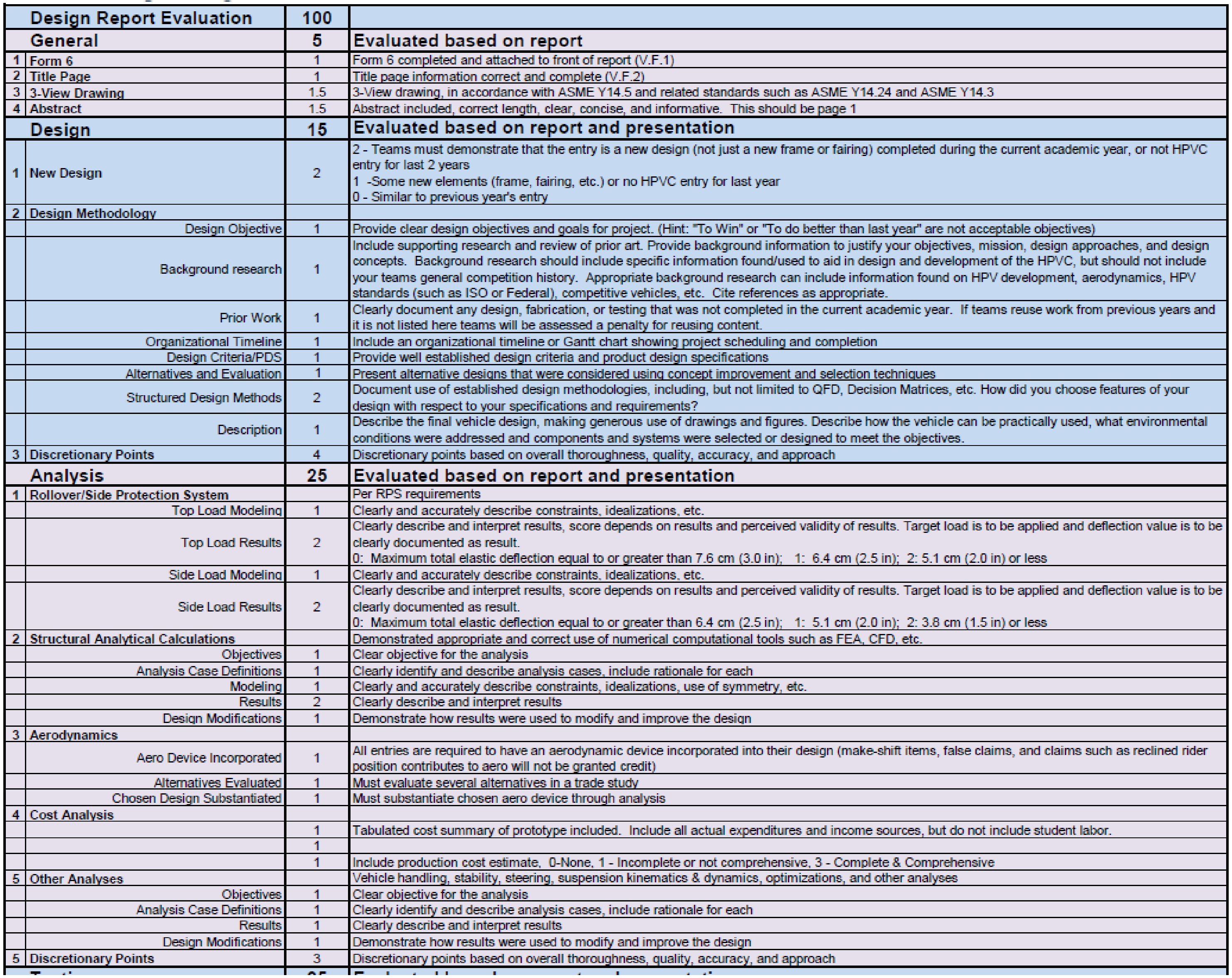
The second reason for including the design report is to highlight some of the required documentation that needs to be recorded throughout the design process. In both reports it can be seen that documentation from all aspects of the design process are required, but there is a heavier focus on analysis, and testing results.

For the purpose of this paper the most important reason for including the design reports is to give a subjective evaluation of the design process presented. The 2015 report did not initially have a design process as the students involved were concurrently enrolled in design courses. The 2016 report on the other hand used many of the methods provided and the progress of the vehicle at the point in which the report was written was much greater. Some of the greater success can be attributed to more experience, but the more thorough design is also linked to project management, scheduling, greater design making, and more analysis as discussed in this paper.

Lastly, the design reports are in their original formatting for the ASME submissions and the page numbers given reflect the format of the submission. In other words, the formatting is purposefully different to better retrain the information in the original submission.

L.1 2015 HPVC Scoring

Table L.1 2015 HPVC Design Report Scoring [7]

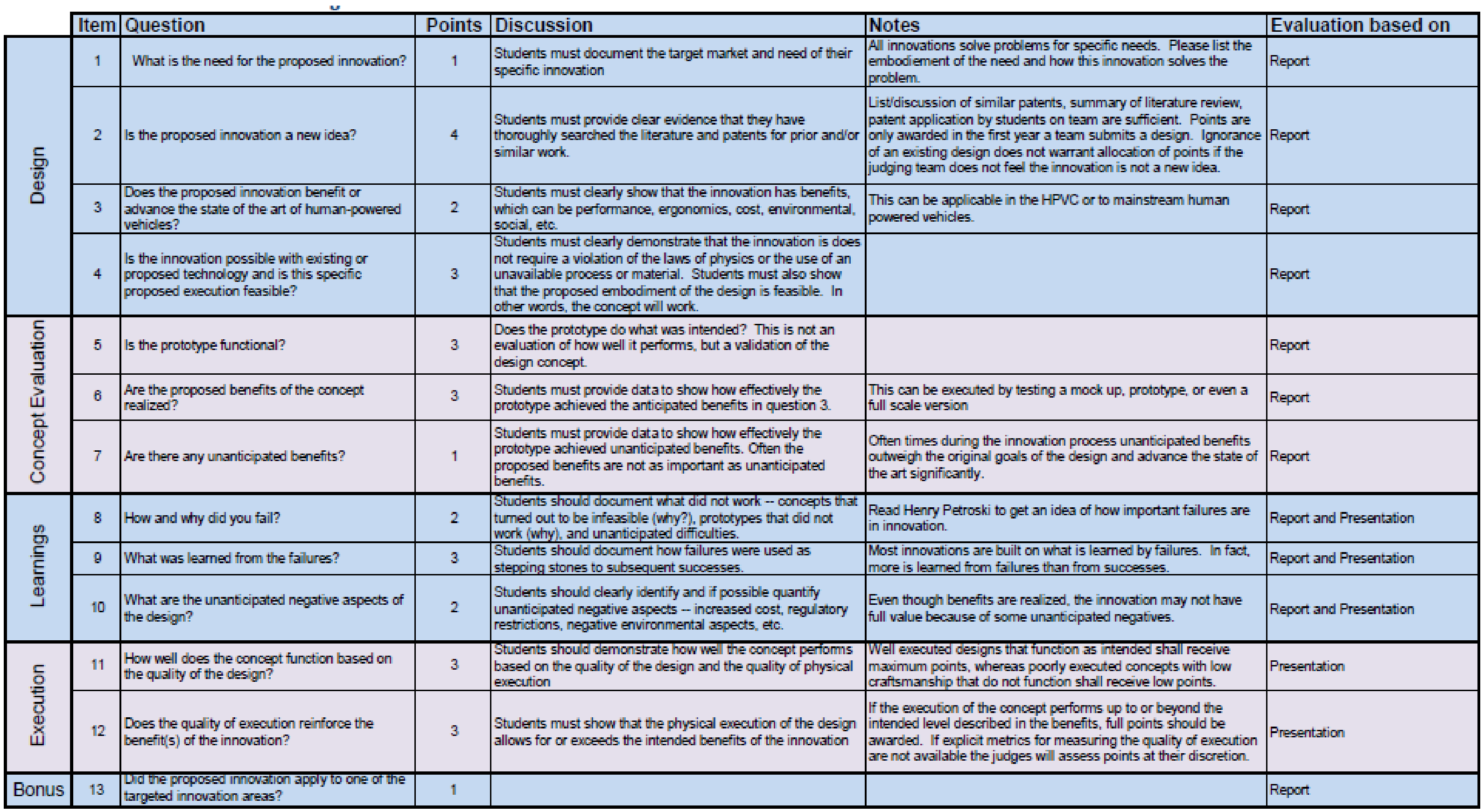


	Design Report Evaluation	100	
	General	**5**	**Evaluated based on report**
1	Form 6	1	Form 6 completed and attached to front of report (V.F.1)
2	Title Page	1	Title page information correct and complete (V.F.2)
3	3-View Drawing	1.5	3-View drawing, in accordance with ASME Y14.5 and related standards such as ASME Y14.24 and ASME Y14.3
4	Abstract	1.5	Abstract included, correct length, clear, concise, and informative. This should be page 1
	Design	**15**	**Evaluated based on report and presentation**
1	New Design	2	2 - Teams must demonstrate that the entry is a new design (not just a new frame or fairing) completed during the current academic year, or not HPVC entry for last 2 years 1 -Some new elements (frame, fairing, etc.) or no HPVC entry for last year 0 - Similar to previous year's entry
2	Design Methodology		
	Design Objective	1	Provide clear design objectives and goals for project. (Hint: "To Win" or "To do better than last year" are not acceptable objectives)
	Background research	1	Include supporting research and review of prior art. Provide background information to justify your objectives, mission, design approaches, and design concepts. Background research should include specific information found/used to aid in design and development of the HPVC, but should not include your teams general competition history. Appropriate background research can include information found on HPV development, aerodynamics, HPV standards (such as ISO or Federal), competitive vehicles, etc. Cite references as appropriate.
	Prior Work	1	Clearly document any design, fabrication, or testing that was not completed in the current academic year. If teams reuse work from previous years and it is not listed here teams will be assessed a penalty for reusing content.
	Organizational Timeline	1	Include an organizational timeline or Gantt chart showing project scheduling and completion
	Design Criteria/PDS	1	Provide well established design criteria and product design specifications
	Alternatives and Evaluation	1	Present alternative designs that were considered using concept improvement and selection techniques
	Structured Design Methods	2	Document use of established design methodologies, including, but not limited to QFD, Decision Matrices, etc. How did you choose features of your design with respect to your specifications and requirements?
	Description	1	Describe the final vehicle design, making generous use of drawings and figures. Describe how the vehicle can be practically used, what environmental conditions were addressed and components and systems were selected or designed to meet the objectives.
3	Discretionary Points	4	Discretionary points based on overall thoroughness, quality, accuracy, and approach
	Analysis	**25**	**Evaluated based on report and presentation**
1	Rollover/Side Protection System		Per RPS requirements
	Top Load Modeling	1	Clearly and accurately describe constraints, idealizations, etc.
	Top Load Results	2	Clearly describe and interpret results, score depends on results and perceived validity of results. Target load is to be applied and deflection value is to be clearly documented as result. 0: Maximum total elastic deflection equal to or greater than 7.6 cm (3.0 in); 1: 6.4 cm (2.5 in); 2: 5.1 cm (2.0 in) or less
	Side Load Modeling	1	Clearly and accurately describe constraints, idealizations, etc.
	Side Load Results	2	Clearly describe and interpret results, score depends on results and perceived validity of results. Target load is to be applied and deflection value is to be clearly documented as result. 0: Maximum total elastic deflection equal to or greater than 6.4 cm (2.5 in); 1: 5.1 cm (2.0 in); 2: 3.8 cm (1.5 in) or less
2	Structural Analytical Calculations		Demonstrated appropriate and correct use of numerical computational tools such as FEA, CFD, etc.
	Objectives	1	Clear objective for the analysis
	Analysis Case Definitions	1	Clearly identify and describe analysis cases, include rationale for each
	Modeling	1	Clearly and accurately describe constraints, idealizations, use of symmetry, etc.
	Results	2	Clearly describe and interpret results
	Design Modifications	1	Demonstrate how results were used to modify and improve the design
3	Aerodynamics		
	Aero Device Incorporated	1	All entries are required to have an aerodynamic device incorporated into their design (make-shift items, false claims, and claims such as reclined rider position contributes to aero will not be granted credit)
	Alternatives Evaluated	1	Must evaluate several alternatives in a trade study
	Chosen Design Substantiated	1	Must substantiate chosen aero device through analysis
4	Cost Analysis		
		1	Tabulated cost summary of prototype included. Include all actual expenditures and income sources, but do not include student labor.
		1	
		1	Include production cost estimate, 0-None, 1 - Incomplete or not comprehensive, 3 - Complete & Comprehensive
5	Other Analyses		Vehicle handling, stability, steering, suspension kinematics & dynamics, optimizations, and other analyses
	Objectives	1	Clear objective for the analysis
	Analysis Case Definitions	1	Clearly identify and describe analysis cases, include rationale for each
	Results	1	Clearly describe and interpret results
	Design Modifications	1	Demonstrate how results were used to modify and improve the design
5	Discretionary Points	3	Discretionary points based on overall thoroughness, quality, accuracy, and approach

Table L.1 (Cont.)

	Testing	**25**	**Evaluated based on report and presentation**
1	**Rollover/Side Protection System**		Per RPS requirements
	Top Load Testing Setup	1	Test method clearly described, appropriate, and scientific
	Top Load Testing Results	2	Clearly describe and interpret results, score depends on results and perceived validity of results. Increasing load is to be added to RPS until maximum defelction is reached and then load achieved is to be clearly stated as the result. 0: Less than 1780N (400 lbf); 1: 1780-2670N (400-599 lbf); 2: ≥2670N (600 lbf)
	Side Load Testing Setup	1	Test method clearly described, appropriate, and scientific
	Side Load Testing Results	2	Clearly describe and interpret results, score depends on results and perceived validity of results. Increasing load is to be added to RPS until maximum defelction is reached and then load achieved is to be clearly stated as the result. 0: Less than 890N (200 lbf); 1: 890-1330N (200-299 lbf); 2: >1330N (300 lbf)
2	**Developmental Testing**		Physical testing to develop or verify design, usually conducted prior to final vehicle construction
	Objective & Methodology	1	Clear objective for the experiment. Methodology clearly described, appropriate, and scientific
	Results and Discussion	1	Data is reported and presented clearly, with appropriate discussion (interpretation, error sources, uncertainty, etc.)
	Statistical Analysis	1	Data is analyzed and presented clearly, with appropriate statistical analyses (t-test, ANOVA, regression, etc.) and measures (mean and standard deviation, confidence intervals, p-value, etc.)
	Conclusions	1	Conclusions and recommendations stated clearly. Results should be quantitative where possible and include applicable statistical analyses (mean, standard deviation, student T test, etc.)
	Design Modifications	1	Demonstrate how testing results used to modify or improve the design
	Comparison with PDS and Analysis	1	Test results clearly compared with analysis results and product design specifications
	Comprehensiveness	1	Extent of developmental testing: 0: few experiments/little significance on design, 1: many experiments/significant effect on design
3	**Performance Testing**		Physical testing (often conducted on final vehicle) to evaluate and optimize performance
	Objective & Methodology	1	Clear objective for the experiment. Methodology clearly described, appropriate, and scientific.
	Results and Discussion	1	Data is reported and presented clearly, with appropriate discussion (interpretation, error sources, uncertainty, etc.)
	Statistical Analysis	1	Data is analyzed and presented clearly, with appropriate statistical analyses (t-test, ANOVA, regression, etc.) and measures (mean and standard deviation, confidence intervals, p-value, etc.)
	Conclusions	1	Conclusions and recommendations stated clearly. Results should be quantitative where possible and include applicable statistical analyses (mean, standard deviation, student T test, etc.)
	Design Modifications	1	Demonstrate how testing results used to modify or improve the design
	Comparison with PDS and Analysis	1	Test results clearly compared with analysis results and product design specifications
	Comprehensiveness	1	Extent of developmental testing: 0: few experiments/little significance on design, 1: many experiments/significant effect on design
4	**Discretionary Points**	5	Discretionary points based on overall thoroughness, quality, accuracy, and approach
	Safety	**20**	**Evaluated based on report and safety inspection**
1	**Rollover/Side Protection System**		
	Installation & Design	2	Rollover/Side protection system installed and functional
	Consistent with RPS rule	2	RPS design and fabrication appears consistent with rules
	Prevents bodily contatct with ground	2	RPS must prevent the riders appendages and head from contacting the ground in the event of a crash where the HPVC falls over or inverts
2	**Seat belt**	2	Seat belt installed correctly and appears to meet rules
3	**Steering system**	2	No excessive play or looseness, correct installation, apparent stability, etc.
4	**Sharp edges, protrusions, pinch points**	1	No sharp edges or protrusions on fairing, frame or components. No hazardous pinch points, especially near spoked wheels, chains, sprockets, etc. (Subtract points for serious hazards)
5	**Other hazards**	1	No other obvious hazards
6	**Rider's field of view**	1	Rider should have more than 180 degrees of visibility
7	**Safety Accessories**		
	Bell/Horn	1	Audible signal device installed and operational
	Headlight	1	White headlight installed and operational, visible 150 meters to the front, installed and operational
	Taillight	1	Red Taillight visible 150 meters to the rear, installed and operational
	Side reflectors	1	Amber reflectors on each side of vehicle properly installed
	Rear view mirrors	1	Mirror(s) installed providing the driver with views to the rear of the vehicle
8	**Materials of construction**	1	Materials of construction and production processes for frame and fairing chosen with safety in mind
9	**Manufacturing process**	1	Explain safety measures used during the construction of the vehicle
	Aesthetics	**10**	**Evaluated based on state of vehicle at safety inspection**
	Overall impression of vehicle	3	Overall impression
	Quality of craftsmanship	3	Craftsmanship (welds, joints, assembly, etc.) is professional and attractive
	Quality of custom parts	2	Team-fabricated and custom parts look professional and of high quality
	Quality of Frame/Fairing Finish	2	Exterior finish and decoration quality is neat, attractive, and professional (frame and/or fairing)

Table L.2 2015 HPVC Innovation Report Scoring [133]



	Item	Question	Points	Discussion	Notes	Evaluation based on
Design	1	What is the need for the proposed innovation?	1	Students must document the target market and need of their specific innovation	All innovations solve problems for specific needs. Please list the embodiement of the need and how this innovation solves the problem.	Report
	2	Is the proposed innovation a new idea?	4	Students must provide clear evidence that they have thoroughly searched the literature and patents for prior and/or similar work.	List/discussion of similar patents, summary of literature review, patent application by students on team are sufficient. Points are only awarded in the first year a team submits a design. Ignorance of an existing design does not warrant allocation of points if the judging team does not feel the innovation is not a new idea.	Report
	3	Does the proposed innovation benefit or advance the state of the art of human-powered vehicles?	2	Students must clearly show that the innovation has benefits, which can be performance, ergonomics, cost, environmental, social, etc.	This can be applicable in the HPVC or to mainstream human powered vehicles.	Report
	4	Is the innovation possible with existing or proposed technology and is this specific proposed execution feasible?	3	Students must clearly demonstrate that the innovation is does not require a violation of the laws of physics or the use of an unavailable process or material. Students must also show that the proposed embodiment of the design is feasible. In other words, the concept will work.		Report
Concept Evaluation	5	Is the prototype functional?	3	Does the prototype do what was intended? This is not an evaluation of how well it performs, but a validation of the design concept.		Report
	6	Are the proposed benefits of the concept realized?	3	Students must provide data to show how effectively the prototype achieved the anticipated benefits in question 3.	This can be executed by testing a mock up, prototype, or even a full scale version	Report
	7	Are there any unanticipated benefits?	1	Students must provide data to show how effectively the prototype achieved unanticipated benefits. Often the proposed benefits are not as important as unanticipated benefits.	Often times during the innovation process unanticipated benefits outweigh the original goals of the design and advance the state of the art significantly.	Report
Learnings	8	How and why did you fail?	2	Students should document what did not work -- concepts that turned out to be infeasible (why?), prototypes that did not work (why), and unanticipated difficulties.	Read Henry Petroski to get an idea of how important failures are in innovation.	Report and Presentation
	9	What was learned from the failures?	3	Students should document how failures were used as stepping stones to subsequent successes.	Most innovations are built on what is learned by failures. In fact, more is learned from failures than from successes.	Report and Presentation
	10	What are the unanticipated negative aspects of the design?	2	Students should clearly identify and if possible quantify unanticipated negative aspects -- increased cost, regulatory restrictions, negative environmental aspects, etc.	Even though benefits are realized, the innovation may not have full value because of some unanticipated negatives.	Report and Presentation
Execution	11	How well does the concept function based on the quality of the design?	3	Students should demonstrate how well the concept performs based on the quality of the design and the quality of physical execution	Well executed designs that function as intended shall receive maximum points, whereas poorly executed concepts with low craftsmanship that do not function shall receive low points.	Presentation
	12	Does the quality of execution reinforce the benefit(s) of the innovation?	3	Students must show that the physical execution of the design allows for or exceeds the intended benefits of the innovation	If the execution of the concept performs up to or beyond the intended level described in the benefits, full points should be awarded. If explicit metrics for measuring the quality of execution are not available the judges will assess points at their discretion.	Presentation
Bonus	13	Did the proposed innovation apply to one of the targeted innovation areas?	1			Report

L.2 **Clemson 2015 Design Report**

ASME SETTING THE STANDARD

http://go.asme.org/HPVC

(Form 6)

Vehicle Description Form

Updated 12/3/13

Human Powered Vehicle Challenge

Competition Location: Gainesville Florida

Competition Date: May 8-10, 2015

This required document for all teams is to be incorporated in to your Design Report. Please Observe Your Due Dates; see the ASME HPVC for due dates.

Vehicle Description

School name: Clemson University

Vehicle name: Panthera Tigris Tigris

Vehicle number: 5

Vehicle configuration

Upright ______ Semi-recumbent X

Prone ______ Other (specify) ______

Frame material: 4130 Chromoly Steel

Fairing material(s): Polyvinyl Chloride

Number of wheels: 3

Vehicle Dimensions *(please use in, in^3, lbf)*

Length 90in Width 36in

Height 49.5in Wheelbase 36in

Weight Distribution Front Unknown Rear Unknown Total Weight: ~70lbs

Wheel Size Front 20in Rear 27.5in

Frontal area 1614in^2

Steering Front x Rear ______

Braking Front ______ Rear ______ Both X

Estimated Cd 6.00

Vehicle history (e.g., has it competed before? where? when?)

New vehicle – Clemson Universities first known at competition

Clemson University

2015 ASME HPVC – East: Gainsville Florida

CLEMSON®
UNIVERSITY
HUMAN POWERED VEHICLE TEAM

Introduces vehicle number 5 the PTT Cruiser:

Panthera Tigris Tigris

Faculty Advisor
Gregory Mocko: (XXX) XXX-XXXX**,** XXXXXX@clemson.edu

Team Officers

Alex Whitman	*Team Captain, Frame Lead*: (XXX) XXX-XXXX, XXXXXXX@g.clemson.edu
Camden Druga	*Drivetrain Lead*: (XXX) XXX-XXXX, XXXXXX@g.clemson.edu
Philip Nich	*Steering Lead*: (XXX) XXX-XXXX, XXXXX@g.clemson.edu
Joshua Fairchild	*Fairing Lead*: (XXX) XXX-XXXX, XXXXXXX@g.clemson.edu

Team Members

Alan Saracina
Andrew Hyman
Austin Clark
Dedrick Smith
Henry Busch
Jonpaul Turner
Morgon Kaufmann
Natalie King
Nathan Huber
Scotty Haas
Taylor Schneider
Win Marks

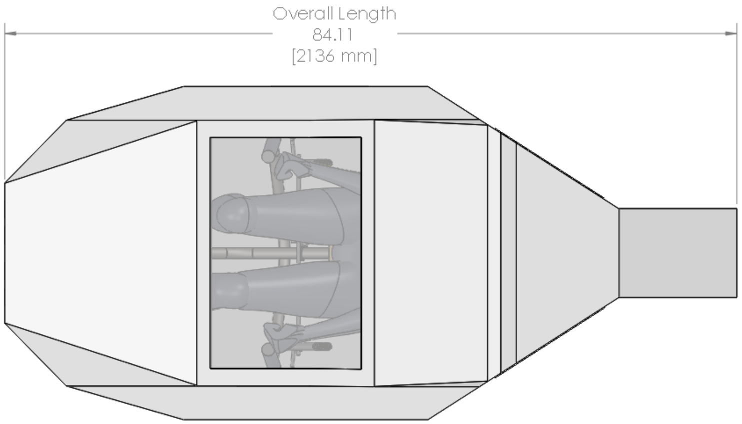


Figure 1. Top View

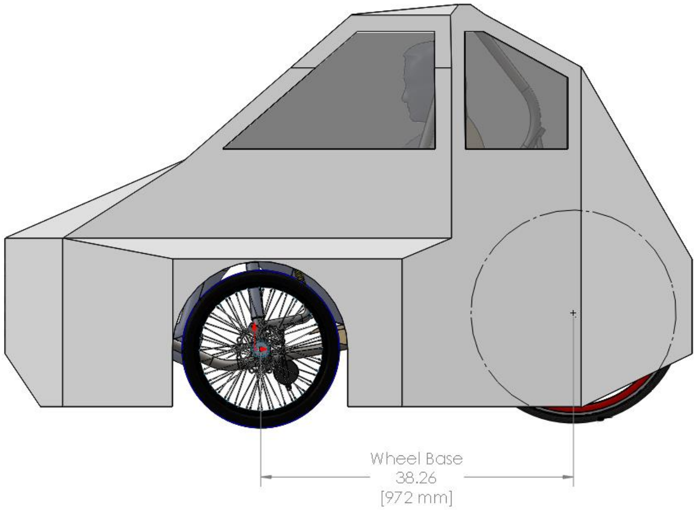


Figure 2. Side View

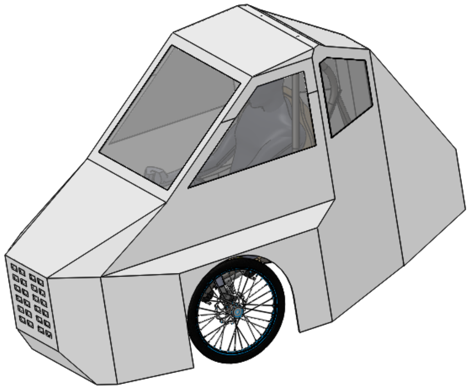


Figure 3. Isometric View

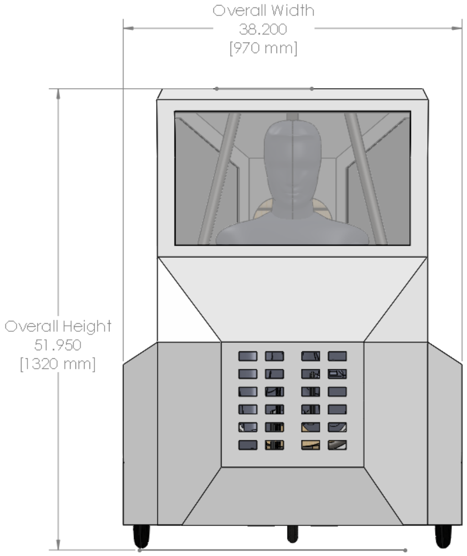


Figure 4. Front View

ABSTRACT

The project aims to design and build a human powered vehicle (HPV) to compete in the American Society for Mechanical Engineers HPVC East competition. Clemson University HPVC identified that there was little development being done to further the use of human powered vehicles in everyday situations. As a result, the team developed a vehicle that has the high performance characteristics of current vehicles but improves on the usability, practicality, and comfort of current offerings. It is the belief of the team that in developing the vehicle in these areas, the state of the technology will move in a direction that will eventually enable HPVs to be seen as a viable zero emission alternative to current transportation methods. The fairing, frame, steering, and drivetrain were all designed in the context of this mission, with the additional goals of safety and performance being introduced as crucial elements to the design. Finally, design for manufacture was taken into consideration in order to produce a design that could result in a commercially viable vehicle.

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I. INTRODUCTION

1.1 Objective

Clemson University's HPV aims to apply engineering concepts learned in the classroom towards the design and manufacture of a human powered vehicle. The vehicle should be designed with safety, manufacturability, marketability, and performance in mind. The product should be a vehicle that could be marketed to consumers, and the design should take into account the features and qualities needed for everyday use.

1.2 Background

The two major design areas researched prior to starting on the design of the vehicle were for the chassis, fairing, and all other aspects of how a three and four wheeled vehicle would have to be designed differently than a two wheeled vehicle. To evaluate design choices more effectively, the Clemson team research various design manuals. That being the case the fairing researched was conducted separately, because it is independent from most vehicle designs.

For the fairing, the team began the design process by looking towards existing competition vehicles for inspiration. What was found was that the current crop of vehicles competing all designed fairings purely for performance. The fairing design group began to think of a different class of fairing, one that displaced a bit more air but was more comfortable and aesthetically pleasing. One of the main design inspirations was Hannes Langeder's "Feridnand GT3 RS". The vehicle maintains the familiar aesthetics of a car while operating solely under human power. This gave the fairing design a goal of blending the vehicle in with what is currently on the roads today while introducing human power. The second design inspiration for the fairing was the design group The Future People and their "Zeppelin" HPV. This is a vehicle that aimed to be a practical city vehicle that was zero emissions but usable everyday to get around. Finally, the team looked towards current commercially available options such as the RBR "Aergo".

1.3 Prior Work

This is Clemson University's first time entering the HPVC Competition. Thus, everything about the design, manufacturing process, construction, and all other aspects of the event completed by Clemson is new to this academic year.

1.4 Design Specifications

Clemson had to two main goals in creating a human powered vehicle. The first goal was to meet the qualifications and abide by the rules given by ASME HPVC. The second goal was to design a vehicle that would be beneficial, affordable, and appealing to the common person. In other words the factors that drove most of the design choices were creating something designed for comfort and usefulness, rather than being optimized for speed and performance. The outcome of our objective defined our constraints and criteria which are summarized in table 1.

Table 1. Constraints for vehicle design

Constraints	Justification
Must come to a stop from a speed of 25km/hr in a distance of 6m	Rule given by HPVC ASME
Use aerodynamic devices	Rule given by HPVC ASME/ Increase efficiency and thus requires less energy from rider
Can turn within an 8.0m radius	Rule given by HPVC ASME
Must be Stable	Rule given by HPVC ASME/ Lower's required rider experience
Must have an RPS system that meets ASME standards	Rule given by HPVC ASME
Must have cargo storage	Rule given by HPVC ASME/ Allows for easy rider travel storage
Must be comfortable to ride	Works for various rider shapes and sizes
No Exposed sharp edges	For rider Safety
Durable vehicle	Long lasting product for rider, which requires low maintenance
Simplicity	Vehicle must remain relatively simplistic for ease of assembly, maintenance, and design complexity.

Criteria	Justification
Fully covered Vehicle	Protects rider from all types of weather conditions
Energy Storage Device	Rule given by HPVC ASME
Producible for under $2,000	Remains relatively cheap for average consumer
Optimizes field of vision	Allows for driver's safety and more environment awareness
Has high maneuverability	Handling responses well to rider

1.5 Concept Development and Selection Methods

Initial concepting started with choosing the overall vehicle type. To do this, human powered vehicles were grouped into three types, based on the number of wheels, and evaluated based on our constraints and criteria. A weighted comparison matrix, shown in Table 2, was complied. The results of the matrix were evaluated along with a pros and cons assessment for each type. The outcome was a decision to move forward with a three wheeled design.

Table 2. Vehicle type evaluation

Weighted Categories	Two Wheels	Three Wheels	Four Wheels
Simplicity (5)	9	3	1
Stability (4)	1	9	9
Comfort (3)	3	9	9
Speed (1)	9	9	3
Maneuverability (2)	3	3	3
Weighted average	4.3	6.2	5.1

For three wheeled vehicles the two major designs are tadpole and delta tricycles. Table 3 encapsulates some of the reasoning and justifications behind our tadpole trike design. In addition aspects of the design such as wheelbase and steering considerations were assessed as well. Design factors such as suspension, frame design, steering alignment, chain routing, and braking systems were developed, iterated on, and improved throughout the design process.

Table 3. Evaluation of trike aspects

		Pros	**Cons**
Style	Tadpole	1.) Excellent Braking 2.) Excellent Handling	1.) More Complex to design overall
	Delta	1.) Easy to design 2.) Low cost to make	1.) Rolls Easily 2.) Single front braking
Wheelbase	Short	1.) Tighter turn radius 2.) Faster handling 3.) Compact Frame	1.) Rider position has more of an effect on weight distribution
	Long	1.) More clearance for seat 2.) Rider has less effect on weight distribution	1.)Large turn radius 2.) More weight 3.) More frame flexing
Steering	Lean Steering	1.) Excellent low speed handling 2.) Allows for larger front wheels due to reduced side loads	1.) Not optimized for high speed 2.) Requires rider experience
	Front Steering	1.) Convectional, highly researched 2.) Stable	1.) Can be complex depending on the design
	Rear Steering	1.) Lighter 2.) Smaller turning radius	1.) Unstable 2.) Requires rider experience

The overarching objective for our HPV design was stability, control, and comfort. From table 3 it can be shown that the tadpole trike with a shorter wheelbase and front steering is the best suited choice to fit these design constraints. As a result the design of Clemson's HPV incorporated all of these aspects. Aside from evaluating the effectiveness of different designs through tables and comparisons, several features were analyzed based on early aspects of their development. Figure 5 shows computer generated models of preliminary steering concepts that were tested. The concepts along with many others were virtually tested for attributes such as stability, complexity, material selection, handling, and load considerations. The concepts were continued on until they will ultimately combined and optimized for Clemson's design requirements.

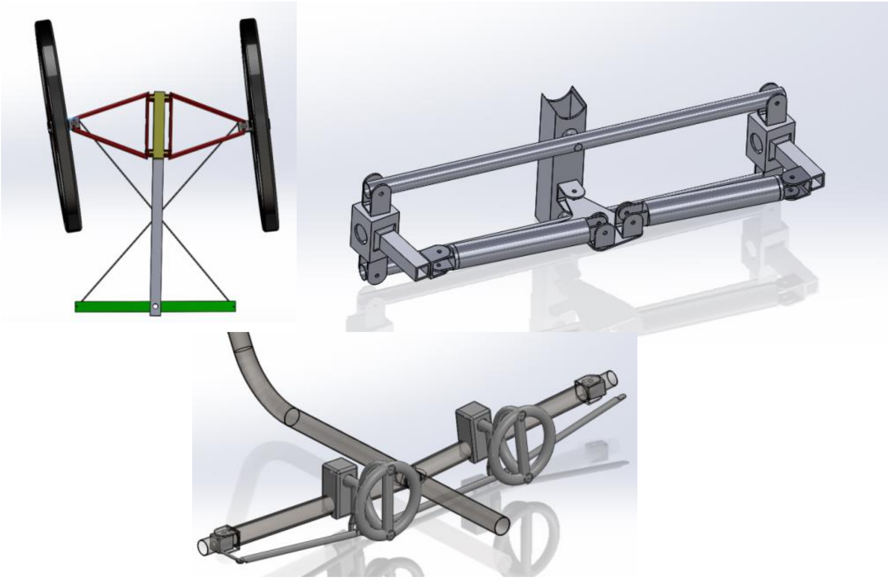

Figure 5. Modeled Front steering concepts a.) Crossed dual drag link concept b.) Lean steering concept c.) Direct knuckle steeing concept.

1.6 Innovation

While our human powered vehicle design may seem simplistic and large, that is what makes its innovative. The Panthera Tigris Tigris, otherwise known as the PTT cruiser, was designed for human comfort, everyday use, and stability, which is what makes it an innovate design. Most HPV's are designed for speed and racing purposes, but not for the everyday commuter. The use of an internally geared hub allows for a large gear range to compensate for the range in different rider abilities. The PTT cruiser's fairing is a prime example of our innovative design. While most fairings have constricted sizes for speed and increased aerodynamics, the PTT cruiser has a large area for a greater range of rider sizes and more comfort for rider movement. Similarly, the fairing is innovative because its design purpose wasn't strictly to improve aerodynamics. The shape was designed to isolate the rider was environmental hazards, such as protection from rain, hail, and smoky and dusty areas.

Material choices for the PTT cruiser were innovative because they consist of a variation of custom parts and standard bicycle parts. The tricycle was designed with standard bicycle parts, to make maintenance practices more common to the standard bike, easier to complete, and lower the cost of replacing parts, due to standardization. The seat and chain stay, head tube, bottom bracket, crankset, rear wheel, brakes, and shifters all came from a standard steel frame road bike for this reason.

1.7 Frame Design

The design of the frame went through several iterations. The major factors leading to the finalization of the frame were rider position, rider height, typical load cases, manufacturing complexity, number of welds, and integrability with standard bike frames. Figure 6 shows the result of all the design considerations.

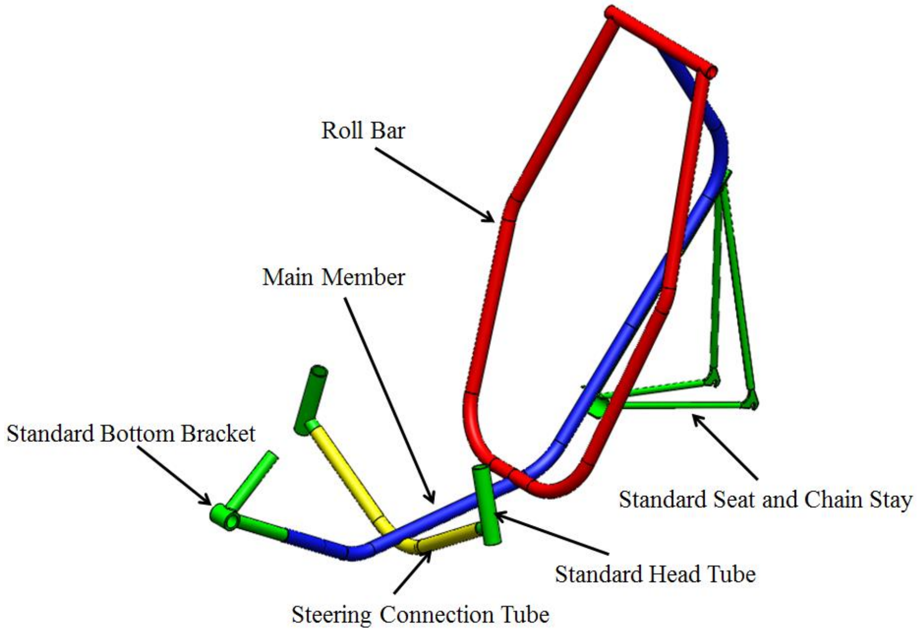

Figure 6. Finalized frame design

For material selection 4130 chromoly steel was chosen to decrease needed welding experience and act a strong material for durability. Carbon and aluminum composites were considered for the frame, but required a higher degree of work and experience. Carbon lay-ups required massive amounts of time materials, and experience that would greatly increase production costs for not much added benefit. Aluminum would be a suitable choice, but requires TIG welding experience, which in turn would increase production costs. The weight saving from aluminum would be relatively negligible after the thickness would have to be increase for structural reasons.

To increase simplicity, the number of members required in the frame construction is minimized and the number of bends is reduced from previous iterations. The reduced number of parts is advantageous for manufacturing quality and time. The lower number of parts means there is a lower chance of manufacturing defects, because of the lower number of interfaces and total machined surfaces. Through bending different sized tubes with a pipe bender and tube bender the team learned that proper equipment is key and as the number of bends in a tube increases the difficulty of keeping all the bends in the same plane. Thus, by decreasing the number of bends the frame design allows for greater producibility.

The shape of the main member shown in figure 6 and 7 is designed for structural and ergonomic purposes. Structurally the rear section of the main member is angled such that it would better support a top load from the roll cage. The front of the main member is shaped to be comfortable for a person to pedal, while having a crank height that allows for good visibility. Lastly, the main member has a compact shape to support the weight of the rider more easily. The steering connection is designed to be integrated with steering alignment to optimize handling and control for the rider. Additionally the wheel base was increased to give the rider more distance from the front wheel on sharper turns, which is an outcome of the steering connection tube shape. The front wheels being 20 inches also helps give the rider's legs more room when turning.

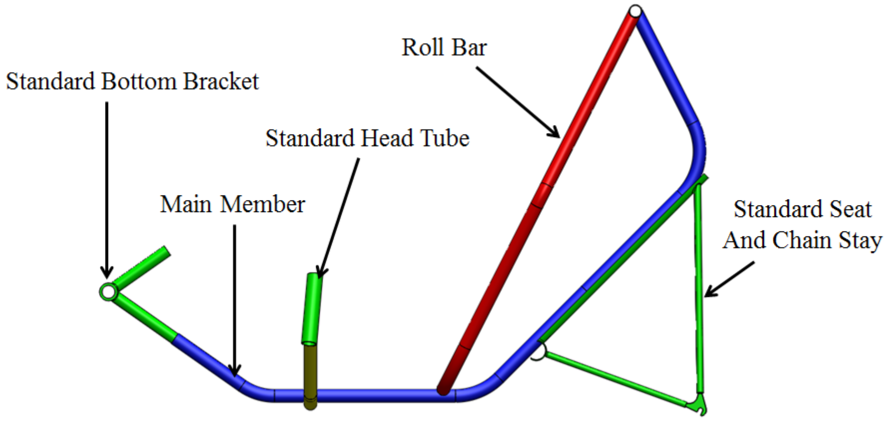

Figure 7. Side view of frame

1.7.1 Roll Protection System

The roll protection system is a vital part in rider safety and as such it is designed to safely encase the rider and prevent them from getting injured from various accidents. The shape of the roll protection system, shown in figure 6, is a result of minimizing manufacturing complexity. Simplifying the roll protection system to three pieces and minimizing the number of bends, allows for less manufacturing time, while still maintaining a semi-round shape. Additionally, the shape of the roll bar and size of the tubing fully supports the load cases defined by ASME for safety, which will be proven with later analysis.

Extra space was given between the rider and roll cage to provide as a buffer in the case of a collision and for comfort. The width of the roll bar could have been decreased to lower drag, but that would have resulted in a tighter fit for the driver and the overall design choice was to be more comfort directed to accommodate the everyday rider. The required height was determined using a person of 6'5" in stature. The width allows for the same person to have a shoulder width of 22 inches as well, which is 2 inches more than the team's tallest rider.

1.8 <u>Steering Design</u>

The steering design chosen for this year's competition is a Direct Knuckle Steering set up slightly ahead of the seat yet also under the seat, shown in figure 8. This configuration creates a tighter frontal area and is fairly simple to configure. This also gives us support during high G turning. The main issues for this set up is the rider's hands are relatively close to the tires and that the side to side motion for steering is counter intuitive.

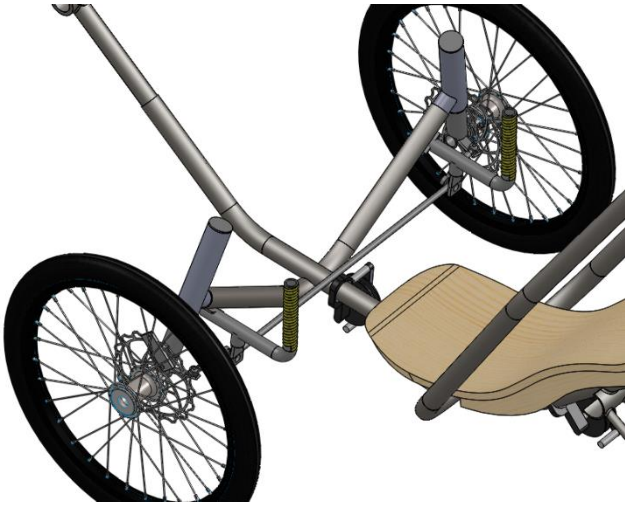

Figure 8. View of steering geometry

The steering linkage system is the drag link system but with two separate links. The second link allows for an easier time turning since either link can be operated to turn the**.** For this trike design the camber angle are chosen to be neutral to improve grip while cornering. There is no toe-in in the design of this trike. Ackermann Compensation is an important consideration in the creation of our steering system. We aligned the two control arms for the wheels to the front tires to the center axle of the back axle. This was done due to the space between the wheels being 36 inches. The minimum turning radius of this geometry is 2.23m and the caster angle is 5°.

1.9 <u>Drivetrain</u>

The goal of the drivetrain was to be as simple and universal as possible. When developing our system the dimensions of frame were not finalized so the routing would need to accompany many different designs. Our design includes an 11-speed internally geared hub that would drive the rear wheel. The crankset has 3 gears that can feature a derailleur that can change gears so the drivetrain can potential have 33 speeds. The chain will be routed with multiple idler gears mounted to the frame. This will transfer the power from the crankset to internal gear hub more effectively. In order to remove the slack from the chain a chain tensioner is used. All of the pieces used are standard bicycle parts which make it easier to integrate them together. The design is simple and should be prove to be reliable way to drive the vehicle.

Our first idea involved the use of a jackshaft to separate the crankset and the rear wheel with two different chains. The routing would have involved two straight paths from the crankset to the jackshaft and then to the rear wheel. The advantage to this system was that the two paths were separated which would make the chain less likely to fall off. Also the jackshaft could have been used to change to gear ratio and be an output to an energy recovery system. We decided against this idea due to the difficulty of manufacturing and the issue of keeping tension in the chain. With further development this setup could work with a future project.

1.9.1 Drivetrain Routing

The routing of the chain goes from the crankset to the internally geared hub which will drive the wheel. Multiple idler gears are used to reduce the amount of angles that the chain has to make. The sharper the angle the less effective the system will be. The idler gears we are using include a high quality bearing to reduce as much friction as possible. This configuration requires the chain to zig-zag over and under the idler gears to maintain tension and to prevent the chain from dragging. The idler gears are attached with an adjustable bracket that will mount to the frame. With these adjustable brackets the position of these brackets can be changed to find the ideal route for the chain.

1.9.2 Internally Geared Hub

The internally geared hub is the main component for our drivetrain system. An internally geared hub is a planetary gear system which can change the gear ratio by locking certain components to increase or decrease the gear ratio. This system is contained in the hub and the chain is attached to a gear on the outside that spins the planetary gears. We chose to go with this system rather than a traditional rear cassette because its gear range is much larger and doesn't require the chain to move to switch gears. A chain tension is than mounted to replace the derailleur so that the chain can be easily put on and the chain won't fall off. We believe with this system the chain will not fall off and shifting gear will not be an issue. The internal gear hub we are using is the Shimano Nexus 11-speed hub By comparing this ratio to traditional cassettes' we can see the advantage of this using a rear hub.

1.10 <u>Fairing Design</u>

The fairing created for our vehicle was designed to make the rider more comfortable, the tricycle more appealing, and the ride safer. Figures 1 through 4 demonstrate how the designed fairing gives the driver plenty of leg and arm room and an overall sense of open space. This way the rider does not feel confined like they would in an HVP designed solely for performance, racing, and speed. The fairing design allows for storage in the back and is large enough to be equipped with other creature comforts such as cup holders, mirrors, electronic charging dock, and etc. To make the fairing appealing to the average person the profile is designed to mimic the style of older automobile like the 1959 Austin Mini and the 1950 Pontiac. The tessellation look is a result of simplifying the manufacturability. The material for the fairing is thin sheets of polyvinyl chloride. The PVC is supported and connected to the frame allowing for a skin on frame design. The PVC was chosen because is it lightweight, cheap, and provides as a suitable buffer to the environmental factors, such as weather and air pollution. Lastly the grill in the front of the fairing was added to act as a ventilation system to allow airflow to cool the rider during hot days. It can simply be covered for colder climates.

II. ANALYSIS

2.1 <u>Roll Protection System Analysis</u>

To analyze the effectiveness of the roll protection system a finite element analysis was constructed. To inspect the structural integrity of the roll bar, the frame was constrained at the weld points of the chain and seat stays and the weld points of the steering connection tube. It was constrained at these points because these are connection points to the components in contact with the ground, which would be the main reaction force.

Two case studies were performed on the system. The first was a top load of 2670N, 12° from the vertical at the top of the roll cage. The second was a side load of 1330N at the side of the roll cage. Both of these cases are required through the ASME HPVC rules. The rules dictate that the resulting maximum elastic deformation be less than 5.1cm. Additionally the PTT Cruiser design was tested for surpassing the yield stress by examining factors of safety. The factory of safety is being defined as the the ratio of yield stress of the material to the von Mises stress at a point, where the von Mises stress is the most critical stress that can occur at a point, based on its shear and axial stress orientation. The displacement effects from the top load scenario are shown in figure 9. The FEA concluded a minimum factor of safety of 4, meaning the most critical point on frame from the roll bar was 75% less than the yield. In other words, all deformation that occurred was in the elastic region. From figure 9 the greatest deformation that occurred of 3.1mm is well below the maximum deformation limit outlined by the rules.

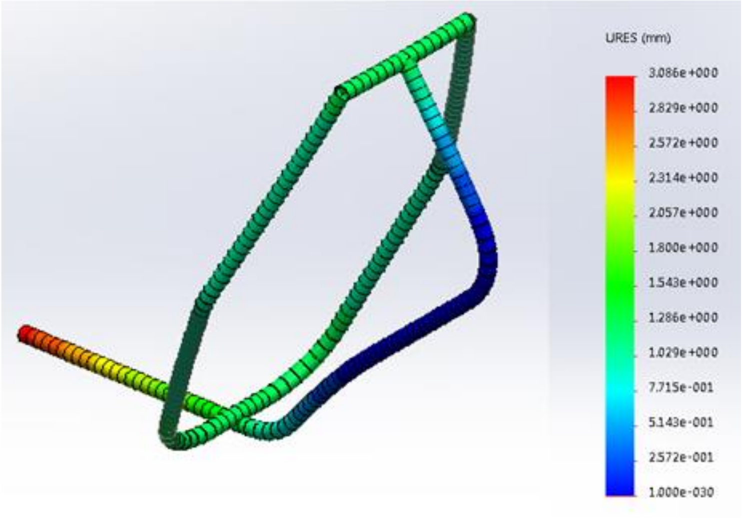

Figure 9. Results of 2670N top load at 12° from vertical

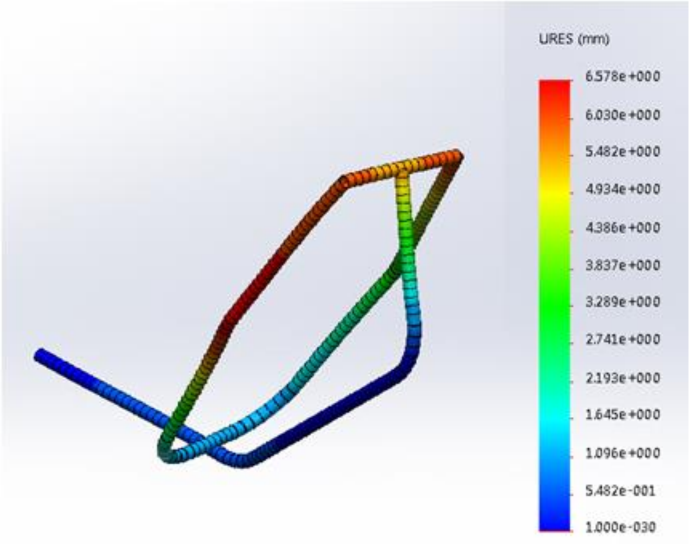

Figure 10. Results of 1330N side load

The side load was performed and the results are shown in figure 10. The factory of safety and maximum deformation were 2.7 and 6.57mm respectively. Values that once again indicate the roll bar is design well within the region for safety and meets the required rules.

At this point some would argue that the factor of safety is high and the design should be changed to lower weight and remove unnecessary material. With that being said, the roll bar design already which through multiple design iterations. The number of support has been decreased to lower weight and manufacturing complexity, the size and thickness of the tubing has already been reduced to lower total weight by 20lbs from the original design, and the roll bar shape has been changed to simply the overall design. Additionally the load cases given are not a worst case scenario. The design of the roll bar has intentionally been made a stronger to better support the rider's protection in the case of a serious accident.

2.2 <u>Structural Analysis</u>

Having a single member support the weight of the rider simplifies manufacturing complexity and reduces weight. As a result of the main member being a single bent tube used to support the entire weight of the rider, it is important to perform a proper analysis to ensure it would not overly flex from the rider weight distribution. Before the analysis was performed design implementations were taken into account to reduce the problem. For one the frame was design to be more compact to reduce bending caused by moments from the rider's weight. Additionally cold working the tubing when bending and having a bend where the rider sits, strengthens the material at the point where the rider's weight is distributed. Lastly, the mounting of the seat helps distribute the rider's weight closer to the chain and stay. This reduces the bending stresses near the rear triangle and lowers the amount of front wheels accept. Lowering the force of the front wheels is also important because they have singled supported axles, which means they are more susceptible to stresses than the rear wheel.

A finite element analysis was performed on the main member using a rider weighing 300lbs. Figure 11 demonstrates how the frame section of held in place. It was fixed at the locations where it was being held by the chain and seat stays as well as the steering connection tube. The results from figure 12 show that the maximum deformation from a sizable rider would only be .1mm with a stress factor of safety of 6.5. Thus, the single member holding the entire weight of the rider is justified through the stress analysis.

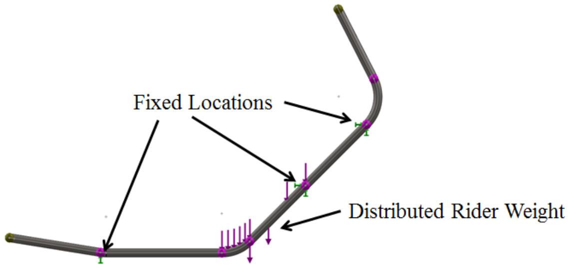

Figure 11. Layout of main member load distribution and fixed geometry

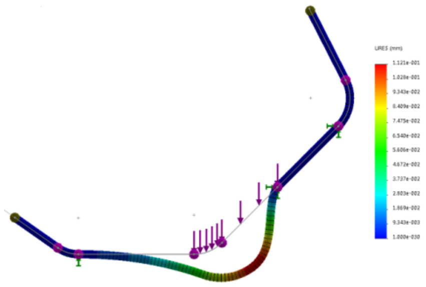

Figure 12. Displacement results of main member loading from figure 11

2.3 Aerodynamic Analysis

In order to justify our design choice of sacrificing overall aerodynamics for rider comfort, usability, and overall aesthetics we performed a CFD analysis on the vehicle using SolidWorks Flow Simulation 2014 to calculate the drag forces on the vehicle at different speeds. In order to simplify the analysis the front vents were closed, as were the cutouts for the front wheels, and a bottom tray was added. To incorporate the full range of speed that the vehicle can achieve the analysis was run at 5, 10, 15, 20, and 25 miles per hour. Since this is Clemson Universities first year competing in the competition, these results were compared to the faired and un-faired vehicle produced by the University of Oklahoma in 2013, which has the standard look associated with human powered vehicles. This comparison showed that despite our vehicle being much larger and visibly less aerodynamic, the actual forces on the cart are not significantly higher, especially at lower speeds.

Table 4: CFD simulation results for direct frontal flow

Vehicle Speed [mph]	Drag Force [lbf]		
	Clemson University 2015 Faired	University of Oklahoma 2013 Un-Faired	University of Oklahoma 2013 Faired
5	0.361	0.213	0.134
10	1.421	0.842	0.412
15	3.223	1.900	0.947
20	5.760	3.375	1.665
25	9.006	5.287	2.585

According to Google Maps, the average driving speed in major cities is less than 20 miles per hour. Table 4 shows that our faired vehicle is subjected to approximately the same drag force at 20 miles an hour as the un-faired University of Oklahoma vehicle experiences at 25 miles per hour. This means that when driving around in our vehicle the rider would approximately experience the same power output as riding an un-faired recumbent bicycle with a 5 mile per hour headwind.

Despite the very geometric look of our vehicle and the harsh edges between panels, the streamlines still flow around the vehicle without causing any significant pressure drops or turbulence, as seen in Figure 13.

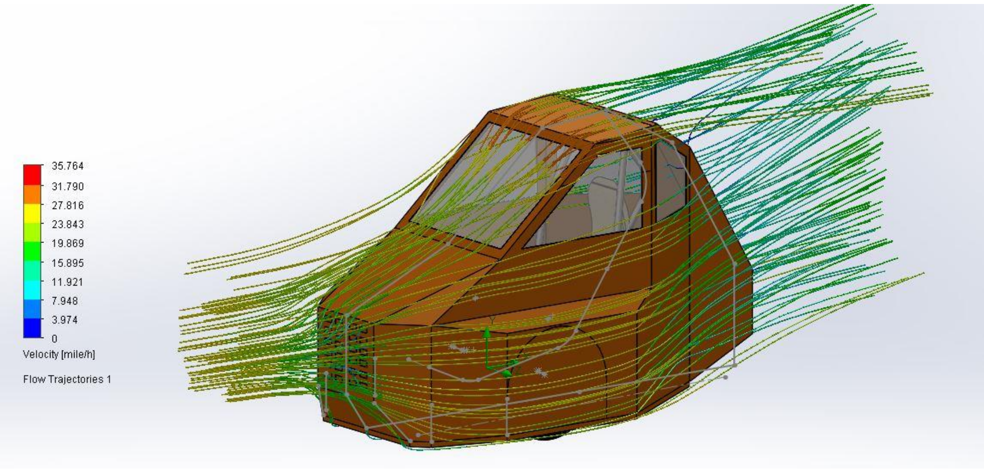

Figure 13: Streamlines at 25 miles per hour and no crosswind

Due to the vehicle being a tadpole style trike, a crosswind would create very little risk of flipping the vehicle over, however, an analysis was still done with a crosswind speed of 10 miles per hour. At a straight line speed of 5 miles per hour the drag force was increased to 7 lbf. This value is to be expected because the vehicle has a very flat side profile, and a large side area.

The presence of a cross wind caused a lot of turbulence on the downwind side of the crosswind. This effect is greater at lower direct frontal flow speeds, as seen in figure 14 where there is a 5 mile per hour frontal speed and a 10 mile per hour cross wind.

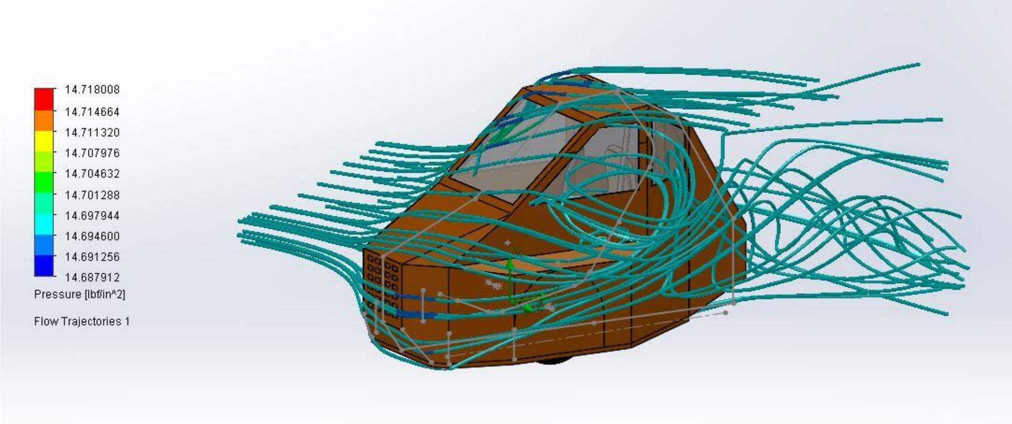

Figure 14: Streamlines at 5 miles per hour and a 10 mile per hour crosswind

By increasing the frontal speed the turbulent effects are decreased as seen in figure 15, but there is still an overall increase in drag force compared to running an analysis without the presence of a crosswind. However, this combination of wind speeds caused an increase in the drag force to 18.5 lbf.

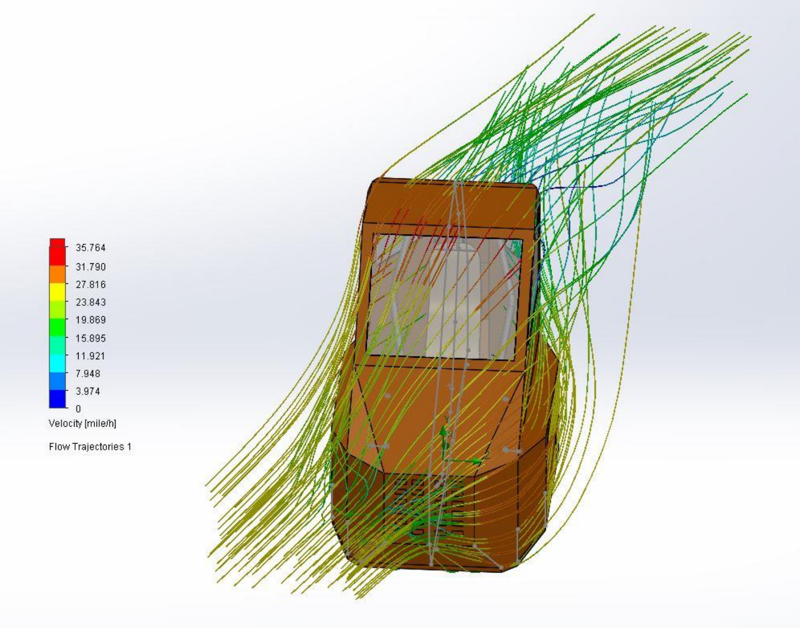

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Figure 15: Streamlines at 25 miles per hour with a cross wind of 10 miles per hour

To find the drag coefficient for the PTT Cruiser fairing design eq. (1) was used to create table 5 from table 4. Equation 1 is the following

$$C_D A = \frac{2F_D}{\rho V^2} \tag{1}$$

,where F_D is the drag force, ρ is the density (of air evaluated at sea level), V is the velocity, A is the frontal area and C_D is the drag coefficient. The estimated drag coefficient are high in comparison to many other models, but the purpose of the PTT cruiser fairing design was for comfort not aerodynamics. While still maintain relatively the same frontal area the current design of the fairing did show aerodynamic improvements from past iterations, while allowing for easer construction.

Table 5 Summary of PTT cruiser fairing drag coefficients

Wind Speed (mph)	Drag Force F_D (lbs)	Drag coefficient C_DA (ft^2)
5	0.361	5.64
10	1.421	5.55
15	3.223	5.60
20	5.760	5.62
25	9.006	5.62

2.4 Cost Analysis

In addition to marketing our design to fit the needs of the average person, the cost of the PTT cruiser was also a factor in the design process fit to consumer needs. To make to design of our tricycle marketable we tried to keep costs low by using cheaper materials, lower grade components, and less complex machining features. Table 6 summarizes the cost our design based on these efforts. The difference in base material cost between the competition and market vehicle comes from the ability to buy more materials at cheaper prices on a production level, i.e. bike frame, tubing, and required parts. Also when buying materials for the competition vehicle some extra materials were purchased for the chance of manufacturing mistakes. The cost of the competition vehicle material is also higher, because two entire bicycles were purchased and used, instead of just buying the frames. The range in the cost base and premium models comes from the ability of the consumer to upgrade components and add features. For example the competition vehicle uses an expense internal gear hub in the drivetrain. The base model of the trike might have a lower end internal gear hub or cheap cassette depending on the consumer preferences to lower cost. The reasoning applies to extra features such as a faring. A consumer may decide they do not want a fairing, want a basic one, or even possibly an upgraded fairing. That the great thing about the PTT cruiser. It is market to a board range of consumers and can be priced to their lifestyles according, similar to the road bike market is today.

Table 6 Cost analysis of competition and production vehicle

		Base and Premium model Costs	Base Model Costs
	Competition Vehicle	Production Cost (per vehicle)	Production Cost (per 120 Vehicles)
Capital Investment (Tube Bender, Bike Tools, Jigging Tables, Etc.)	$600	$3,000	$3,000
Tooling (Molds, Fixtures, Etc.)	$50	$50	$6,000
Base Material (Tubing, rear triangle, wheels, chain, idler gear Etc.)	$1,850	$800	$96,000
Upgradable Parts (Crank set, gear hub brakes, etc.)*	$800	$200-$2000	24000
Extra Features (Tail lights, Fairing, etc.)*	$500	$0-$2000	$0
Labor (Welding, Assembly, Wheel Lacing, Etc.)	$100.00	$200	$24,000
Overhead	$0.00	$200	$24,000
Total	**$3,900**	**$4450-$8450**	**$174,000**
		Cost per Vehicle	**$1,450**

*The difference in cost comes from the the quality and upgradability from the customer. Base model cost is the low end cost and premium cost is the upper end cost.

2.5 <u>Drivetrain Analysis</u>

Table 7 Gear range analysis of internal gear hub

Gear	Internal Hub Ratio	XTR Cassette Ratio
1	0.88	0.75
2	1.13	0.86
3	1.28	0.97
4	1.47	1.11
5	1.67	1.25
6	1.88	1.43
7	2.15	1.58
8	2.43	1.76
9	2.78	2.00
10	3.15	2.31
11	3.58	2.73

Table 7 contains the gear ratios for the Shimano Nexus 11-speed hub on our bike compared to a traditional Shimano XTR Cassette. These ratios were generated by using a crank with 30 teeth and 18 teeth attached to the hub. While developing our drivetrain system we wanted it to be about to provide a large amount of torque. The XTR cassette is a fair comparison because it is a cassette design for a mountain bike which deals with going up step hill which will require a high gear ratio. This internal gear hub is able to produce a much higher gear ratio than this cassette. It also produces a similarly low gear ratio on the lowest gear. These calculations are done with only a single crank, with a derailleur on the crankset the gear range will be even greater. This hub was chosen because it provides a 409% gear range which is very large range which makes it very versatile and it also removes the need for a rear derailleur.

III. TESTING

Vehicle construction is currently in progress and all physical testing performed will be presented at the design presentation with all design changes since the report submission. This is a direct result of the inexperience from all members of the team being new to the hpvc competition, and consequently inexperience in time management for the competition. As Clemson’s involvement grows in continued years, the newfound experience gained will lead to better time management and sooner vehicle construction. This earlier physical testing will be conducted allowing the results to be properly discussed in the design report.

IV. SAFETY

The vehicle is a recumbent type giving it a low center of gravity which prevents capsizing of the vehicle during moments of instability. However, the bike does sit approximately six inches off the ground to protect against small obstacles that may be in the road. A tadpole shape was chosen over other recumbent shapes as it provided the best stability during turning while also allowing stability at a standstill. The large frame and fairing shape ensure that the vehicle, while recumbent, is tall enough to be noticed by other vehicles on the road such as cars or trucks preventing collisions.

A commercially produced three point harness is to be used for the vehicle. The harness will be attached directly to the main member under the bike and to the roll bars to provide maximum stability. A windshield and two side windows of Plexiglas ensure that the driver has a minimum of 90 degrees in either direction. Side mirrors are also to be implemented to give the rider a rear view. In addition the relaxed build of the PTT Cruisers gives the rider an even greater field of vision compared to vehicle optimized for speed. This helps the rider see environmentally factors more clearly, meaning they will be more appear of factors like pedestrians, other vehicle, and road hazards. This will in turn make it safe for others on the road as well.

A roll bar system was designed to meet the load specifications set by the HPVC rules as well as encompass the rider in such a way that protects against both collisions and turnovers should they occur. The vehicle design leaves a handful of exposed tube openings which are to be plugged and covered to avoid any injury. The vehicle also employs a number of parts recycled from two commercially sold bikes, any exposed cutting points are ground down and covered in a protective material to protect against sharp edges. Any other sharp edges, such as zip ties, pvc edges, screws, brackets, and metal burs are to be covered using protective material. In the interest of road safety reflectors, fore and aft lights and a bell are to be installed on the vehicle.

Lastly, manufacturing safety was a priority during vehicle construction. The majority of manufacturing took place in a university workshop, which required all members to earn certifications before being granted access to the workshop and secondary certifications to use any tools therein. The workshop was outfitted with proper safety measures such as fire extinguishers, first aid kits, and trained shop supervisors. All team members observed the use of personal protective equipment including wearing safety glasses at all times in the workshop and wearing an approved mask, apron, and gloves when welding.

V. CONCLUSION

5.1 Comparison

The design goals for Clemson HPV were to make a vehicle that was marketable, long-lasting, and practically to the average user. The overall design follows the goal completely by giving the rider a realistic amount of room, a stabile ride, with great handling and a vehicle that was designed for safety. The analysis behind the vehicle shows the construction is durable and the production costs are low. The frame is design specifically to give the rider a upright and relaxed sitting position. The steering is constructed to be stable, with great handling. The drivetrain is intended to offer a board range of gear ratios that account for riders of different athleticism, and terrain of different difficulties. The fairing is fabricated to give the rider safety, by allowing a wide field of vision and protection from the environment, while maintaining a comfortable space.

5.2 Evaluation

To evaluate how well the design goals were met table 8 was created to quantify the results. A category this is green means the goals was meet completely. Yellow means the goal was almost met or further analysis is required. Red means the design feature was not met. The table shows that almost all of the design goals were either obtained or almost obtained. Thus the PTT cruiser final design is a success based on the established goals.

Table 8. Evaluation of design goals

Must come to a stop from a speed of 25km/hr in a distance of 6m	🟨
Use aerodynamic devices	🟨
Can turn within an 8.0m radius	🟩
Must be Stable	🟩
Must have an RPS system that meets ASME standards	🟩
Must have cargo storage	🟩
Must be comfortable to ride	🟩
No Exposed sharp edges	🟨
Durable vehicle	🟩
Simplicity	🟩
Fully covered Vehicle	🟩
Energy Storage Device	🟥
Producible for under $2,000	🟩
Optimizes field of vision	🟩

5.3 Recommendations

Although the Panthera Tigris Tigris is a well-designed vehicle there are some aspects that could be improved on. For one the fairing did go through iterations and the aerodynamics improved, but to be more competitive they could be improved more. The design could become simmer and more curved to lower the drag coefficient. At the same time this may slightly increase manufacturing difficulty and slightly decrease rider comfort, but it could add more appeal. Another big recommendation is the time management that went into the project. Too much time was spent on design, which has placed a time crunch on vehicle production and testing. As a result, the testing findings were not included in the report. Lastly, more analysis could have been completed on the drivetrain routing to examine the efficiency. By doing so and iterating the design, the efficiency could have been improved. Thus less effort would be required by the rider.

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L.3 Clemson 2015 Innovation Report

http://go.asme.org/HPVC

(Form 6)

Vehicle Description Form

Updated 12/3/13

Human Powered Vehicle Challenge

Competition Location: Gainesville Florida____________
Competition Date: May 8-10, 2015 __________________

This required document for all teams is to be incorporated in to your Design Report. Please Observe Your Due Dates; see the ASME HPVC for due dates.

Vehicle Description

School name: Clemson University
Vehicle name: Panthera Tigris Tigris
Vehicle number: 5

Vehicle configuration

Upright ______ Semi-recumbent X_____
Prone ______ Other (specify) ___________________

Frame material 4130 Chromoly Steel
Fairing material(s) Polyvinyl Chloride
Number of wheels 3
Vehicle Dimensions *(please use in, in^3, lbf)*

Length 90in Width 36in
Height 49.5in Wheelbase 36in

Weight Distribution Front Unknown Rear Unknown Total Weight: ~70lbs
Wheel Size Front 20in Rear 27.5in
Frontal area $1614in^2$
Steering Front x Rear ______
Braking Front ______ Rear ______ Both X
Estimated Cd 6.00

Vehicle history (e.g., has it competed before? where? when?)__________________________

New vehicle – Clemson Universities first known at competition

Clemson University

2015 ASME HPVC – East: Gainsville Florida

CLEMSON
UNIVERSITY
HUMAN POWERED VEHICLE TEAM

Introduces vehicle number 5 the PTT Cruiser:

Panthera Tigris Tigris

Faculty Advisor
Gregory Mocko: (404) 803-4734, gmocko@clemson.edu

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Camden Druga	*Drivetrain Lead*: (803) 543-8432, cdruga@g.clemson.edu
Philip Nich	*Steering Lead*: (843) 501-8998, pinch@g.clemson.edu
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Team Members

Alan Saracina
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Natalie King
Nathan Huber
Scotty Haas
Taylor Schneider
Win Marks

Introduction

The ASME human powered vehicle competition began in 2002, with human powered vehicles becoming popular among designers long before. However, these vehicles are not currently used by consumers. The broader scope of the competition is attempting to answer this question: *Why are human powered vehicles not seen on the roads today?*

Two main issues are to be considered, first being the efficiency of a HPV. The most recent HPV spotlight is on the VeloX3 and its top speed of 83 mph.

For this speedy HPV, the consumer only has to sacrifice their leg room, storage space, back support, safety, driver independence, stability, and dignity. One must be a professional biker to drive this it. Engineers have over-engineered the technical aspects without asking if consumers will, or can, drive the vehicle. Below are some recent ASME HPV winners.

Top-Left: Rose-Hulman 2014, 1st Place Design
Bottom-Left: Olin 2014, 3rd Place Design

Top-Right: Central Florida 2014, 2nd Place Design
Bottom-Right: Missouri 2013, 2nd Place Design

Like the VeloX3, these vehicles look more like a torpedo on wheeland provide little insight into today's problem. The vehicles provide a sleek racing design, but do consumers want to drive them on the roads? Based on the performance of these technical vehicles combined with the apparent lack of demand, the answer is an overwhelming **NO**. The vehicles are engineered but not practical.

Fairing Design

Therefore, the solution lies within more consumer-friendly features, in hopes of obtaining a demand. The most obvious feature is the outer fairing. Instead of the generic torpedo design, our team pursued a more car-like design, drawing inspiration from the 1959 Austin Mini and 1950 Pontiac.

Left: Front view of 1959 Austin Mini

Right: Back view of a 1950 Pontiac

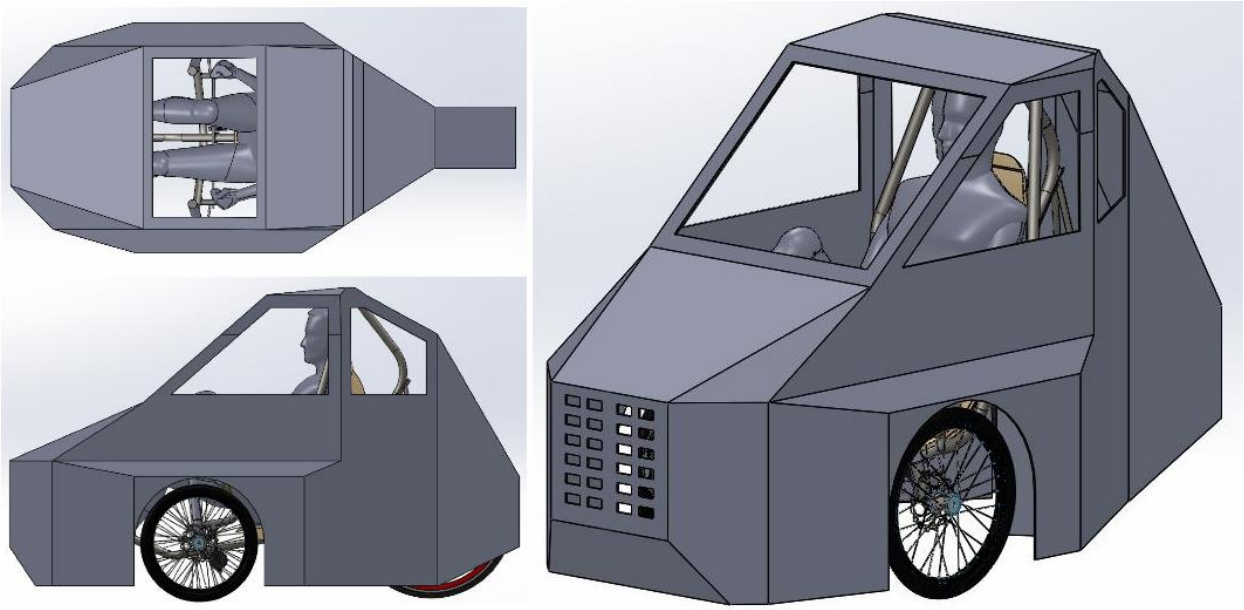
Drawing inspiration from these designs, the overall shape of the Austin Mini was heavily considered. The shape fits well with the frame's roll cage and fully retracted location of the driver's knees, and provides a design that is still popularized today with the Mini Cooper. The Pontiac influenced the tail of our design. The downward slope improves aerodynamics and works well with the rear wheel placement in our vehicle. Modeling our fairing design after these cars not only provides a more visually appealing design, but also offers a more comfortable seating arrangement and allows for grocery space.

Drag

Drag was not a large influence on our design. At low velocities (under 30 mph) drag forces have little influence on the actual performance of the vehicle. In comparison with the weight of our trike and hypothesized top speed, while drag was not to be ignored, it certainly is not central to our design. Therefore, a rough replication of the Pontiac rear with tapered sides for aerodynamics seems a fitting balance of aerodynamics and trunk space.

Landing Gear?

Many reports claim landing gear as a vehicle innovation. While these systems offer an interesting design, sometimes the best solution is avoiding innovation for the purpose of practicality. Instead of worrying about landing gear on a 2-wheel cycle, simply give the vehicle a third wheel. This lowers the cost of production and increases driver independence and safety.



Clemson University HPV fairing design

Component Vehicles

Apart from the fairing, Clemson University was able to recycle a bicycle's frame to attach to as the rear wheel support. Future production of cycles is a consideration in the design, with our team utilizing the possibility of selling the bike as a kit. Component cars gained popularity in the 1950s, and offered a cheap do-it-yourself option. Certain components of our trike, such as wheels and the rear wheel frame, can be left out for consumers to salvage independently, or included in the kit. This not only removes assembly cost, but also offers a variable cost to consumers with pre-existing resources.

Conclusion

While many teams focus on over engineering simple problems, the Clemson University team is centered on practicality and addressing the actual problem. Innovation without demand is worthless. So far these vehicles have zero consumer demand, and the speeds achieved within this competition does not justify much of the engineering done by many teams. This year is iteration one of the Clemson HPV, providing a design to serve as our foundation in future years. By focusing on aspects that non-engineers can more easily relate to, the Clemson University team hopes to produce a market demand and a shifted design focus within the ASME Human Powered Vehicle Competition.

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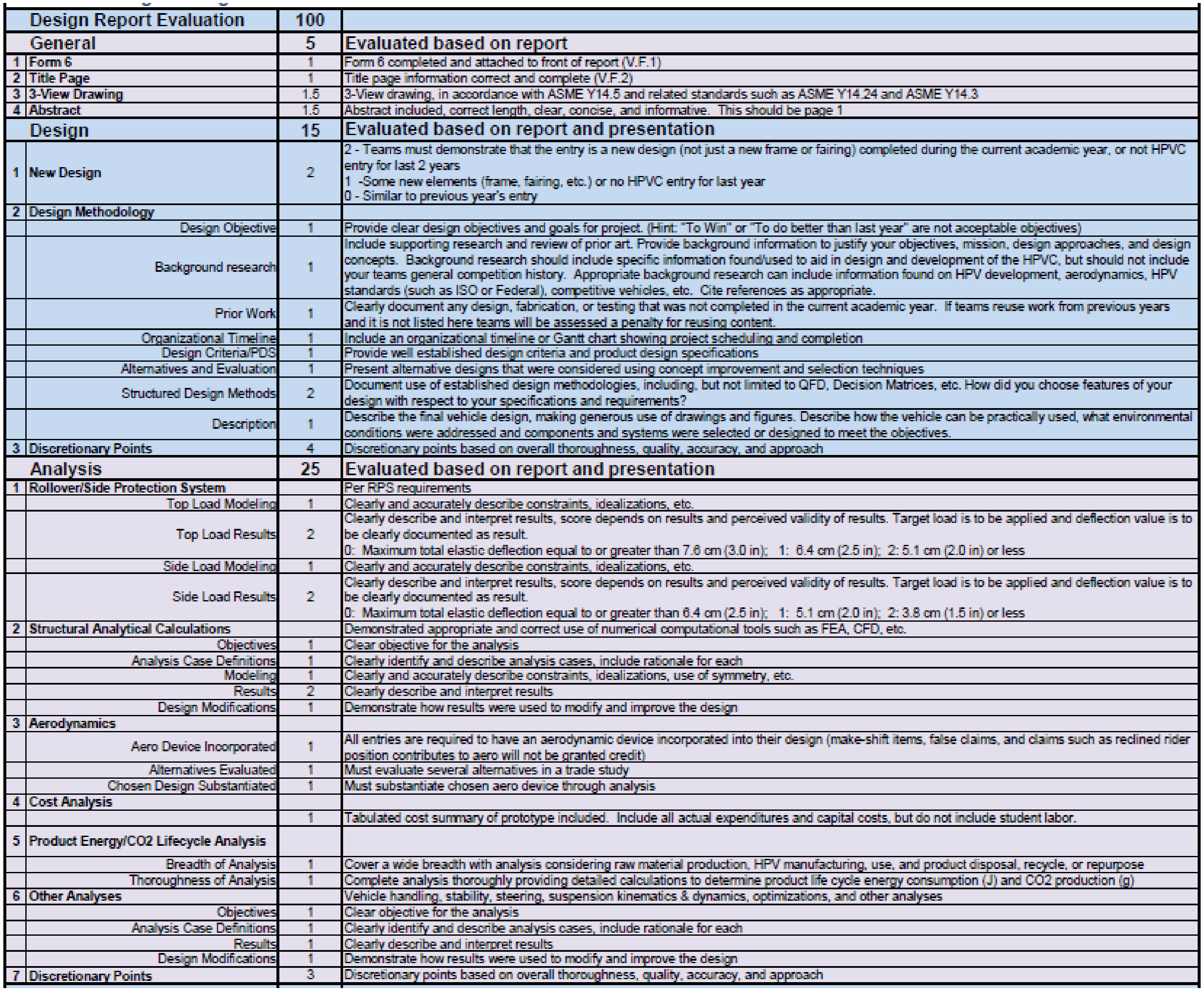
L.4 2016 HPVC Scoring

Table L.3 2016 HPVC Design Report Scoring [134]

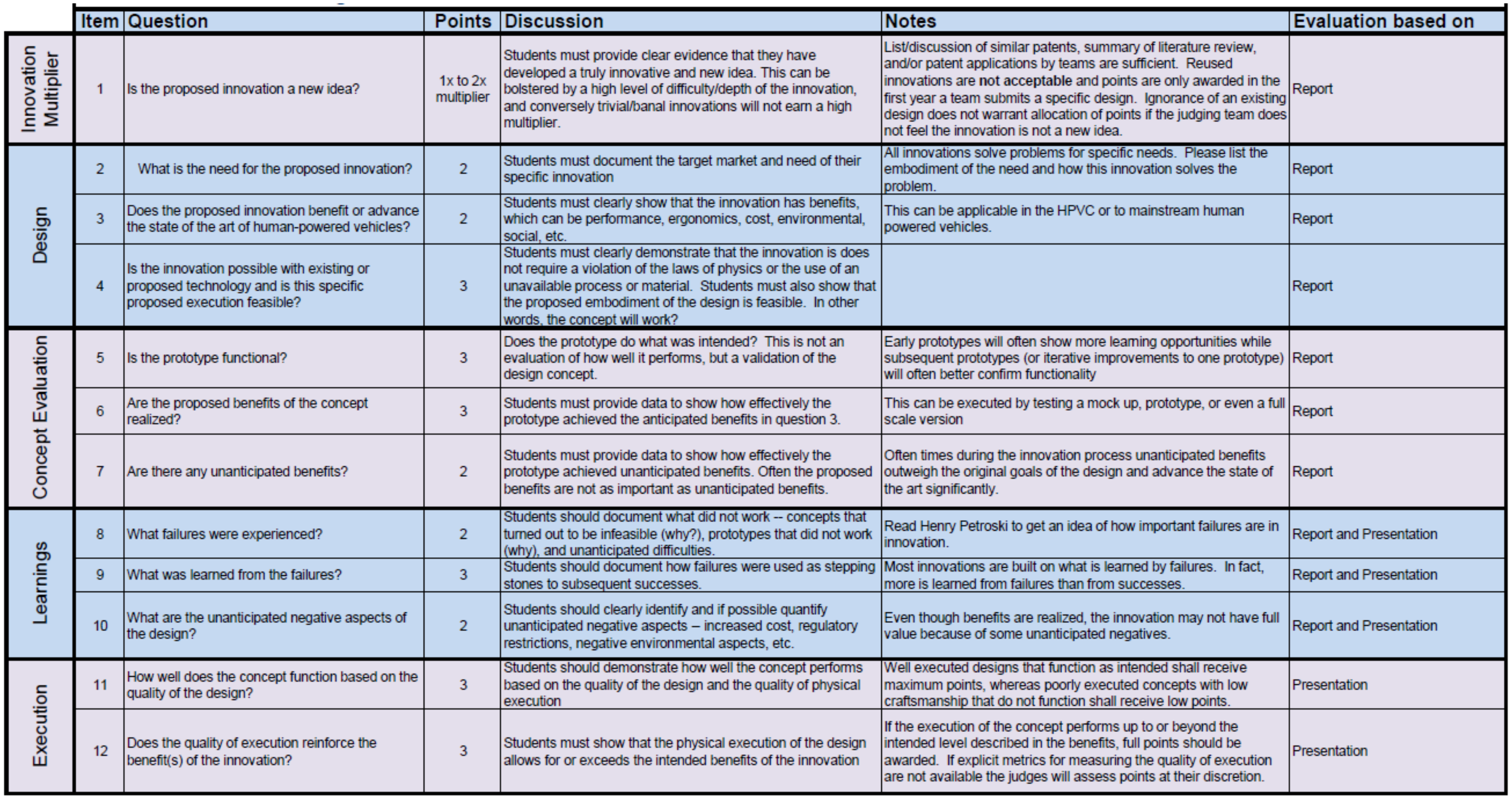


	Design Report Evaluation	**100**	
	General	**5**	**Evaluated based on report**
1	**Form 6**	1	Form 6 completed and attached to front of report (V.F.1)
2	**Title Page**	1	Title page information correct and complete (V.F.2)
3	**3-View Drawing**	1.5	3-View drawing, in accordance with ASME Y14.5 and related standards such as ASME Y14.24 and ASME Y14.3
4	**Abstract**	1.5	Abstract included, correct length, clear, concise, and informative. This should be page 1
	Design	**15**	**Evaluated based on report and presentation**
1	**New Design**	2	2 - Teams must demonstrate that the entry is a new design (not just a new frame or fairing) completed during the current academic year, or not HPVC entry for last 2 years 1 -Some new elements (frame, fairing, etc.) or no HPVC entry for last year 0 - Similar to previous year's entry
2	**Design Methodology**		
	Design Objective	1	Provide clear design objectives and goals for project. (Hint: "To Win" or "To do better than last year" are not acceptable objectives)
	Background research	1	Include supporting research and review of prior art. Provide background information to justify your objectives, mission, design approaches, and design concepts. Background research should include specific information found/used to aid in design and development of the HPVC, but should not include your teams general competition history. Appropriate background research can include information found on HPV development, aerodynamics, HPV standards (such as ISO or Federal), competitive vehicles, etc. Cite references as appropriate.
	Prior Work	1	Clearly document any design, fabrication, or testing that was not completed in the current academic year. If teams reuse work from previous years and it is not listed here teams will be assessed a penalty for reusing content.
	Organizational Timeline	1	Include an organizational timeline or Gantt chart showing project scheduling and completion
	Design Criteria/PDS	1	Provide well established design criteria and product design specifications
	Alternatives and Evaluation	1	Present alternative designs that were considered using concept improvement and selection techniques
	Structured Design Methods	2	Document use of established design methodologies, including, but not limited to QFD, Decision Matrices, etc. How did you choose features of your design with respect to your specifications and requirements?
	Description	1	Describe the final vehicle design, making generous use of drawings and figures. Describe how the vehicle can be practically used, what environmental conditions were addressed and components and systems were selected or designed to meet the objectives.
3	**Discretionary Points**	4	Discretionary points based on overall thoroughness, quality, accuracy, and approach
	Analysis	**25**	**Evaluated based on report and presentation**
1	**Rollover/Side Protection System**		Per RPS requirements
	Top Load Modeling	1	Clearly and accurately describe constraints, idealizations, etc.
	Top Load Results	2	Clearly describe and interpret results, score depends on results and perceived validity of results. Target load is to be applied and deflection value is to be clearly documented as result. 0: Maximum total elastic deflection equal to or greater than 7.6 cm (3.0 in); 1: 6.4 cm (2.5 in); 2: 5.1 cm (2.0 in) or less
	Side Load Modeling	1	Clearly and accurately describe constraints, idealizations, etc.
	Side Load Results	2	Clearly describe and interpret results, score depends on results and perceived validity of results. Target load is to be applied and deflection value is to be clearly documented as result. 0: Maximum total elastic deflection equal to or greater than 6.4 cm (2.5 in); 1: 5.1 cm (2.0 in); 2: 3.8 cm (1.5 in) or less
2	**Structural Analytical Calculations**		Demonstrated appropriate and correct use of numerical computational tools such as FEA, CFD, etc.
	Objectives	1	Clear objective for the analysis
	Analysis Case Definitions	1	Clearly identify and describe analysis cases, include rationale for each
	Modeling	1	Clearly and accurately describe constraints, idealizations, use of symmetry, etc.
	Results	2	Clearly describe and interpret results
	Design Modifications	1	Demonstrate how results were used to modify and improve the design
3	**Aerodynamics**		
	Aero Device Incorporated	1	All entries are required to have an aerodynamic device incorporated into their design (make-shift items, false claims, and claims such as reclined rider position contributes to aero will not be granted credit)
	Alternatives Evaluated	1	Must evaluate several alternatives in a trade study
	Chosen Design Substantiated	1	Must substantiate chosen aero device through analysis
4	**Cost Analysis**		
		1	Tabulated cost summary of prototype included. Include all actual expenditures and capital costs, but do not include student labor.
5	**Product Energy/CO2 Lifecycle Analysis**		
	Breadth of Analysis	1	Cover a wide breadth with analysis considering raw material production, HPV manufacturing, use, and product disposal, recycle, or repurpose
	Thoroughness of Analysis	1	Complete analysis thoroughly providing detailed calculations to determine product life cycle energy consumption (J) and CO2 production (g)
6	**Other Analyses**		Vehicle handling, stability, steering, suspension kinematics & dynamics, optimizations, and other analyses
	Objectives	1	Clear objective for the analysis
	Analysis Case Definitions	1	Clearly identify and describe analysis cases, include rationale for each
	Results	1	Clearly describe and interpret results
	Design Modifications	1	Demonstrate how results were used to modify and improve the design
7	**Discretionary Points**	3	Discretionary points based on overall thoroughness, quality, accuracy, and approach

Table L.3 (Cont.)

	Testing	**25**	**Evaluated based on report and presentation**
1	**Rollover/Side Protection System**		Per RPS requirements
	Top Load Testing Setup	1	Test method clearly described, appropriate, and scientific
	Top Load Testing Results	2	Clearly describe and interpret results, score depends on results and perceived validity of results. Increasing load is to be added to RPS until maximum deflection is reached and then load achieved is to be clearly stated as the result. 0: Less than 1780N (400 lbf); 1: 1780-2670N (400-599 lbf); 2: ≥2670N (600 lbf)
	Side Load Testing Setup	1	Test method clearly described, appropriate, and scientific
	Side Load Testing Results	2	Clearly describe and interpret results, score depends on results and perceived validity of results. Increasing load is to be added to RPS until maximum deflection is reached and then load achieved is to be clearly stated as the result. 0: Less than 890N (200 lbf); 1: 890-1330N (200-299 lbf); 2: >1330N (300 lbf)
2	**Developmental Testing**		Physical testing to develop or verify design, usually conducted prior to final vehicle construction
	Objective & Methodology	1	Clear objective for the experiment. Methodology clearly described, appropriate, and scientific
	Results and Discussion	1	Data is reported and presented clearly, with appropriate discussion (interpretation, error sources, uncertainty, etc.)
	Statistical Analysis	1	Data is analyzed and presented clearly, with appropriate statistical analyses (t-test, ANOVA, regression, etc.) and measures (mean and standard deviation, confidence intervals, p-value, etc.)
	Conclusions	1	Conclusions and recommendations stated clearly. Results should be quantitative where possible and include applicable statistical analyses (mean, standard deviation, student T test, etc.)
	Design Modifications	1	Demonstrate how testing results used to modify or improve the design
	Comparison with PDS and Analysis	1	Test results clearly compared with analysis results and product design specifications
	Comprehensiveness	1	Extent of developmental testing: 0: few experiments/little significance on design, 1: many experiments/significant effect on design
3	**Performance Testing**		Physical testing (often conducted on final vehicle) to evaluate and optimize performance
	Objective & Methodology	1	Clear objective for the experiment. Methodology clearly described, appropriate, and scientific.
	Results and Discussion	1	Data is reported and presented clearly, with appropriate discussion (interpretation, error sources, uncertainty, etc.)
	Statistical Analysis	1	Data is analyzed and presented clearly, with appropriate statistical analyses (t-test, ANOVA, regression, etc.) and measures (mean and standard deviation, confidence intervals, p-value, etc.)
	Conclusions	1	Conclusions and recommendations stated clearly. Results should be quantitative where possible and include applicable statistical analyses (mean, standard deviation, student T test, etc.)
	Design Modifications	1	Demonstrate how testing results used to modify or improve the design
	Comparison with PDS and Analysis	1	Test results clearly compared with analysis results and product design specifications
	Comprehensiveness	1	Extent of developmental testing: 0: few experiments/little significance on design, 1: many experiments/significant effect on design
4	**Discretionary Points**	5	Discretionary points based on overall thoroughness, quality, accuracy, and approach
	Safety	**20**	**Evaluated based on report and safety inspection**
1	**Rollover/Side Protection System**		
	Installation & Design	2	Rollover/Side protection system installed and functional
	Consistent with RPS rule	1.5	RPS design and fabrication appears consistent with rules
	Prevents bodily contact with ground	2	RPS must prevent the riders appendages and head from contacting the ground in the event of a crash where the HPVC falls over or inverts
2	**Seat belt**	2	Seat belt installed correctly and appears to meet rules
3	**Steering system**	1.5	No excessive play or looseness, correct installation, apparent stability, etc.
4	**Sharp edges, protrusions, pinch points**	2	No sharp edges or protrusions on fairing, frame or components. No hazardous pinch points, especially near spoked wheels, chains, sprockets, etc. (Subtract points for serious hazards)
5	**Other hazards**	1	No other obvious hazards
6	**Rider's field of view**	1	Rider should have more than 180 degrees of visibility
7	**Safety Accessories**		
	Bell/Horn	1	Audible signal device installed and operational
	Headlight	1	White headlight installed and operational, visible 150 meters to the front, installed and operational
	Taillight	0.5	Red Taillight visible 150 meters to the rear, installed and operational
	Side reflectors	0.5	Amber reflectors on each side of vehicle properly installed
	Rear view mirrors	0.5	Mirror(s) installed providing the driver with views to the rear of the vehicle
8	**Additional Safety Features**	1.5	An additional safety feature(s) are incorporated specific to their design (beyond required safety features)
9	**Discretionary Points**	2	Discretionary points based on the quality and thoroughness of design to maximize HPVC safety
	Aesthetics	**10**	**Evaluated based on state of vehicle at safety inspection**
	Overall impression of vehicle	3	Overall impression
	Quality of craftsmanship	3	Craftsmanship (welds, joints, assembly, etc.) is professional and attractive
	Quality of custom parts	2	Team-fabricated and custom parts look professional and of high quality
	Quality of Frame/Fairing Finish	2	Exterior finish and decoration quality is neat, attractive, and professional (frame and/or fairing)

Table L.4 2016 HPVC Innovation Report Scoring [8]



	Item	Question	Points	Discussion	Notes	Evaluation based on
Innovation Multiplier	1	Is the proposed innovation a new idea?	1x to 2x multiplier	Students must provide clear evidence that they have developed a truly innovative and new idea. This can be bolstered by a high level of difficulty/depth of the innovation, and conversely trivial/banal innovations will not earn a high multiplier.	List/discussion of similar patents, summary of literature review, and/or patent applications by teams are sufficient. Reused innovations are **not acceptable** and points are only awarded in the first year a team submits a specific design. Ignorance of an existing design does not warrant allocation of points if the judging team does not feel the innovation is not a new idea.	Report
Design	2	What is the need for the proposed innovation?	2	Students must document the target market and need of their specific innovation	All innovations solve problems for specific needs. Please list the embodiment of the need and how this innovation solves the problem.	Report
	3	Does the proposed innovation benefit or advance the state of the art of human-powered vehicles?	2	Students must clearly show that the innovation has benefits, which can be performance, ergonomics, cost, environmental, social, etc.	This can be applicable in the HPVC or to mainstream human powered vehicles.	Report
	4	Is the innovation possible with existing or proposed technology and is this specific proposed execution feasible?	3	Students must clearly demonstrate that the innovation is does not require a violation of the laws of physics or the use of an unavailable process or material. Students must also show that the proposed embodiment of the design is feasible. In other words, the concept will work?		Report
Concept Evaluation	5	Is the prototype functional?	3	Does the prototype do what was intended? This is not an evaluation of how well it performs, but a validation of the design concept.	Early prototypes will often show more learning opportunities while subsequent prototypes (or iterative improvements to one prototype) will often better confirm functionality	Report
	6	Are the proposed benefits of the concept realized?	3	Students must provide data to show how effectively the prototype achieved the anticipated benefits in question 3.	This can be executed by testing a mock up, prototype, or even a full scale version	Report
	7	Are there any unanticipated benefits?	2	Students must provide data to show how effectively the prototype achieved unanticipated benefits. Often the proposed benefits are not as important as unanticipated benefits.	Often times during the innovation process unanticipated benefits outweigh the original goals of the design and advance the state of the art significantly.	Report
Learnings	8	What failures were experienced?	2	Students should document what did not work -- concepts that turned out to be infeasible (why?), prototypes that did not work (why), and unanticipated difficulties.	Read Henry Petroski to get an idea of how important failures are in innovation.	Report and Presentation
	9	What was learned from the failures?	3	Students should document how failures were used as stepping stones to subsequent successes.	Most innovations are built on what is learned by failures. In fact, more is learned from failures than from successes.	Report and Presentation
	10	What are the unanticipated negative aspects of the design?	2	Students should clearly identify and if possible quantify unanticipated negative aspects – increased cost, regulatory restrictions, negative environmental aspects, etc.	Even though benefits are realized, the innovation may not have full value because of some unanticipated negatives.	Report and Presentation
Execution	11	How well does the concept function based on the quality of the design?	3	Students should demonstrate how well the concept performs based on the quality of the design and the quality of physical execution	Well executed designs that function as intended shall receive maximum points, whereas poorly executed concepts with low craftsmanship that do not function shall receive low points.	Presentation
	12	Does the quality of execution reinforce the benefit(s) of the innovation?	3	Students must show that the physical execution of the design allows for or exceeds the intended benefits of the innovation	If the execution of the concept performs up to or beyond the intended level described in the benefits, full points should be awarded. If explicit metrics for measuring the quality of execution are not available the judges will assess points at their discretion.	Presentation

L.5 Clemson 2016 Design Report

(Form 6)

Vehicle Description Form
Updated 12/3/13
Human Powered Vehicle Challenge
Competition Location: Athens, Ohio
Competition Date: May 13-15, 2016

http://go.asme.org/HPVC

This required document for all teams is to be incorporated in to your Design Report. Please Observe Your Due Dates; see the ASME HPVC for due dates.

Vehicle Description

School name: Clemson University

Vehicle name: Adventure

Vehicle number : 2

Vehicle configuration

Upright ______ Semi-recumbent X

Prone ______ Other (specify) ______

Frame material 4130 ChroMoly Steel

Fairing material(s) Fiberglass

Number of wheels 3

Vehicle Dimensions *(please use in, in^3, lbf)*

Length 98.5in Width 41.8 in

Height 49 in Wheelbase 52.6 in

Weight Distribution* Front 70% Rear 30% Total Weight ~ 65lbs

Wheel Size Front 24in Rear 27.5in (700mm)

Frontal area 1100 in^2

Steering Front x Rear ______

Braking Front x Rear ______ Both ______

Estimated Cd 0.32

Vehicle history (e.g., has it competed before? where? when?) New vehicle

*Based on current model estimate. The true weight will be measured on the final prototype.

For the 2016 ASME HPVC East located at Athens, Ohio

CLEMSON UNIVERSITY

HUMAN POWERED VEHICLE TEAM

Introduces vehicle number 2:

Adventure

Faculty Advisor

Gregory Mocko: (XXX) XXX-XXX**,** XXXXXX@clemson.edu

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Team Members

Artis Johnson
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Sean Suter
Kelton Wiseman
Philip Nich
Sean Kelly

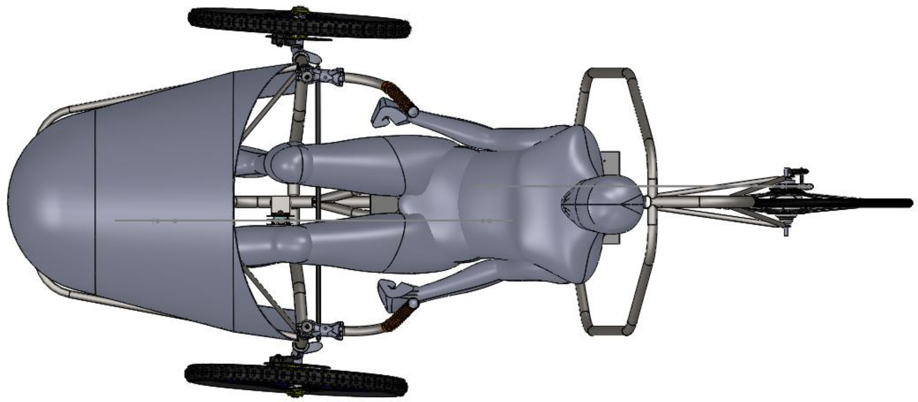

Figure 1 *Top View*

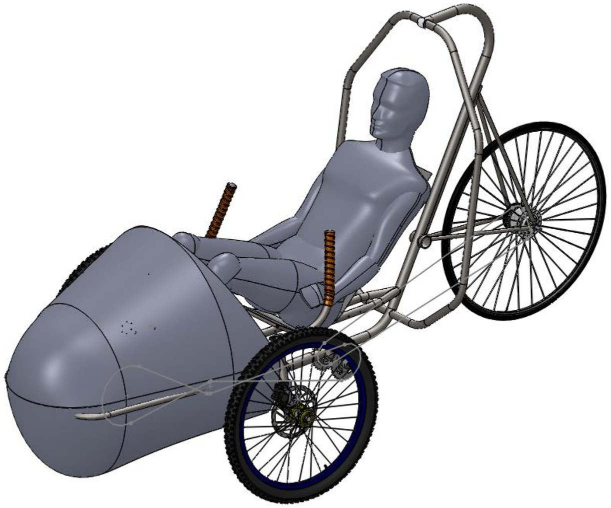

Figure 2 *Isometric View*

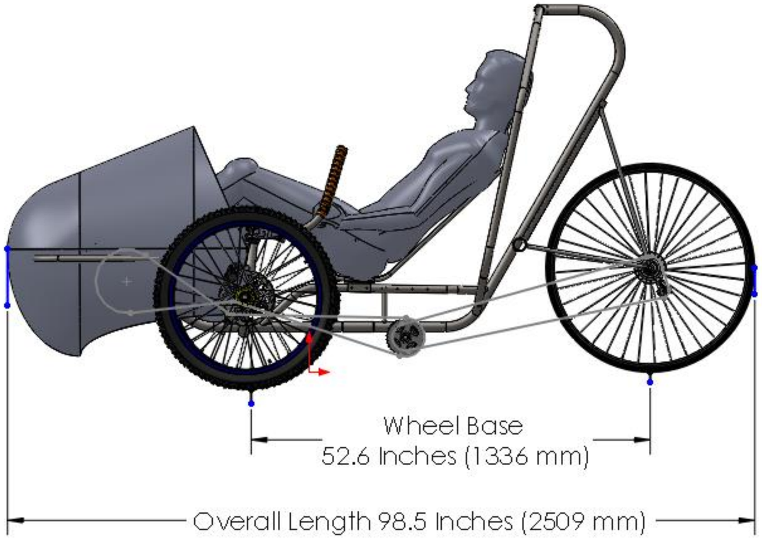

Figure 3 *Front View*

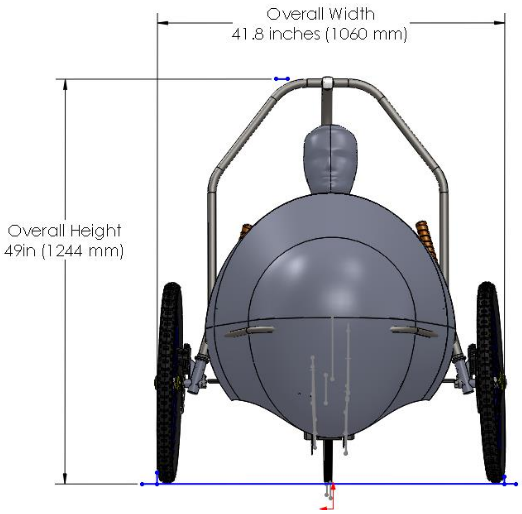

Figure 4 *Side View*

ABSTRACT

Alternative transportation is an increasingly important field as the world exhausts its supply of fossil fuels. In order to meet this demand, Clemson's human powered vehicle team tapped the power of humans to provide zero-emission, fossil-fuel free transportation. In order to be a reasonable choice for a consumer, the vehicle was required to be practical for everyday use, which meant it had to be both efficient and ergonomic. Clemson's team approached the design of the vehicle with the intention of excelling in efficiency and ergonomics, thereby minimizing the physical toll on the rider. Cost was also considered a key factor, as the vehicle needed to be financially attainable to the consumer. At the end of the design and manufacturing process, the Clemson team developed a safe, practical human-powered vehicle durable enough for everyday use. The overall design of the vehicle was a fully faired tadpole tricycle that makes use of direct knuckle steering and a jackshaft. The overall vehicle is shown in figures 1-4.

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Chapter: 1 THE HPV DESIGN OF CLEMSON'S ADVENTURE

1.1 Objective

Clemson University's Adventure Human-Powered Vehicle is intended to provide a viable form of alternative transportation using concepts learned in the classroom. The vehicle should be designed with practicality in mind, meaning it should be built with an emphasis on performance and ergonomics. Emphasis in these areas should allow for a user-friendly vehicle that is minimally taxing on the rider.

1.2 Background

After our first experience with the HPVC last year, the team first went back to the ASME HPVC rules and scoring to create initial requirements and goals for the design [6–8]. Additionally to help with requirement development a thorough literature review of ergonomics was completed. This revealed the need to account for power production, performance factors, fatigue, muscle and skeletal comfort, safety, environmental considerations, thermal comforts, maintenance, repair, energy recovery, and anthropometric relations [3,4,12,29,30,41,53–93][1]. From there several past design reports were examined to explore how Clemson could improve its design process, innovative aspects, and how the overall design could be improved. To use a more systematic design process elements of the traditional and systems engineering design processes were used [1,2,25]. For the embodiment process research was conducted on different HPV standards including but not limited to components, tooling, and manufacturing process to help simplify fabrication requirements [5,35,37,46,48,49,135]. To understand tadpole tricycles more guidelines regarding design were used [4,5]. To assist in understanding the engineering principles involved in HPV multiple sources and past knowledge from engineering education were used for analytical problem solving and development.

1.3 Prior Work

While this year's vehicle shares the tadpole trike design and use of direct knuckle steering with the previous year, adventure was entirely new design and fabrication. That being said to save on costs some components were reused. These components include the internal gear hub and its corresponding shifter, a double sided idler gear, a crankset, two stems, the chains, the commercial harness, and the method of attachment for the harness.

To begin describing the how the previous design is different from the current design, the frames can first be examined, as shown in figure 1.1. It is important to note that days before the 2015 competition a front bumper bar and stiffening bars running from the RPS to the head tubes were welded on, but not designed or dimensioned beforehand. Thus, one difference in the front bumper has been designed in the 2016 and sized to fit the HPV system. The use of the stiffening bars from the RPS to the head tubes were remove and the need for stiffness is somewhat combated by the use of the seat rails. The new angle of the main member in the frame better

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[1] Non published literature review in ASME conference paper format available upon request. This is where the large amount of references comes from

reflects the seat tube angle on a bicycle and as a result the triangle and rear wheel is better supported. A longer wheelbase helps negate previous problems of rotating forward during hard braking. This is assisted by a new weight distribution ratio of 70/30 front to rear compared to the previous 80/20 of the final design. 24” wheels are now being used in place of the previous 20” wheels. A sharper connection at the top of the RPS is used to allow for a more reclined position of the rider. The position of the rider is more forward of the RPS in the current model as well. The seat in the current model can also adjust to different rider positions, whereas the previous HPV used a stationary seat. The center of gravity is noticeable lower which improves handling and reduces the probability of rollover. The negative ramification of this is a slightly decreased ground clearance from the previous model. The drivetrain and fairing systems were completely redesigned as well. Now the drivetrain uses a jackshaft compromised of two shorter chain paths. Lastly, this year’s fairing is made to be streamlined and not intended to have “car like” features.

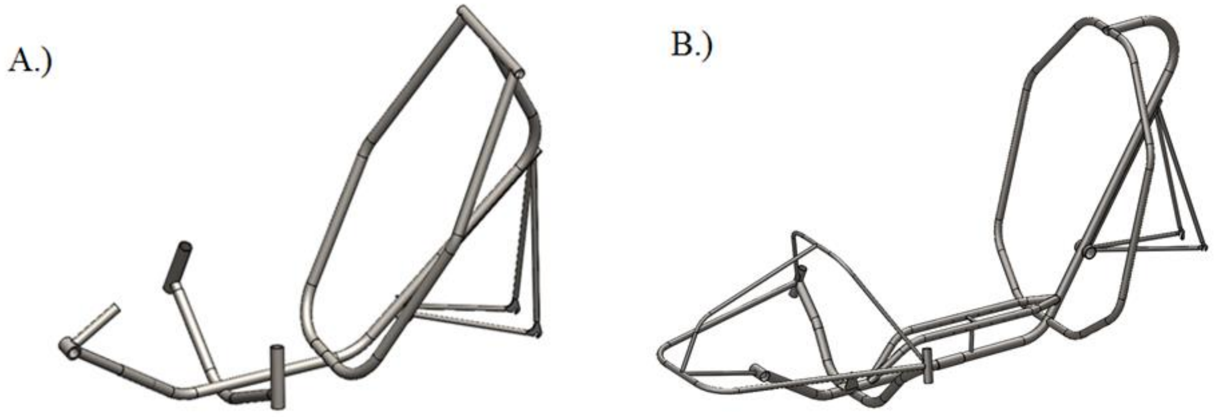


Figure 1.1 *Frame for Clemson’s various HPVs A.) HPVC 2015 submission B) HPVC 2016 Submission*

1.4 Design Specifications

In order to make a vehicle that was both practical and safe, many requirements were considered. A requirements list was created for each of four individual subsystems; frame, drivetrain, steering and braking, and fairing. The lists from each of the four subsystems were combined into a single list, which showed the large amount of overlap of requirements. From here additional requirements were added to reflect the systems performance. Lastly, design requirements outlined by the ASME rules were outlined and added to the requirements. A short list of these requirements is provided in table 1.1.

In addition to the requirements, a schedule for completion was compiled. Figure shows the project management outline including key milestones for the individual subsystems and the vehicle as a whole. The presented Gantt chart is shortened from the original schedule to include only major milestones. The overall schedule ensured that a safe and viable vehicle was built and adequately tested before the design report was due. Overall, this meant more developed content can be included in the report and recommendations and design modifications can be incorporated before the competition.

Table 1.1 *Compressed requirements list*

#	Category	Requirements	Subsystem	Justifications
GR1	Geometrical restrictions	Maximum Size: 36 x 25 x 90 inches with 6 inches of ground clearance	Frame and Steering	Allows vehicle to be easily transported and appropriately sized for a person.
GR2	Geometrical restrictions	Frame leaves adequate space for all other subsystems	All	Needed for functionality
GR3	Geometrical restrictions	Ergonomic features allowing adjustability to the driver are present	All	Allows vehicle modification to suit the current rider
SP1	System's performance	Rigid and stable at all speeds and different road conditions	Frame and Steering	Eliminates safety hazards associated with loss of control
SP2	System's performance and safety	No loss of control when turning or encountering obstacles	Frame and Steering	Eliminates safety hazards associated with loss of control
SP3	System's performance	Minimal Weight	All	Easier to ride
S1	Safety	Durable enough to withstand rolling without danger to driver	Frame	Protects rider in case of accidental rolling
S2	Safety	Adequate visibility in all directions	Fairing	Safety
ST1	Storage and transportation	Easy disassembly for storage or transport	All	Easier transportation
M1	Maintenance	Easy to maintain	All	Improves longevity
CC1	Complexity and cost	Cheap and easy to manufacture	All	Simpler to manufacture and on at a lower cost
CC2	Complexity and cost	Total cost: under $4,000	All	Gives more consumers the chance to purchase
ER1	Energy recovery	Energy recovery system does not pose any danger to driver	Drivetrain	Safety
ER2	Energy recovery	Energy recovery system provides more power to the wheel than is required from the driver	Drivetrain	Functionality
AR1	ASME requirement	Come to a complete stop from a speed of 25km/hr in a distance of 6.0m	Steering	Vehicle has efficient brakes
AR2	ASME requirement	Can turn within an 8.0m radius	Steering	Demonstrates maneuverability
AR3	ASME requirement	Can travel in a straight line for 30m at a speed between 5 to 8 km/hr	Frame and Steering	Demonstrates vehicle stability
AR4	ASME requirement	Must include a roll protection system (RPS) structural attached to the frame that absorbs energy to minimize risk, prevents body contact with the ground, and able to withstand a top load of 600lbs 12° from vertical directed aft ward and a 300lbf side load.	Frame	To predict the possible damage of an accident and show the RPS is capable of protecting the rider
AR5	ASME requirement	A Harness must be used to secure the rider	System	To ensure the rider is secure for accidents
AR6	ASME requirement	Exterior and interior must be free from sharp edges	all	To minimize risk and injuries

Task Name	Duration
1 Lead Project planning	**220 days**
1.1 Structure Product Requirements	5 days
1.2 Structure Conceptual Design Selection	31 days
1.3 Structure Product Development	33 days
1.4 Final Design Details	7 days
2 Structure (Frame) subsystem	**97 days**
2.1 Product Definition	7 days
2.2 Conceptual Design	13 days
2.3 Product Development	60 days
2.4 Final Prototype Manufacturing	31 days
2.5 Testing and Analysis of Prototype	12 days
2.6 Final Product Development	7 days
3 Controls (Steering) subsystem	**122 days**
3.1 Research Background Information	14 days
3.2 Product Definition	7 days
3.3 Conceptual Design	13 days
3.4 Final Prototype Manufacturing	17 days
3.5 Testing and Analysis of Prototype	7 days
3.6 Final Product Development	17 days
4 Energy Supply (Drivetrain) subsystem	**119 days**
4.1 Product Definition	7 days
4.2 Conceptual Design	13 days
4.3 Product Development	68 days
4.4 Testing and Analysis of Prototype	7 days
4.5 Final Product Development	10 days
5 Performance and Comfort (Fairing) subsystem	**140 days**
5.1 Research Background Information	14 days
5.2 Conceptual Design	28 days
5.3 Product Development	53 days
5.4 Final Prototype Manufacturing	39 days
5.5 Testing and Analysis of Prototype	10 days
5.6 Final Product Development	10 days

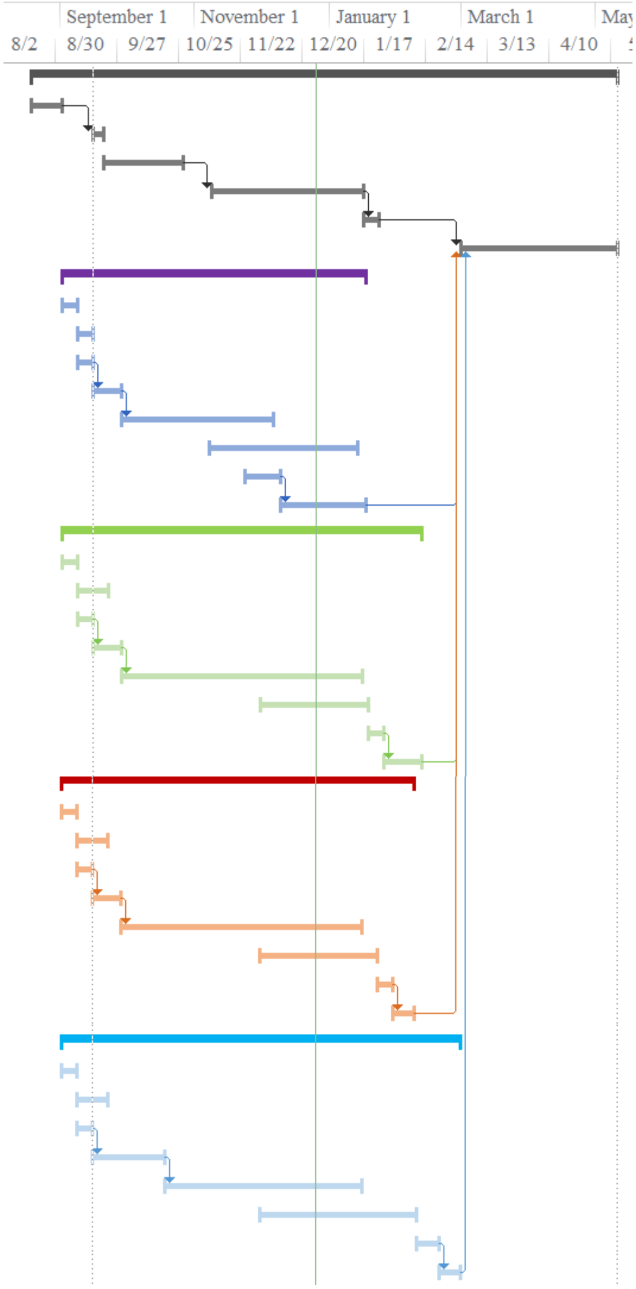


Figure 1.2 *High level Gantt chart describing Clemson 2016 project management*

1.5 Concept Development and Selection

For the concept development, the overall HPV system was broken down to into sub systems and concepts were developed for each of the subsystems. Additionally before concepting a function tree model was created to reflect to the different features of the system and their functional requirements as shown in figure 1.3. This was performed to abstract the typical HPV product architecture and allow for more abstraction in the conceptual process in the hopes to create more innovate ideas.

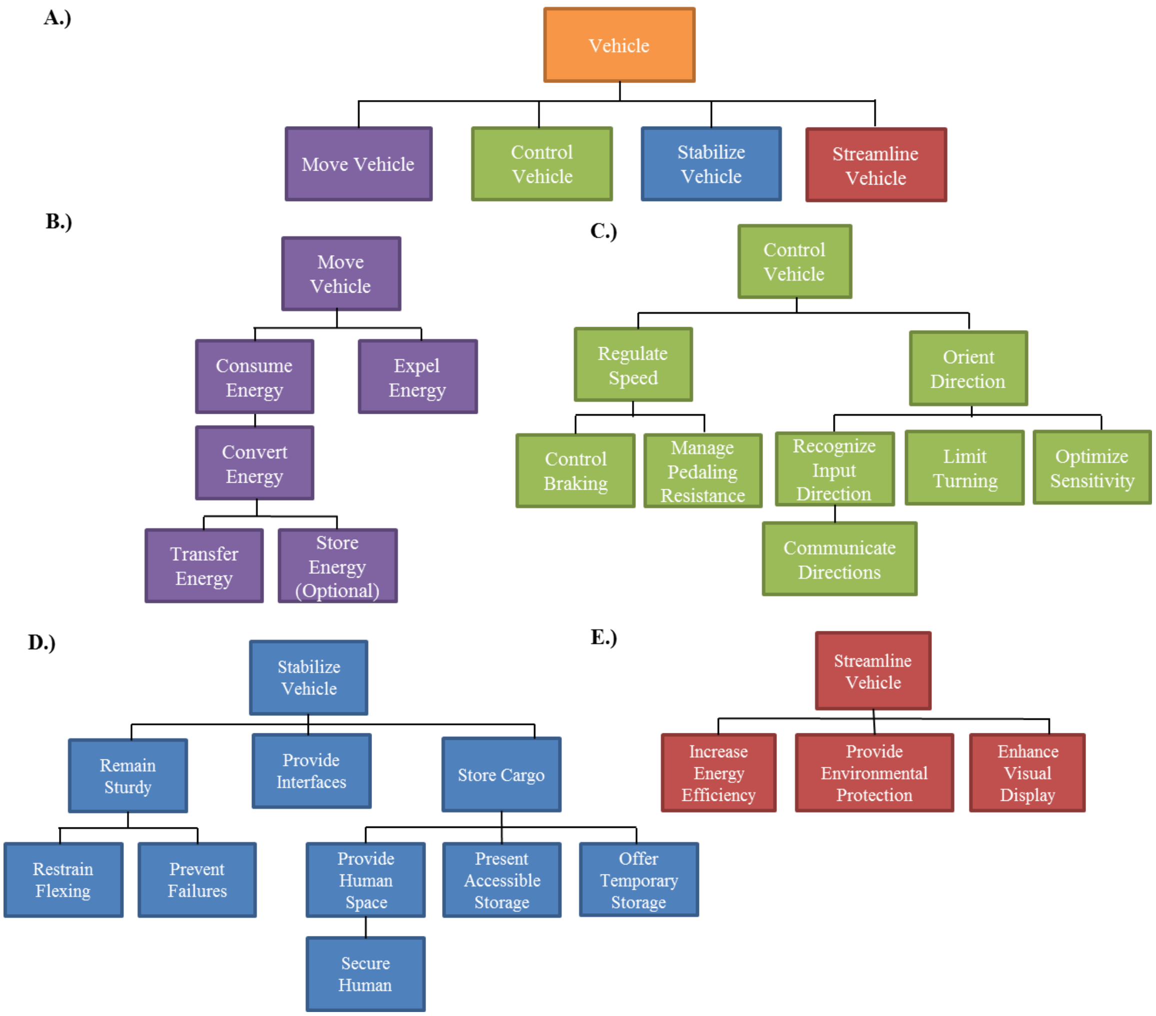


Figure 1.3 *Function tree of human powered vehicle A.) Main functions B) Move function C.) Control function D.) Stabilize function E.) Streamline function*

Once the function tree was established concept generation occurred using individual and group brainwriting (completed in a way that combined elements of germination and progressive concept generation methods), group brain storming after individual preparations of brainwriting, and morphological charts. Morphological charts were used primarily for the fairing subsystem, because here the manufacturing process was deemed as important as the design of the fairing itself. In the chart the main design considerations were shape, degree of coverage, material, manufacturing method, structure, attachment process, ventilation, visibility, and vehicle access.

To evaluate the many concepts generated a proper selection methods were needed to determine the leading solution variants, based on our design requirements. To accomplish this the thorough concept selection method established by Mistree *et al* was used [28]. These essential requirements were developed based on the initial list of requirements created. Then criteria were created to describe those essential requirements. To evaluate the concepts a pair wise comparison was used to compare all the generated concepts for each criterion. Next different weights were applied to each of the essential requirements to examine their effect on the overall results. This was completed for multiple datums to eliminate any possible datum biasing. The being said the pairwise evaluation remained constant regardless of datum. Justifications for each evaluation were recorded and they were combined to highlight the top leading solution variants. Tables 1.2-1.4 summarize some aspects of the frame concept selection process. Here the acronyms represent the different concepts.

Table 1.1 *Sample frame evaluation using SMCR as a datum*

Essential Requirements	SMCR	DMFS	ASDM	SMRR	RFSR	FSMR	FSDM	SMOR	CRCF	TRHF
Structural Integrity										
Stability	0	1	-1	1	0	1	1	-1	0	0
Flexing	0	1	-1	0	1	-1	-1	-1	-1	1
Durability	0	-1	-1	1	1	-1	-1	-1	0	0
Environmental Adaptiveness	0	1	0	0	0	1	-1	0	0	1
Normalized Score	0.600	1.000	0.000	1.000	1.000	0.600	0.200	0.000	0.400	1.000
Manufacturability										
Components	0	-1	-1	-1	1	-1	-1	1	-1	1
Ease of fabrication	0	0	1	-1	1	1	-1	1	-1	0
Assembly	0	-1	-1	0	0	-1	-1	0	-1	0
Cost	0	-1	0	0	0	-1	-1	0	0	0
Normalized Score	0.667	0.167	0.500	0.333	1.000	0.333	0.000	1.000	0.167	0.833
Performance and Ergonomics										
Position and Comfort	0	0	-1	1	0	1	-1	0	0	1
Entering/Exiting	0	1	1	0	0	1	1	0	0	1
Controls	0	0	-1	1	0	0	1	0	0	-1
Weight (Distribution)	0	-1	-1	1	0	-1	-1	-1	0	0
Normalized Score	0.400	0.400	0.000	1.000	0.400	0.600	0.400	0.200	0.400	0.600
Safety										
Harness Support	0	1	-1	1	0	-1	-1	0	-1	0
RPS System	0	-1	-1	-1	-1	-1	-1	-1	-1	0
Visibility	0	1	-1	-1	0	1	1	1	1	0
Normalized Score	0.750	1.000	0.000	0.500	0.500	0.500	0.500	0.750	0.500	0.750
Integratability										
Seat	0	-1	-1	-1	0	0	0	-1	-1	1
Steering	0	1	-1	0	0	1	1	0	0	0
Fairing	0	-1	-1	0	1	-1	-1	-1	-1	1
Drivetrain	0	-1	-1	0	0	1	0	-1	-1	0
Normalized Score	0.667	0.333	0.000	0.500	0.833	0.833	0.667	0.167	0.167	1.000

Table 1.3 *Sample frame evaluation weight*

Essential Requirements	Case						
	1	2	3	4	5	6	7
Structural Integrity	2	1	1	1	1	5	1.833
Manufacturability	1	2	1	1	1	4	1.667
Performance and Ergonomics	1	1	2	1	1	1	1.167
Safety	1	1	1	2	1	3	1.500
Integratability	1	1	1	1	2	2	1.333
Total	6	6	6	6	6	15	7.5
						Perceived Weighting	Combined Score

Table 1.4 *Subset of combined frame results using normalize version of case 7 weighting*

	Concepts					
	SMCR	DMFS	SMRR	RFSR	FSMR	TRHF
SMCR Datum	0.626	0.603	0.663	0.777	0.562	0.851
THRF Datum	0.509	0.607	0.628	0.783	0.676	0.779
SMRR Datum	0.551	0.666	0.744	0.794	0.562	0.835
FSDM Datum	0.817	0.711	0.911	0.817	0.422	0.861
Averages	0.626	0.647	0.737	0.793	0.557	0.831
Final Ranks	5	**4**	**3**	**2**	6	**1**

This method was used for the frame and steering systems. After the selection of those subsystems enough information was defined that the fairing and drivetrain subsystems concepts could be selected using subjective reasoning combined with preliminary analysis for feasibility estimates. To examine the usefulness of this selection method figure 1.4 shows how the top three leading frame concepts were combined into a single embodied design.

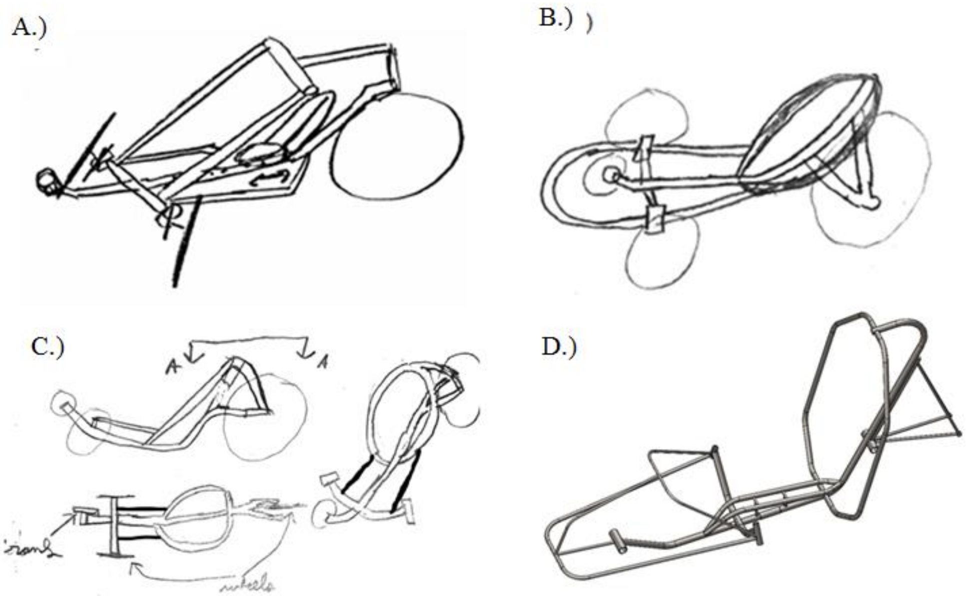


Figure 1.4 *Top leading concepts A.) TRHF B) RSFR C.) SMRR D.) Initial Embodied solution*

1.6 Innovation

The main innovation behind the design is the seating system, which is adjustable to account for different rider heights. Figure 1.5 shows how the seat adjusts by having a mount slide on seat rails which also provide stiffness to the frame. The adjustability and seat angles were also designed in such a way to try and optimize visibility as shown in figure 1.6. Lastly the stiffening for the rails was meant to eliminate possible stiffening bar requirements connecting the head tube to the roll protection system (RPS), which in turn makes it easier to get in and out of the vehicle. The seat itself was an innovative combination of fiber glass layers with a tubing substructure.

Figure 1.5 *Innovative seating system*

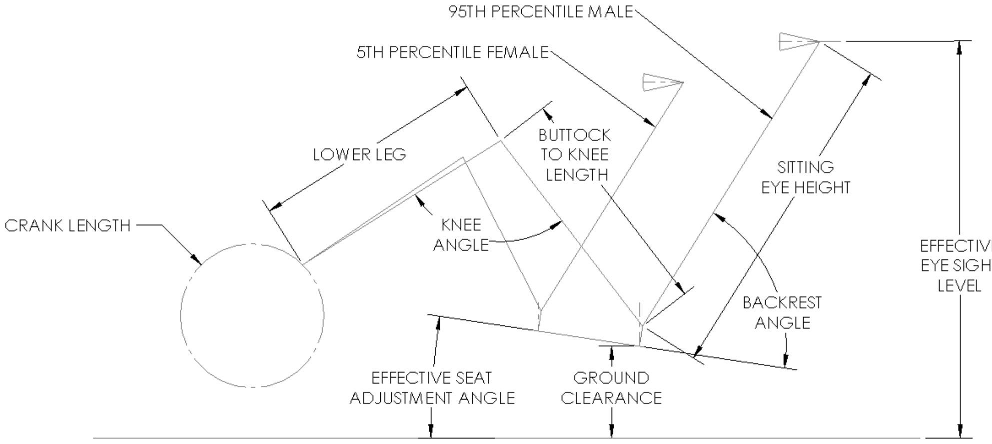


Figure 1.6 *Visibility of seating configuration*

Other innovative aspects include trying to reduce the carbon footprint of student production, some of the manufacturing processes used, and the overall use of anthropometric data for dimension sizing in addition to physical prototypes. To reduce the carbon footprint of the student production vehicle, multiple components, such as the handlebars, iterations of the front bumper fabrication, and axle spacer were made using left over scrap materials. Additionally, excess materials were ordered originally to account for the possibility of insufficient scarp, which reduce the shipping emissions and cost that would come with additional order. This was necessary considering the design and fabrication of different subsystems occurred at different times. In other words, a complete BOM was not established before the manufacturing started. For aspects of innovative manufacturing, figure 1.7 give an example of how wood was used in combination with a vice and milling machine to produce an offset miter.

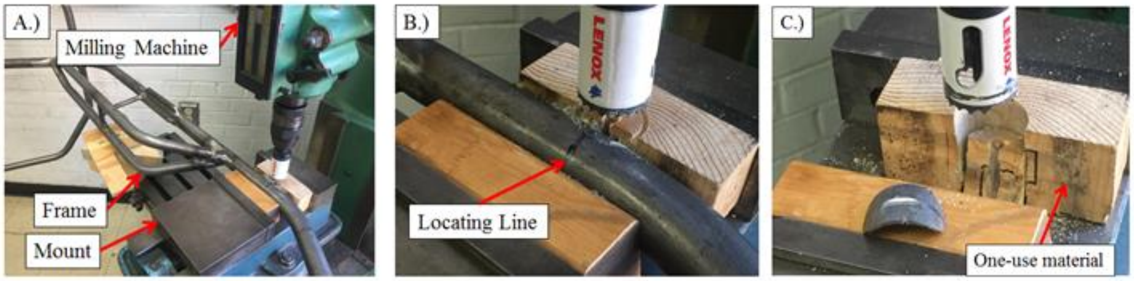


Figure 1.7 *Mitering an offset hole A.) Frame mounted to milling machine B.) Before miter C.) Post miter*

1.7 Frame design

The overall style of the frame is a tadpole tricycle. The fabrication of the frame is made using a combination of tube bending, mitering, and welding. The frame was made using 4130 CroMoly Steel tubing. It consists of several main features, as shown in figure 1.8. The function of the features is outlined in table 1.5.

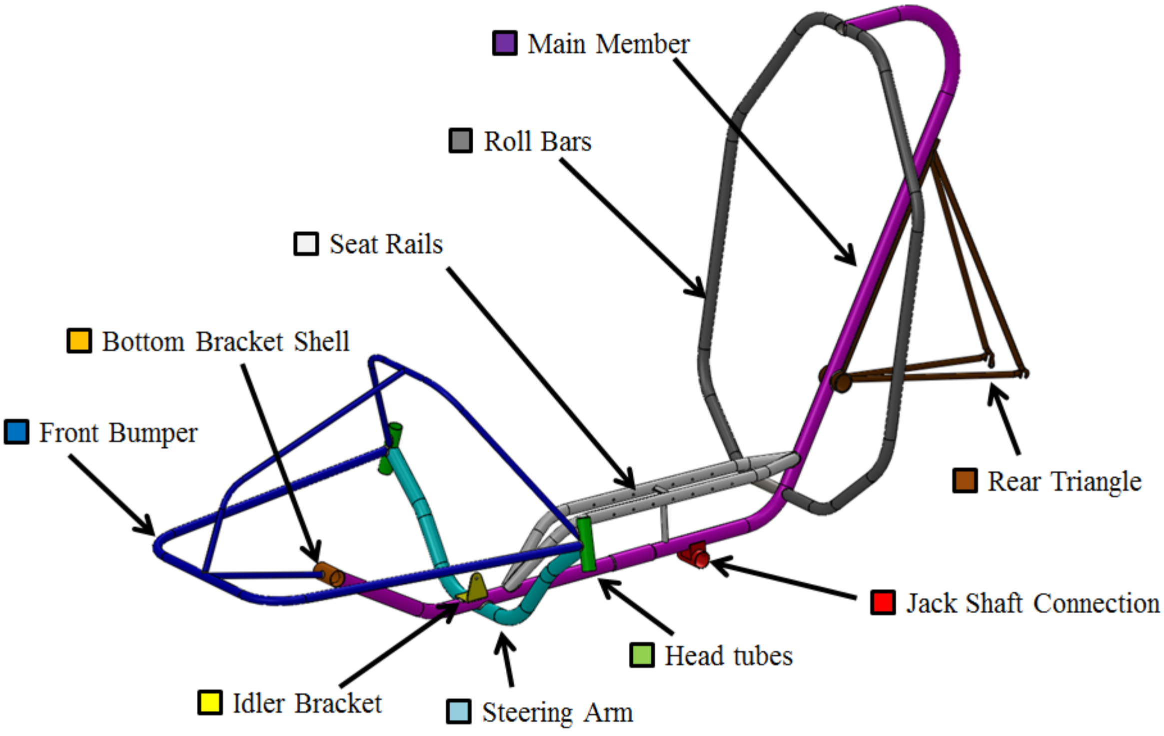


Figure 1.8 *General Layout of the frame*

Table 1.5 *Function outline of different frame features*

Frame Feature	**Function**
Front Bumper	Provides an attachment location for the fairing and protects the rider in the event of a collision.
Idler Bracket	Provides a connection point for the idler gear
Steering Arm	Aligns and positions the head tube to the correct orientation and location. Placed under the main member to support frame and person’s weight in normal conditions.
Head Tubes	Provides a connection for steering tube
Seat Rails	Provides a connection for seat mount and stiffness/rigidity to the main member
Roll Bars	Protects the rider in the event of a roll over
Main Member	Provides a central structure member for the vehicle
Bottom Bracket Shell	Provides an attachment for a crankset
Jack Shaft Connection	Provides an attachment for the jack shaft.
Rear Triangle	Provides an attachment method of the rider wheel

The wheelbase of the given frame is 52.6in, the modeled caster is 6°, the wheel track is 42in, the ground clearance is 3.5in when combined with the drivetrain, the geometry of the frame center gravity is 15in above the ground without a rider and 20inches above the ground with a 200lbs rider, and the weight distribution is 70% on the front wheels, and 30% on the rear wheels. In addition to all the frame features have individual features when combined that are designed to fit ergonomically around riders of different sizes. In addition to the visibility aspects shown in figure 1.6, the RPS was specifically designed design around a 95th percentile male as shown in figure 1.9. Overall the shape and dimension of the frame is practical to many aspects of the vehicle use. First, it fits a wide range of people due to being designed around anthropometric data. Secondly the low center gravity improves the handling of the overall vehicle. The ground clearance is reasonable for typical road conditions and expected obstacles of everyday riding (speed bumps, pot holes, etc.). Lastly, the larger wheel base and wheel track make the overall design more stable, without taking away from performance. The wheel track could (and should) be smaller to allow the vehicle to fit through doorways easier. The point when this was realized was post fabrication, and thus it would be difficult to change on our current prototype.

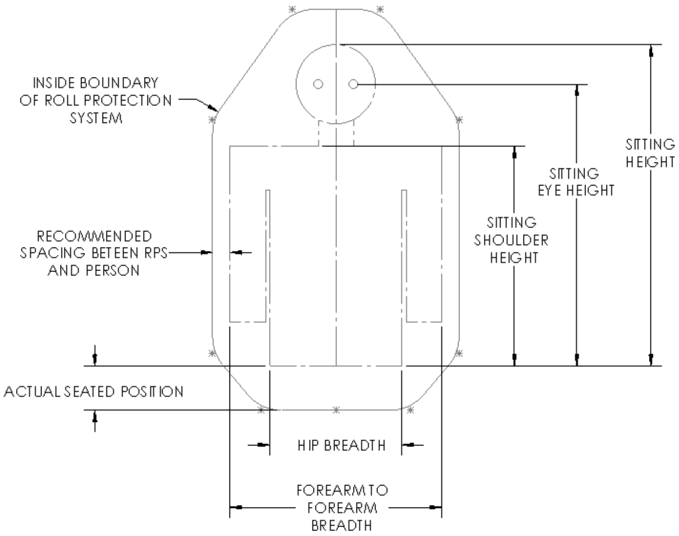


Figure 1.9 *RPS designed using anthropometric data* [29]

1.8 Steering

Given a tadpole tricycle design, conventional steering methods have already been established. Of these, under seat steering, over steering, lean steering, and other unique configurations were explored, but ultimately direct knuckle steering was chosen as the solution alternative, based on the selection method outlined in section 1.5. Overall direct knuckle steering is simple to corporate and brutally effective [4]. The design of direct knuckle steering includes a head tube of some kind, and a steering tube for each wheel. Handle bars to control the wheels, axles connecting the wheel, mount for the front brakes, and brackets to connect the tie rods are all features that need to be connected to the steering tubes. When creating the steering design, the important factors considered were the kingpin alignment, camber, caster, toe, and Ackerman compensation. For steering stability and performance a caster of 5° and a negative camber of about 6° is recommended by Horwitz [4]. For better steering alignment, with a negative camber the tie rod was sized to allow the toe of the wheel to be slightly outward. To apply proper Ackerman compensation the pivot brackets connecting the rear wheel were aligned to point towards the center axle of the rear wheel, as shown in figure 1.10. This helps reduce the effects of tire rubbing during cornering. Lastly, to establish a well-defined steering system the kingpin alignment intersected the center of the tire patch as shown in figure 1.11.One challenge of the steering design is the single side supported front wheels. To combat this, the spacer and axles were combined in a single part to increase the strength of the axle. Additionally, a larger inside diameter for the front wheel hubs ensured the wheels themselves were stronger. The resulting turning radius in the prototype resulted in an inside turning radius of 6ft 10in. So the turning radius of the center would be 8'7" and outside turning radius 10'4".

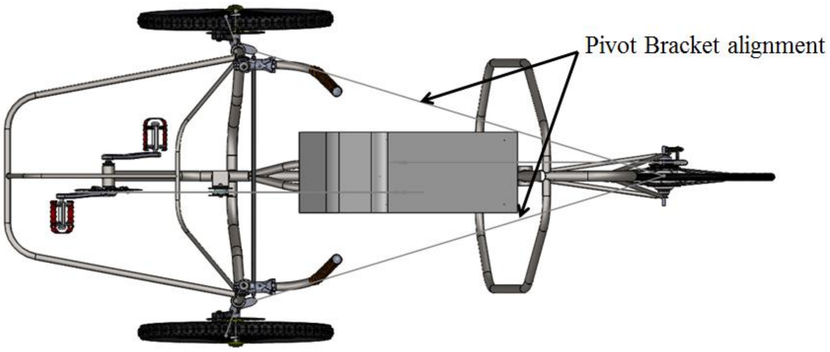


Figure 1.10 *Ackerman compensation incorporated into steering*

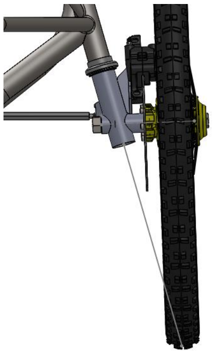


Figure 1.11 *Kingpin alignment with the center of the tire patch*

1.9 Drivetrain

In the development of the drivetrain, three main concepts were evaluation; a single chain system with idler gears, a single chain system with chain tubing, and a dual chain system with the use of a jackshaft. The pros and cons are given in table 1.6. Ultimately the dual chain with jackshaft was used, because it allowed for easier tension adjustment and would allow for the implementation of an energy recovery system, if an ERS were used. It was also considered more dependable. Additionally, several energy recovery systems were considered, such as fly wheels, solar panels, piezo electric recovery systems to absorb dampening from suspension, and other regenerative braking systems. Overall the energy recovery system concepts were not used because the amount of energy provided by any one of them was too small relative to the weight and/or cost of each system. Thus, the advantages of having one seemed negligible. This resulted in the final drivetrain configuration, shown in figure 1.12, which utilizes the jackshaft, pictured in figure 1.13.

Table 1.6 *Main drivetrain concepts*

Drivetrain concept	**Description**	**Benefits**	**Downsides**
Idler gear drivetrain system	Single chain used in combination with idler gears to transfer rider power to rear wheel. Idler gears help define the chain path	Simple to design and manufacture	Difficult to set proper tension in the chain
Single chain with chain tubing	Similar to IDGS, but chain tubing is used to control chain slack and reduce the number of idler gears needed.	Safe shielding for chain, few idler gears needed	Difficult to route correctly
Dual chain and jack shaft	A jack shaft is used to simplify the chain paths and lower the chain length require for each chain path.	Two smaller segments are easy to tension and route	Requires large amount of space under seat

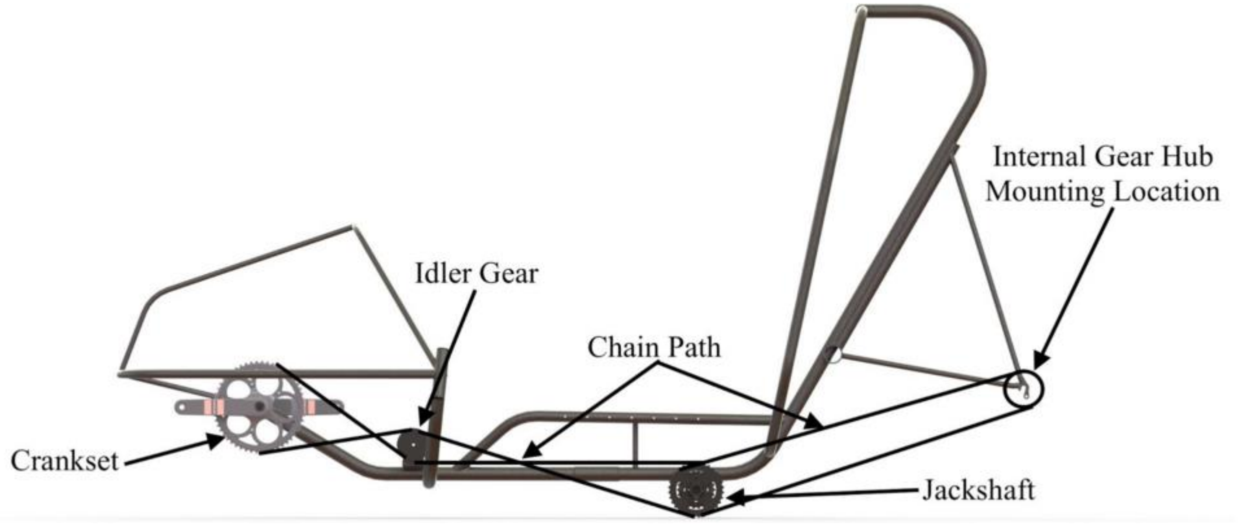


Figure 1.12 *Final drivetrain configuration*

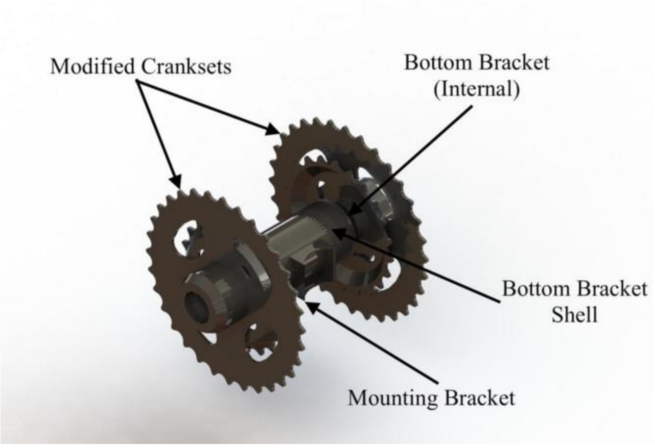


Figure 1.13 *Assembled jackshaft*

The front cranks utilize a 52 tooth sprocket, which connects directly to a 32 tooth sprocket on the jackshaft. The jackshaft is composed of a bottom bracket welded into place with sprockets on either side, as seen in figure 1.13. On the secondary end of the jackshaft, a 32 tooth and a 22 tooth sprocket are connected coaxially. The second segment of chain runs from these sprockets to the 18 tooth sprocket of the internal gear hub, where the gear ratio is further modified. The minimum and maximum gear ratios attainable cover a wider range than most bicycles, which frequently have a minimum around 1.39 (39/28) and a maximum of 4.73 (52/11). Because the vehicle is heavier than bicycles, the lower gear ratio allows for easier acceleration. Table 1.7 provides an exhaustive list of gear combinations, which were analyzed to provide a sense of step changes in the gear. The average step size here is 14.7%, which is reasonable but higher than a standard cassette. Overall this illustrates a tradeoff between gear range and step size. Here we concluded gear range was more important.

Table 1.7 *Useable Gear and step size analysis*

Front drivetrain (52/32) and Rear drivetrain (32/18 or 22/18 + IGH ratios)			**Gear Ratios**			**Usable Gears**	**Gear Ratio**	**Step Size**
			52/32 x 32/18	52/32 x 22/18		*22-1*	1.05	
IGH Gear and ratio	*1*	*0.527*	1.52	1.05		*22-2*	1.35	28.6%
	2	*0.681*	1.97	1.35		*22-3*	1.53	13.3%
	3	*0.770*	2.22	1.53		*22-4,32-1*	1.74	13.7%
	4	*0.878*	2.54	1.74		*22-5,32-2*	1.98	13.8%
	5	*0.995*	2.87	1.98		*22-6,32-3*	2.25	13.6%
	6	*1.134*	3.28	2.25		*22-7,32-4*	2.57	14.2%
	7	*1.292*	3.73	2.57		*22-8,32-5*	2.90	12.8%
	8	*1.462*	4.22	2.90		*22-9,32-6*	3.31	14.1%
	9	*1.667*	4.82	3.31		*22-10,32-7*	3.75	13.1%
	10	*1.888*	5.45	3.75		*22-11,32-8*	4.28	14.1%
	11	*2.153*	6.22	4.28		*32-9*	4.82	12.6%
						32-10	5.45	13.1%
						32-11	6.22	14.1%
							Mean Step	**14.7%**

Several ratios across the range were further selected to determine possible the speeds of the vehicle using a given input cadence. Table 1.8 reveals that the vehicle's highest gear yields a very high top speed of 61.1 mph at 120 input RPMs, which is likely unattainable under purely human power. However, the low speed is at 5 mph with an input of 60 RPMs. This value is a reasonable number for the lowest gear on the vehicle. Overall, this shows the drivetrain will not be a limiting factor in terms of speed. As mentioned the likely limiting factor would be a lack of power input or human energy.

Table 1.8 *Speed Analysis of select gear ratios*

Output: Speed [mph]		**Input RPM**			
		60	**80**	**100**	**120**
Gear Ratio	**1.047**	5.1	6.9	8.6	10.3
	2.904	14.3	19.0	23.8	28.5
	6.220	30.5	40.7	50.9	61.1

1.10 Fairing

Initially, we planned on using a full fairing, but after conducting flow analysis simulations, it was shown that a full fairing would have a higher drag coefficient than having no fairing at all. Because of this, we now plan on using just the front portion of the fairing. Figure 1.14 shows the initially planned full fairing is shown on the left, and the frame with the currently planned fairing on the right.

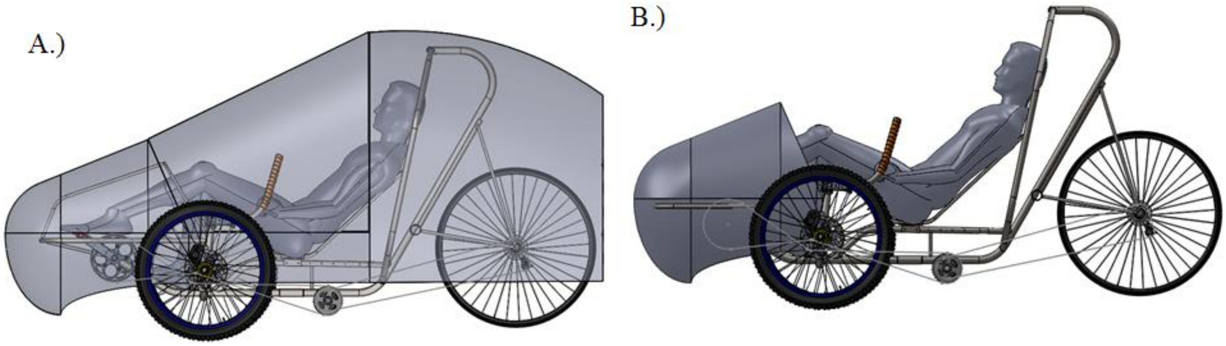


Figure 1.14 *Fairing Concepts A.) Fully faired design (ruled out) B.) Partially faired design (Current fairing)*

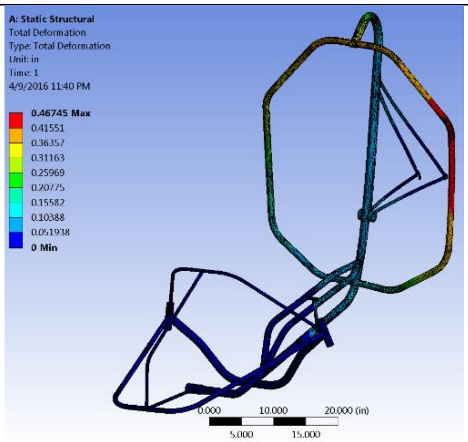
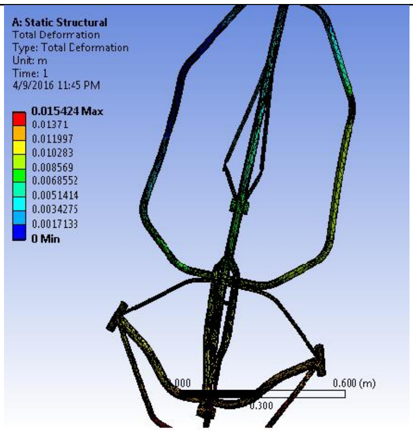
One of the priorities for fairing design is forward and side visibility. Although we concluded that it is beneficial to not have a fully faired vehicle, the initial fairing design has a large, curved, windscreen which would allow good visibility through the front, and excellent visibility on each side. Without a full fairing, outward visibility will be further improved, now allowing for over-the-shoulder visibility. The fairing is constructed of fiberglass with a substructure attaching it to the frame. Fiberglass was selected because it can be molded into the desired shape, and is rigid, while still being flexible enough to avoid shattering in the event of a collision. It was chosen over Kevlar or carbon fiber because it is sufficiently strong, and much more affordable, while the weight shaved from using carbon fiber or Kevlar would be negligible.

Chapter: 2 ANALYSIS

2.1 RPS Analysis

To analyze well how the RPS meets the requirements laid out by ASME a FEA was conducted. The analysis was completed using Ansys due to the inability of our normal CAD package (Solidworks) to mesh the given frame geometry. To model the required forces two separate cases were conducted for the side and top loads. The assumptions, method, results, and conclusions for the top load and side load cases are summarized in table 2.1.

Table 2.1 *Analysis for RPS System*

Case	**Top Load Testing**	**Side Load Testing**
Objective	Model a 600lbf at a 12° from the vertical and record the max deformation. The max deformation should be less than 1.5 inches, no plastic deformation should occur, and any deformation that does occur should not touch the rider's helmet.	Model a 300lbf to the side and record the max deformation. The max deformation should be less than 1.5 inches, no plastic deformation should occur, and any deformation that does occur should not touch the rider's body
Method and Assumptions	It was assumed this force was meant to reflect a force being applied to the wheel in a neutral position. The locations where the wheels are connected were fixed; the head tubes and the rear dropouts. It was assumed if the wheels would be subjected to the given force they would be fine. Thus fixing the rear dropouts and head was sufficient.	It was assumed the side load case was meant to reflect a case where the vehicle is being crushed, meaning the vehicle would be placed on its side and a 300lbs would be placed on top of it.. As such, one roll bar had a 300lbf applied to the center of the side inward and the roll bar on the side opposite side was fixed.
Results	 Max Deformation – 0.47in Max von misses stress – 39.5 ksi	 Max Deformation – 0.61in Max von misses stress – 61.1 ksi
Conclusions	First the yield strength of 4130 steel is 63.1 ksi so nether of the cases cause the RPS to plastically deform [136]. That being said the factor of safety for the side load is small and needs improvement. To combat this adequate testing will be necessary. Additionally, the deformations of each case were well within the acceptable range. In terms of RPS design, if was desired to have the top of the RPS as modeled to allow the rider to recline more, but due to having the angle of the force it with make the RPS more susceptible to deformation. The FEA validated the design was adequate. In terms of the side loading the FEA helped validate a dimension of 2" for the recommended space between RPS and person in figure 1.9 was reasonable. Additionally the overall width of the RPS is still able to fit through a doorway.	

2.2 Structural Analysis

Of the various features on the design of Adventure, the strength of the seat needed verification to ensure it would be strong enough. After realizing that fiber glass alone would not be strong enough hand calculations were conducted to examine the strength difference of creating a tubing substructure. The objectives, methods, results, and conclusions are summarized in table .

***Table 2.2** Analysis for different seat configurations*

<table>
<tr><th>Case</th><th>Solely fiberglass structure</th><th>Fiberglass structure combined with a 0.5” OD tubing substructure</th></tr>
<tr><td>Objective</td><td colspan="2">Examine the strength of different seat configurations. Evaluate the stress and deformations of of the seat and compare these results to the material properties to inspect if the seat is strong enough</td></tr>
<tr><td>Method and Assumptions</td><td colspan="2">First a free body diagram (FBD) was created to model the seat configuration. Based on the FBD it was assumed the seat could be treated as a single supported beam with a single load would reflect the seat appropriately without over-simplifying the analysis

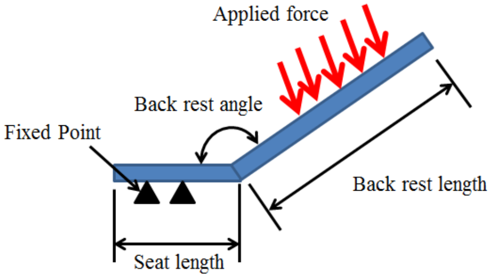


***Figure 2.1** FBD of seat*

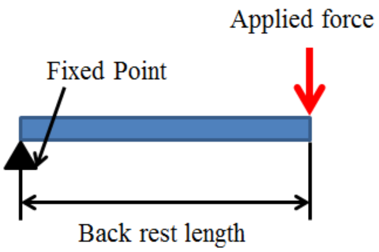


***Figure 2.2** Simplified FBD of seat*

From here the stress and deformation could be modeling using equations (1) and (2) respectively, where σ is the stress, M is the moment acting on the beam, distance from the center of the cross section to the end, I is the area moment of inertia, θ is the deformation at the end of the beam, and E is the modulus of elasticity. For the different structure configurations the differences were assumed to be only the material and the area moment of inertia. For the case of the fiber glass and tubing substructure it was assumed all the material of 4130 steel. This assumption is reasonable because although the fiberglass is not as strong as steel there are sections where spacing tubes are used to connect the circles representing the “ripping” tubes in the cross section of figure 2.4. Here the spacing tubes are never represented by the cross section.

$$\sigma = \frac{My}{I} \qquad (1)\ [50]$$

$$\theta = \frac{ML}{2EI} \qquad (2)\ [50]$$

***Figure 2.3** Area moment of inertia for fiberglass*

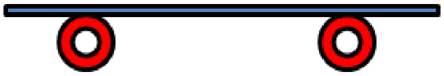


***Figure 2.4** Area moment of inertia for fiberglass with tubing substructure*</td></tr>
</table>

Table 2.2 (Cont.)

Case	Solely fiberglass structure	Fiberglass structure combined with a 0.5” OD tubing substructure
Results	Force applied on beam = 50lbf Back rest length = 20in Area moment of inertia = .000229 in^4 E = 10400 ksi [137] Deformation at top of back rest = .42 in Stress between seat and backrest = 141.9 ksi Yield strength= 28.2 ksi [137]	Force applied on beam = 50lbf Back rest length = 20in Area moment of inertia =.014884in^4 E= 29700 ksi [136] Deformation at top of back rest = .0023 in Stress between seat and backrest = 1.898 ksi Yield strength=63.1ksi [136]
Conclusions	From the results it is evident the original idea of making the seat solely from fiberglass would not work. From the analysis a normal loading condition would surpass the yield strength and break the seat. The addition of the substructure greatly reduce the amount of stress the seat would see making deformation negligible and the substructure has a factor of safety greater than 30 before it reaches the yield strength. In other words the addition of the seat frame is a success. That being said it is important to consider the assumptions made. This analysis only reflects the critical stress acting on the back support. In other words, the mount may have issues with stress as well, especially considering the mount has holes that will act as stress concentrations. Therefore thorough testing is still needed.	

2.3 Aerodynamic Analysis

For recumbent tricycles, the front portion of the fairing has become somewhat standardized, using a rounded cone-shaped nose, but there are three common choices for the shape of the rear portion of the fairing. The rear fairing is usually rounded, wedge shaped, or ends abruptly in a flat, vertical surface. Taking interior space, weight, and ease of manufacturing into consideration, the wedge shape was ruled out, as it allows less room for storage, and would have to extend much further behind the vehicle in order to show any gains in aerodynamics, which would increase weight, as well as overall length of the vehicle. Figure 2.5 shows the flow trajectories of a shape ending with a long wedge, short wedge, rounded, and flat end. Using a flow simulation, it was found that if long enough, the wedge shape is the most aerodynamic, but when shortened it becomes much less aerodynamic. Here, the flat end offered the best compromise between overall length, interior space, and drag.

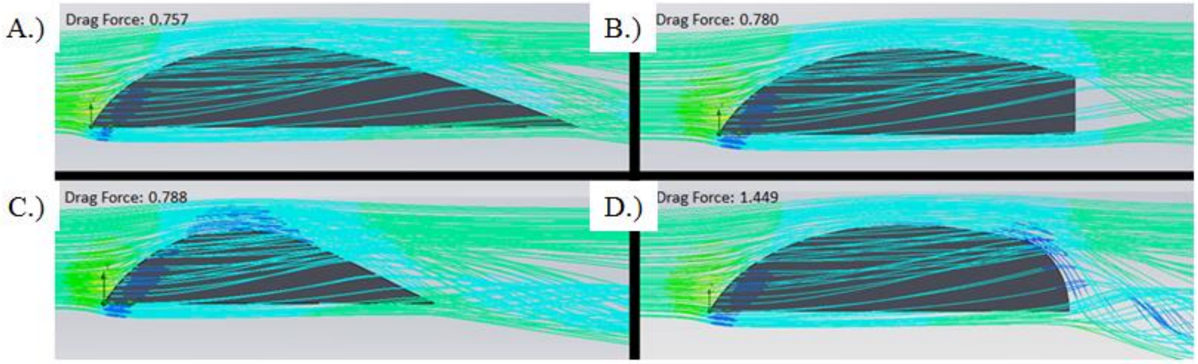


Figure 2.5 *Initial development of the fairing A.)Long wedge design B.) Flat back design C.) Short wedge design D.) Round edge design*

Using this idea a model for a fully faired vehicle was created, as well as a model for a partial fairing. CFD was completed on these as well as the frame geometry itself. After completed the CFD on each model with a 10m/s direct head wind, the results were given in figure 2.6. Here the unfaired design had a drag force of 4.5N, the partially faired vehicle a drag force of 13.8N, and the fully faired design had a drag force of 18.1N. Thus, the unfaired design was the best option. That being said, the partial fairing will be used and more developed because it showed aerodynamic advantages over the fully faired design and it is strongly believed that the shape can be further optimized. This will be explored through future testing of the fairing, and comparison to the unfaired vehicle as a baseline moving forward.

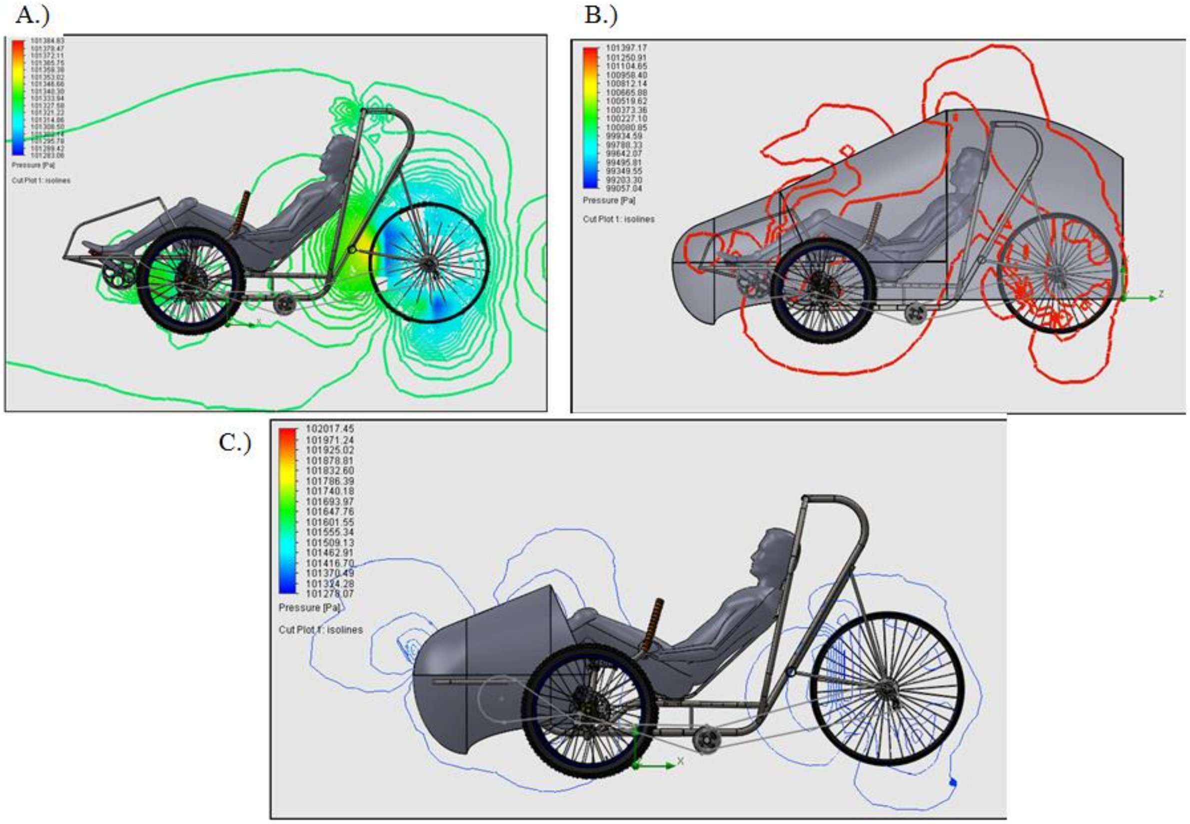


Figure 2.6 *Development and selection of the fairingA.)Unfaired B.) Fully faired C.) Partial Fairing*

2.4 Cost Analysis

The cost analysis is provided in table 2.3. The cost of materials includes the costs incurred by the team from purchasing materials for each section of the vehicle. Capital Investments are the tools needed for this year and future years. The tooling costs include the price of tooling needed specific to the design of Adventure. All values include the shipping and taxes. All labor was student labor. The results show the vehicle cost less than $3,000 to create and after expenses for going to the competition there is a little more than $100 still left in the budget.

Table 2.3 *Accounting balances of project spending*

Subsystem	**Materials**	**Capital Investments**	**Tooling**	**Miscellaneous**	**Total**
Frame	$755	$212	$38	-	$1,005
Steering	$762	$175	-	-	$937
Drivetrain	$127	-	$30	-	$157
Fairing	$519	-	-	-	$519
Safety/Lost Purchase/Other	$56	$55	$20	$100	$231
				Production Total	$2,849
	Team Attire	Gas/Rentals	Lodging	Competition Fees	
Travel Costs	$300	$600	$650	$476	$2,026
				Total Spent	$4,875
				Budget	$5,000
				Remaining	$125

2.5 Product lifecycle analysis

The objective of the lifecycle analysis is to comparatively determine how environmentally friendly the design is. To accomplish this the bicycle was used as a benchmark and energy consumption requirements were made for each of the stages outline in table 2.4 The material for the majority of the vehicle is 4130 steel. The average energy usage from the production of a bicycle is calculated to be 319 kJ per mile traveled by the bicycle [138]. That energy is the combination of all of the steps listed in the LCA breakdown. Given the increase in the steel used in the human powered vehicle as well as the fairing material a conservative estimate of 650 kJ per mile. Since our vehicle is approximately twice the mass of the average bicycle, this estimate makes sense. Given the life span of a bicycle being 15 years both bikes and the vehicle designed will eventually make up for the energy expended in the production [138].

The life cycle for the material follows table 2.4 where the metal is produced and then processed to form the steel tubes used throughout the vehicle, the metal is then shipped, and processed by our team to form the vehicle. This is where the majority of the energy is used in the production of the tricycle. Recycling the majority of the steel requires significantly less energy than the production of new steel [139]. The reusing of the tires and other parts of the vehicle prevent the increase of the energy for both the production and the maintenance of the vehicle.

Table 2.4 *Breakdown of the lifecycle analysis*

Life cycle stages	Materials	Raw Material Processing	Manufacturing	Assembly	Use	End-of-life
Adventure design aspects	Steel Tubing	Steel processing	Cutting Bending Welding Finishing	Installation Inspection Testing	Operation Maintenance	Recycle metal parts (80%)

2.6 Roll Over Analysis

To examine how well the vehicle can corner a roll over analysis was conducted. The roll over analysis was used because it was assumed the limiting turning speed would be the speed that caused the vehicle to rollover. The synopsis of this analysis is provided in table 2.5.

Table 2.5 *Analysis for roll over probability*

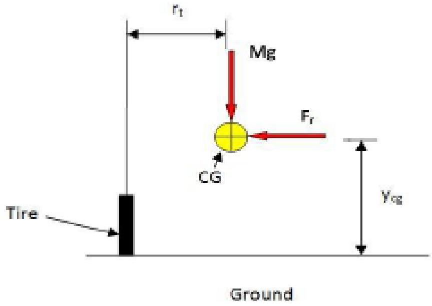
Case	**Roll Over Analysis**
Objective	Determine the limiting speeds for different turning radii
Method and Assumptions	From the Portland State 2011 design report, figure 2.7 and equations (3)-(5) outline the analysis that can be used describe the roll over predications, where F_r is the force applied to the vehicle (from centrifugal forces), y_{cg} is the height to the center of gravity from the ground, mg if the weight of the weight (where g is acceleration due to gravity and m is the mass), r_{corner} is the radius of the corner, v is velocity, and a_r is the centripetal acceleration of the vehicle [13]. Overall the method is established by applying simply physics. First the sum of the moments are taken about the cg and the reaction forces are assumed to act entirely on the front outside wheel, because if the vehicle rolls over there will be no reaction forces from the inside wheel. The assumption of rider is the overall center of gravity is independent of forward/aft position. Here it is also assumed the effects of caster and camber are negligible. Lastly it is assumed the r_t is centered for the vehicle.  ***Figure 2.7*** *Free body diagram for rollover analysis* [65] $F_r y_{cg} = m*g*r_t$ (3) [13] $a_r = \frac{v^2}{r_{corner}}$ (4) [13] $v(r) = \sqrt{\frac{g * r_{corner} * r_t}{y_{cg}}}$ (5) [13]

Table 2.5 (Cont.)

<table>
<tr><td>Results</td><td>With a 200lb rider: y_{cg}=20.5in and r_t=20.5in (center of wheel to center of vehicle). This yields to the following
<table>
<tr><td>Turning Radius (ft)</td><td>7</td><td>10</td><td>15</td><td>20</td><td>25</td></tr>
<tr><td>Limiting Velocity (mph)</td><td>10.2</td><td>12.2</td><td>15.0</td><td>17.3</td><td>19.3</td></tr>
</table></td></tr>
<tr><td>Conclusions</td><td>The minimum turning radius for a standard roads is about 6.5m (21.5ft) and a standard vehicle (car) must that at a speed of 10mph [140]. Here our design could take the same turn at 18mph, 8pmh greater than the recommended speed. Additionally the vehicle is able to take the minimiam designed turning radius at 10mph, which was determined to be acceptable. Overall, the analysis confrims can at reasonable speeds, without rolling over.</td></tr>
</table>

2.7 FMEA

A Failure Mode and Effects Analysis (FMEA) is a useful tool to assess potential failures of a design problem and mitigate or prevent them altogether. Our team used FMEA with the objective to identify the most major forms of failure. The method for completing the FMEA involves inspecting different possible failure modes in the design, and rating them based on subjective probabilities of occurrence (A), severity (B), and detection (C). The results are recorded in table 2.6. After completing the first assessment the analysis was completed again with the recommended changes. This resulted in improvements for all cases. The top three failures assessed were: chain separates from gear system, flat tire, and riding causes seat to vibrate. The recommended design, requirement, and/or inspection changes that occur as a result are noted in the actions column.

Table 2.6. *FMEA of model and physical prototype*

Potential failure	**Potential failure reason**	**Effect**	**A)**	**(B)**	**(E)**	**RPZ**	**Action**
Chain separates from gear system	Linkage breaks, chain derails	Vehicle loses drive force transfer ability	6	10	6	360	Inspection of Chain/Lubrication Possible use of chain tension/chain guides or locating/limit guides on gears
Wheel separates from vehicle	Axle/Knuckle breaks	Driver loses control/Vehicle comes to abrupt stop	3	10	7	210	Inspection of Wheel and Axle Components
Tire goes flat	Pinched tube	Increased tire rolling resistance, Vehicle requires more drive force	7	7	8	392	Inspect Tires/inflate to proper pressure, pre ride check tire pressure requirements

Table 2.6 (cont.)

Potential failure	Potential failure reason	Effect	A)	(B)	(E)	RPZ	Action
Pedal disintegrates/breaks	Plastic exposed to sun/high temps for prolonged time	Vehicle loses drive force transfer ability	2	9	5	90	Store pedals in cool, dry place out of sunlight
Handbrake cable snaps	Cable is under too much tension	Driver must use foot/hand/another object to abruptly slow down vehicle	6	7	6	252	Inspection/Testing of Brakes
Main frame member fails	Stress due to unit rolling and greater loads	Can begin to separate and breaks rendering the vehicle unusable.	4	8	1	32	Stress Testing frame with excess loading conditions
Steering tie rod failure	High torque applied or over-rotated	Steering lost or erratic	4	7	2	56	Secure connections with thread locker
Handle bends	Large moment applied by driver	Steering may become difficult or impossible	4	3	3	36	Attach handles securely
Wheel bends	Collision or hard turning	Vehicle will may not be drivable	6	8	3	144	Exercising caution on turns. Avoiding collisions
Chain stuck between gears	Shifter not operating properly	Chain must be manually moved and only in one gear	2	6	3	36	Maintenance all small parts before use
Handbrake cable gets caught on something and tears	Cable is too loose	Driver must use foot/hand/another object to abruptly slow down vehicle	3	6	3	54	Tape down cable
Vehicle flips	Turn too quickly, front brake to hard	Driver must sit there awkwardly until rescued	1	7	3	21	Limit turn radius
Gear bends	Chain tension too tight	Can’t shift gears/ bike can’t move	4	6	7	168	Loosen chain/bring extra gears
Vehicle collides with second vehicle	Rider error/handling problems	Potential to damage vehicle	4	7	1	28	Testing and driving practice
Fairing shatters	Excessive force applied to fairing	Fairing must be removed/repaired	1	1	2	2	Have supplies for repair on hand
Fairing falls off	Improperly secured	Fairing must be reattached	1	1	5	5	Have supplies for reattachment
Jackshaft hits ground due to low ground clearance	Flex in vehicle due to speed bump is too great	Gears could be damaged	6	7	7	294	Add a guard made of sheet to take impact damage
Riding causes seat to vibrate	Radial harmonic frequency matches seat frequency/not stiff enough	Rider experience is uncomfortable/performance is hindered	8	9	5	360	Add telescoping mechanisms to act as additional support behind seats

Chapter: 3 TESTING

3.1 RPS and Harness Testing

RPS testing is needed to validate previous analysis and ensure the RPS will not fail. The objective of the testing was to ensure the deformation did not occur when force exceeded 600lbs applied 12° from the vertical, or a 300lb loading on the sides. To test the loading scenarios on the RPS a hydraulic press was used. The hydraulic press had a mounting location to attach a spring scale to the frame and to the member driven be the hydraulic press. The way the spring scale scale was set up the force applied was twice as much as the force that was measured by the scale. For better clarity this is shown in figure 3.1. For the testing the rear wheel was removed from the hydraulic press, because it would not fit. As with the previous analysis this was assumed to be adequate. Diagrams of the applied top load and side load forces are given in figure 3.2. From the applications the frame was positioned such that with the rear wheel removed, the top load was close to the 12° from the vertical. In the side load testing both roll bars underwent an outside force, due to the reactions applied from the frame mount.

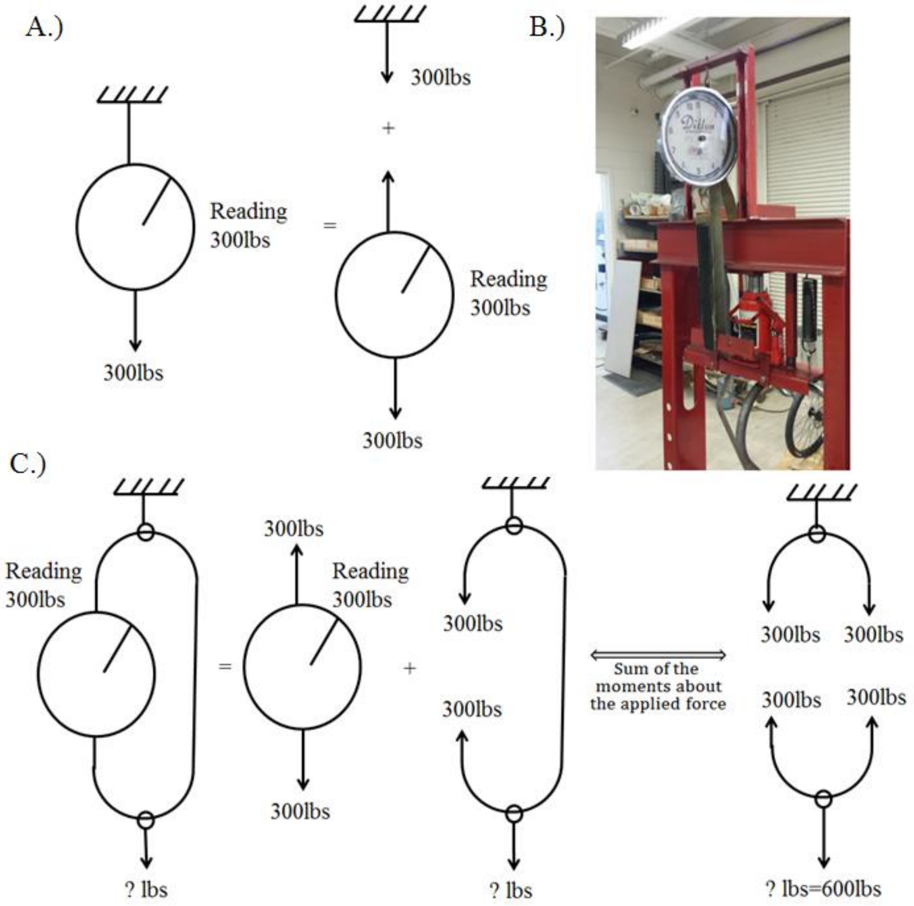


Figure 3.1 *RPS force measurement setup using a spring scale A.) normal force application and spring scale measurement B.) Our measurement setup C.) FBD of our setup and reasoning for scale only reading half of the applied force.*

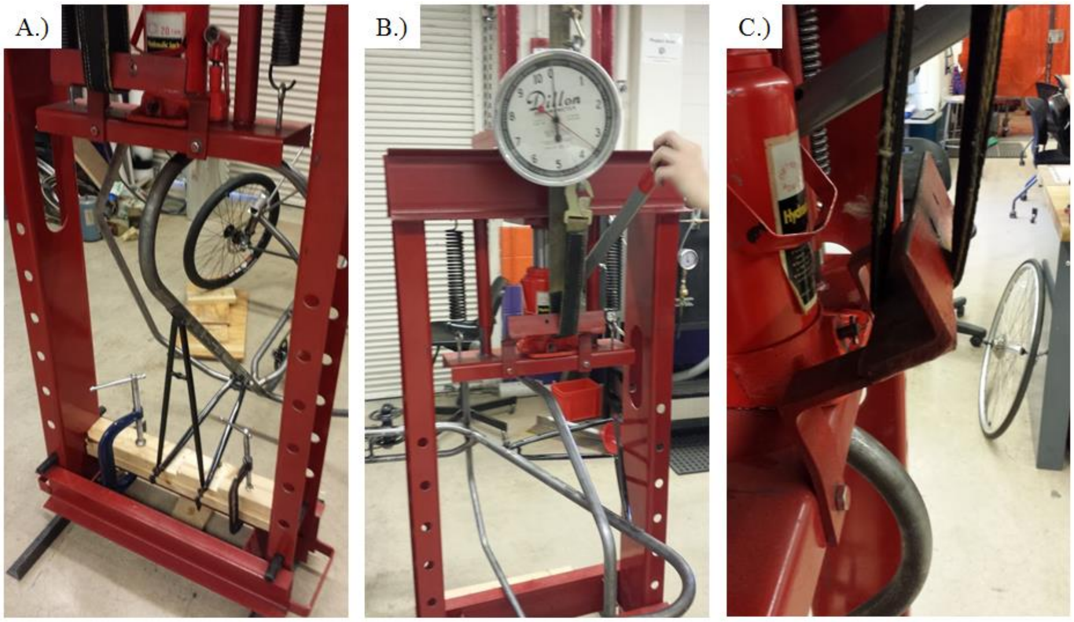


Figure 3.2 *Application of loading scenarios A.) Top load B.) Side load C.) Mount attached to press deforming indicating even more load was applied than normal.*

The results indicated that there was no plastic deformation. In terms of elastic deformation when side loaded the deformation was .75" and and the deformation for the top loading was 1", both of which are under the required deformation limits set. The spring scale measured 400lbs for the top load and 300lbs to side load. According to figure 3.1, this means 800lbs for the top load and 600lbs were applied to the side loads. In addition to this the mount connecting the spring scale to the press visibly deformed in the process, as shown in figure C. Based on perceived deformation the top loading case receive an additional 200 lbf load to measured value and the side load received an additional 100 lbf side load. For the top load case the wood may have absorbed some of the energy from the top load, and this is why so much extra force was applied to the top loading case. Overall, design modifications were unneeded and the testing verified the current design was reasonable

To further test the RPS the harness was inspected with the objective of examining its ability to prevent the rider from falling out or touching the RPS in the event of a crash. To complete this inspection the vehicle was placed upside down and a rider was secured in the harness. Then the rider was inspected as shown in figure 3.3 to examine if they touched the ground or any other part of the RPS system. Once harnessed in the rider tried to shake themselves (relatively) violently to examine if the harness could support impact forces as well. Our results indicated our setup succeeded in both of these tests. Additionally, the riders had to be harnessed upside down because it was too difficult to flip the vehicle over with the rider in it. Doing so meant the straps were not as tight as they would be normally. In other words, for normal conditions the harness would support the rider more than the test indicated. This was completed for multiple riders of varying sizes and the harness passed the tests for every case. At this point from the testing no design modifications are required for the harness. Lastly, testing the seat and attachment hardware more will be completed when once the seat is fully functional. As of now the seat can support a person's weight, when attached and stationary.

Figure 3.3 *Rider harnessed in vehicle upside down*

3.2 Developmental Testing

In terms of developmental testing the seat and steering have undergone the most testing. To test the seat, steering, and drivetrain initial prototypes were made and added to the frame. The objective of testing was to record any failures, discomforts, and otherwise noticed problem in the design and prototyped configurations of the vehicle. The method of testing was simply riding with and/or using the described aspects. Meanwhile, all problems and other notes for improvements or otherwise were recorded. The testing was completed using at least 10 different riders and completing a minimum of 30 rides, short (as small as 20ft) to relatively long rides (.5 miles or longer).

First the wooden prototype seat, shown in figure , was tested with the objective of inspecting the fit, visibility, and it functional abilities. From these subjective results were recorded for 6 different riders, ranging from 5’1” in statue to 6’2”. After these participants all riders recorded appropriate visibility. In terms of fit the adjustability of rider less than 5’3” was lacking. According to Gordon’s survey, this means the seat fits the majority of men’s but 30% of females would have difficulties [29]. The problems with fit were reached the pedals adequately and the handlebars bars being too close. To solve this problem additional seat holes need to be added towards the front of the seat rails for more adjustability and a telescoping or positional change in the handlebars could be used. All riders noted discomfort in terms of not having a seat head rest and as such one will be added. The prototype seat emphasized the final seat design could be more reclined as well. Lastly, based on normal foot position on the pedals and the seating position, riders with larger feet would hit the steering arm. To negate this, the front bumper will be expanded (widened slightly) to allow the rider to place their feet further forward.

Similar to the seat steering, after inspecting the steering through multiple rides many changes are required, based on the initial steering prototype. First the turning radius was measured to be 6’10”, meaning the vehicle is able to ride in relatively tight turns. Smaller riders noted problems with the handlebars when turning. Initially in hard turning, they would scrape the rider’s legs. After adjustments the handler bar could no longer hit the person, but they could interfere in the future addition of the fairing. One solution may be to adjust the overall handlebar configuration in general. The largest problem with the steering was the overall normal alignment of the prototype. First the camber of the wheels was not equal. Second, the toe was inward, while having a negative camber. Traditionally in vehicle design a negative camber, means the toe should be outward. Overall these problems caused the steering to be very sensitive and even small bumps and slight input changes caused large changes in the steering. The steering also has a tendency to turn towards the right because of the camber and overall alignment. To fix this the camber of wheels will first be made equal. To fix the steering sensitivity, a shorter tie rod will be used to connect the wheels to provide slight outward toe, which should stabilize most of the steering problems. The Ackerman compensation was initially measured using a string and it was noted creating an outward toe would negatively affect this compensation. Thus further testing is needed to compare the Ackerman compensation and toe as the toe changes. If the sensitivity continues to be a problem pneumatic actuators will be added and pressurized accordingly. For now it is assumed changing the pressure in the pneumatic actuators would change the effective spring stiffness, which would allow us to adapt them as necessary.

For the drivetrain inspection the pedaling resistance, chain derailment and chain slippage were the measurements used to validate effectiveness. Here the pedal resistance refers to resistance caused by the chain path and alignment, and the gear ratios used. Of the 30 rides recorded 10% reported at least a minimal problem with increases in pedaling resistance, due to problems with chain tension. Chain slippage was only reported once, but after investigation it was caused by a chain derailleur. Lastly chain derailments happened 40% of the time. With an average riding distance of .2 ± .01 miles, with a standard deviation of .2 mile, assuming a Gaussian distribution a t table indicates a chain derailment would occur every .19 miles on average. An average of 50 miles or more would be much more acceptable, in terms of the requirements we generated. Thus, main concern of the drivetrain prototype was the occurrence of of chain derailment. To fix this, the custom half link added needs to be replaced with an industry standard half link. The stiffness of the custom half link used for prototyping typically causes the chain to misalign with the chainring, because the half link is too stiff to conform to the gear rotation. Replacing the half link would negate this problem. Additionally, chain guards could be added to stop prevent from derailing. Other notes include the idler gear guard fell off once and the guard on the idler gear interferes with the tie rod. To solve these problems the position of the idler gear will be slightly translated, and the guard will be torqued down more.

Comparing the developmental testing to the requirements outlined in the requirement generation, the recommended design modifications are necessary for our design to meet many of a few more of the design requirements. This comparison is shown in table 3.1.

Table 3.1 *Evaluation of design from developmental testing aspects.*

Requirement	**Requirement Evaluation**	**Justification**
No loss of control when turning or encountering obstacles	🟥	Steering alignment needs to be greatly adjusted
Frame leaves adequate space for all other subsystems	🟨	There are minor issues between interfacing subsystems and the rider
Ergonomic features allowing adjustability to the driver are present	🟩	Seating and steering systems currently fit about 85% of the adult population
Adequate visibility in all directions	🟩	Requires further testing with fairing, but overall visibility was noted as adequate by all riders
Easy to maintain	🟨	Currently there is an unreasonable amount of chain derailment.

3.3 Performance Testing

The final physical testing completed was performance testing. The objective of this testing was to evaluate the vehicle handling ability, examine current average speeds for the prototype, and note other possible improvements in the design. The method used to evaluate these aspects was to have multiple riders of varying skill levels. Additionally, a segment of the slalom obstacle outline by the rules was used [6]. Here three cones were spaced 9m apart length wise and 1.5m apart width wise, as shown in figure 3.4. Riders were required to follow the outside path of the cones, while being timed. Timing started once the front wheel passed the first cone and ended when they passed the second cone. The direction of the course alternated to eliminate possible biases. The total path length of the course was more than 60ft. The competition times and path length were then used to calculate average speeds. The results are compiled in table 3.2

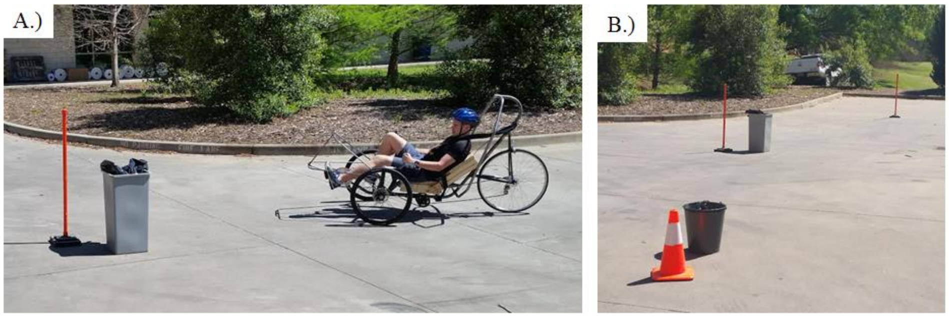


Figure 3.4 *Shortened slalom test setup A.) Rider on course B.) Course by itself*

Table 3.2 *Summary of performance testing results*

Rider skill level	Beginner	Moderate rider	Advanced rider
Average speeds (mph)	4.7	4.6	5.9
Standard deviation	0.19	0.55	0.72
Number of trials	3	3	3

Completing two-sample t tests between each of the riders reveals that none of the speeds were different with statistical significance of at least 10%. This means in terms of performance currently it is not fabricated or designed well enough to highlight differences in rider skill levels, based on the testing completed. This is an indicator that aspects of the vehicle should be more optimized to improve overall performance. One aspect to note is that through all of the testing none of the cones were touched by the riders. From a handling perspective this shows that relatively good handing, but due to the low speeds, this statement does not apply to all speeds. Additionally the handling was noted to be jerky and power transfer issues limited the riders. There was a slight learning curve for the rider, but this was fixed through practice before the trials started. All of the problems recorded were found in the developmental testing, thus design modifications for them have already been discussed. The need to improve overall performance is indicated by the low average speeds, and lack of difference between rider skill levels. Additional recommendations would be to redesign heavier features to reduce weight. The reduction is weight we be seen in better acceleration speeds, which heavily affected the testing, due to such a short course. This would also correspond to minimal weight requirement established initially.

Chapter: 4 SAFETY

During manufacturing, several measures were taken to ensure the safety of team members. New purchases of personal protection equipment (PPE), such as face shields and more goggles, along with previously owned PPE were used during the use of power and hand tools, both by the tool operators and any assisting team members. New and improved tear-resistant gloves were used during drilling and cutting of metal. Welding was only completed by trained students on the team. Additionally, miters and jigs were used for welds and other position-sensitive manufacturing to prevent any students from holding materials while welding. This year most fabrication was carried out in a university-run machine shop that required student certification for all tool usage. The small remaining fabrication comprised mostly of cutting and assembly procedures were completed in a different university building, with its own set of standards and rules. In the overall manufacturing process general shop etiquette was always followed and proper attire used.

Testing involving riding did not begin until a harness was properly installed. All testing took place in bystander-free well-lit areas. Any riders during testing were required to wear helmets and appropriate footwear. The testing completed also helps to validate the design and address and modifications that need to occur, before long term use of the vehicle or racing. This is also backed by the thorough analysis in the design, such as calculating maximize turning speeds to roll overs. Additionally, to increase rider safety the vehicle design called for a low center of gravity. A front bumper and a longer wheel base were used to prevent flipping from the use of hard (front) braking. In the event of flipping a commercial harness keeps the rider in the seat, and a roll cage prevents the rider’s head, arms, and body from coming into contact with the ground while the front bumper protects the rider’s feet. Sharp surfaces have been sanded or covered and tripping hazards have been minimized to prevent rider injury. The overall design also makes it easier for the rider to get in and out of the vehicle compared to the previous design. For bystander safety bells, head and taillights, and reflectors will be added to the final design to improve visibility and communication of the vehicle. An adjustable seat as well as future adjustable mirrors allow for increased visibility regardless of rider height.

Lastly, the front bumper was added as specific safety aspect to improve the overall safety of the vehicle. As mentioned the front bumper in combination with the longer wheel base better rider/vehicle weight distribute help prevent the vehicle from flipping over during hard braking. This was a problem that developed in the previous design. Additionally, it protects the rider’s feet from any hazards in the event of the vehicle being flipped over. It also adds protection in the event of a collision. In the event of a collision, immediately the rider’s feet are protected, but the front bumper is also designed to absorb impact energy and prevent possible further damage to the rider. If a bystander was involved in the collision the bumper protects them from the sharp crankset in the front of the vehicle and it will distribute the impact energy. Unfortunately the shin or calves would likely be hit, whereas a higher front bumper would impact the thighs, which would likely cause less overall damage to the bystander. That being said the height to the front bumper would cause the bystander to fall on top of the vehicle instead of being run over, if the vehicle maintained enough momentum after the crash.

Chapter: 5 CONCLUSIONS

5.1 Design evaluation

The final evaluation of the prototype was based on its fulfillment of the original requirements presented in table 1.1. The results of the evaluation are shown in table 5.1. Here all of the original requirements for the vehicle were met with the exception of the ERS requirements, general size and storage ability. The ERS requirements were not applicable as there was not an ERS system. The prototype size is much wider and taller than desired, and the overall length is slightly greater the desired distance. The ability to transport the vehicle is hindered by the overall width, and inability of the vehicle to fold or decrease in size. Additionally, a storage system still needs to be added. Overall a large portion of the design requirements are met and as such the final design is considered adequate. That being said some changes to the design are still necessary based on testing and the recorded problems.

Table 5.1 *Evaluation of the Adventure design*

#	Category	Requirements	Requirement Met?
GR1	Geometrical restrictions	Maximum Size: 36 x 25 x 90 inches with 6 inches of ground clearance	**No**
GR2		Frame leaves adequate space for all other subsystems	**Yes**
GR3		Ergonomic features allowing adjustability to the driver are present	**Yes**
SP1	System performance	Rigid and stable at all speeds and different road conditions	Needs Validation
SP2		No loss of control when turning or encountering obstacles	**Yes**
SP3		Minimal Weight	Some Areas could be improved
S1	Safety	Durable enough to withstand rolling without danger to driver	**Yes**
S2		Adequate visibility in all directions	Needs Validation
ST1	Storage and transportation	Easy disassembly for storage or transport	**No**
M1	Maintenance	Easy to maintain	**Yes**
CC1	Complexity and cost	Cheap and easy to manufacture	**Yes**
CC2		Total cost: under $4,000	**Yes**
ER1	Energy recovery	Energy recovery system does not pose any danger to driver	N/A
ER2		Energy recovery system provides more power to the wheel than is required from the driver	N/A
AR1	ASME requirement	Come to a complete stop from a speed of 25km/hr in a distance of 6.0m	Needs Validation
AR2		Can turn within an 8.0m radius	**Yes**
AR3		Travel in a straight line for 30m between 5 and 8 km/hr	Needs Validation
AR4		Must include a roll protection system (RPS) that meet specified standards	**Yes**
AR5		A Harness must be used to secure the rider	**Yes**
AR6		Exterior and interior must be free from sharp edges	**Yes**

5.2 Future Work

Based on the problems involved in testing and current state of the prototype there are still minimal changes that need to occur before the competition. Mandatory changes are outlined in table 5.2 If time permits, tasks that are desired to be completed are given in table 5.3.

Table 5.2 *Mandatory changes that need to occur before competition*

1.) Camber of wheels is not the same Bend steering arms to correct this and create equal camber.
2.) Decrease tie rod length and allow front wheels to slight toe out, given negative camber in design. Complete testing again as seen fit.
3.) Change idler gear position so it doesn't intersect with tie rod.
3.) Prototype front bumper geometry is off. Additionally it hits the rider's feet when they pedal. Cut off current bumper and recreate a new one, using old material.
4.) RPS and rear section after the seat rails need more stiffness. Analysis different methods to increase stiffness and make changes to the prototype.
5.) Chain continually falls off. Replace custom made half link with industry stand and add chain guards to prevent this.
6.) Add telescoping supports to seat in order to provide more strength and stiffness.
7.) Complete physical testing, once the fairing is added. (Coast down testing and visibility testing again and more in depth).
8.) Finalize front brake mount designs and add to vehicle. Also complete brake and speed testing.
9.) Add shifter to jackshaft for the rear drivetrain.
10.) Add safety features to vehicle (Mirrors, bell, lights, reflectors)
11.) Add sheet metal cover to jackshaft to protect it from ground hazards due to low ground clearance
12.) Add storage system to prototype.
13.) Add a head rest to the seat for more comfort.
14.) For pedals, and bottom brackets that loosen as the vehicle is driven, either drill holes for set/button screws according or reinstall and use excess lock tight.

Table 5.3 *List of additional tasks desired to be completed*

1.) RPS is wider than necessary. Remove 2in from each side and complete RPS Testing again.
2.) Rear of the frame is rotated by five degrees and rear triangle is slight misaligned with front wheels (May be fixed by adjusting wheel camber). Cut member and reattach to realign components and retest vehicle aspects.
3.) Recreate steering arm and decrease wheel track. Perform testing again as necessary.
4.) Vehicle is slightly more reclined, thus extra height of RPS is unneeded. Decrease height and seen fit.

L.6 Clemson 2016 Innovation Report

ASME SETTING THE STANDARD

http://go.asme.org/HPVC

(Form 6)

Vehicle Description Form

Updated 12/3/13

Human Powered Vehicle Challenge

Competition Location: Athens, Ohio

Competition Date: May 13-15, 2016

This required document for all teams is to be incorporated in to your Design Report. Please Observe Your Due Dates; see the ASME HPVC for due dates.

Vehicle Description

School name: Clemson University

Vehicle name: Adventure

Vehicle number: 2

Vehicle configuration

Upright ______ Semi-recumbent X

Prone ______ Other (specify) ______

Frame material 4130 ChroMoly Steel

Fairing material(s) Fiberglass

Number of wheels 3

Vehicle Dimensions *(please use in, in^3, lbf)*

Length 98.5in Width 41.8in

Height 49in Wheelbase 52.6in

Weight Distribution* Front 70% Rear 30% Total Weight ~ 65lbs

Wheel Size Front 24in Rear 27.5in (700mm)

Frontal area 1100in^2

Steering Front x Rear ______

Braking Front x Rear ______ Both ______

Estimated Cd 0.32

Vehicle history (e.g., has it competed before? where? when?) New vehicle

*Based on current model estimate. The true weight will be measured on the final prototype.

For the 2016 ASME HPVC East located at Athens, Ohio

CLEMSON
UNIVERSITY
HUMAN POWERED VEHICLE TEAM

Introduces vehicle number 2:

Adventure

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Team Members

Artis Johnson
Natalie King
Richard Matthews
Henry Busch
Patrick Zalecki
Sean Suter
Kelton Wiseman
Philip Nich
Sean Kelly

Innovation Design

For Clemson's 2016 HPV Adventure, the innovative design aspect was the seating system. Figure 1 shows that the seating system is comprised of two parallel seat rails, a mount to slide across the rails, and the seat itself. Not shown is the method to change seating positions. To accomplish this oversize 3/16" are spaced 2" apart to allow for different rider heights. Normal bicycle skewers are then placed through the holes in the seat mount and the holes in the seat rail corresponding to the specific rider's height. The main reason the system is innovative is because it allows for adjustability to account for different rider sizes, while simultaneously providing optimal visibility, and frame stiffness to resistance flexing. The way in which the seat is strengthened is innovative as well. From a retrospective analysis, for similar tadpole tricycle designs the most similar seat adjustability that reflects this design was found in the Olin 2011 and UCF 2008 HPVC design reports as shown in figure 2 [141,142].

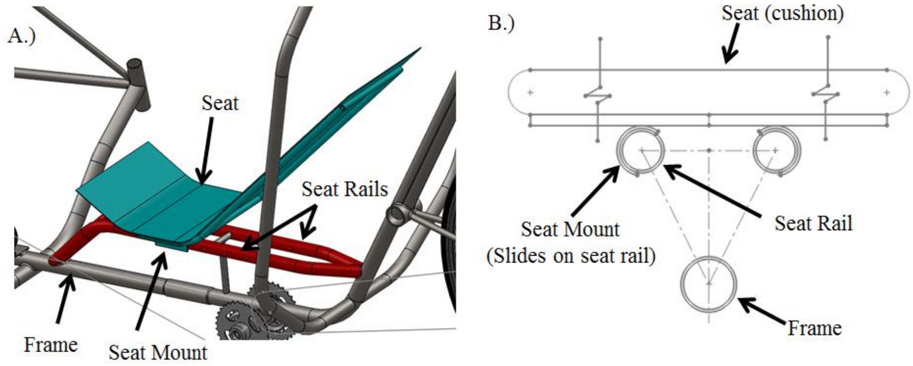

Figure 1. *Overall of innovate seating system. A.) Incorporated into the HPV B.) Cross section for understanding*

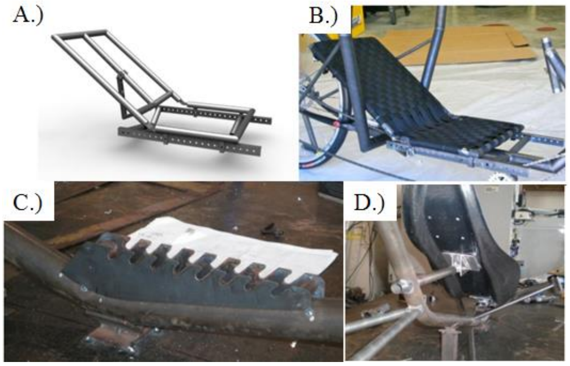

Figure 2. *Similar adjustable seating systems. A.) CAD model of Olin College 2011 B.) Physical build of Olin College 2011 C.) Seat adjustment for UCF 2008 D.) Telescoping support for seat, UCF 2008* [141,142].

To prove Clemson's concept is innovative it is important to make some distinctions between the other designs. First both adjusting systems do not improve the stiffness of the frame. In Olin's design the seat adjustment supports help distribute the load and nothing more. UCFs design is comparative to resting the seat on the frame itself. Our design increases the strength and distributes the weight, because the triangular configuration of seat rail and frame, shown in figure 1B, extends across the majority of the frame and acts as a supporting sub frame structure. The innovation's need for seat adjustability and extra stiffness is founded the requirement of different sized riders and lack of frame stiffness to prevent flexing on previous designs.

Additionally there is a great need of visibility for safety and rider awareness. The positioning and dimensioning of Adventure's seating system provides this.

Concept Evaluation

To prove the stiffness of the frame is increased consider equation (1), where S is stiffness, C_2 is a constant (based on geometry), E is the young's modulus, I is the area moment of inertia, and L is the length of the (frame) cross section. Assuming the changes in the constant are negligible and the material is constant throughout, per unit length the stiffness is directly proportionally to I. The evaluated the area moment of inertia for the cross section in figure 1b was $.85\text{in}^4$ about the horizontal axis and 1.27in^4 about the vertical access. Comparatively the single tube has an area moment of inertia of $.04\text{in}^4$. This correlates to a minimum stiffness increase of more than 2000%. The area of the seat rail configuration is twice as much as the single tube. This means the innovative geometry is at 1000% stiffer per unit weight. The initial prototype of the seat rail can be seen in figure 3. Additionally constructing the prototype yielded no difficulty.

$$S = \frac{C_2 EI}{L^3} \geq S^* \qquad (1)\ [50]$$

Figure 3. *Seat rail, holes, and seat mount for seating system adjustments A.) Side view B.) Top view*

In terms of visibility and adjustability, anthropometric data was used to size different riders to the system, as shown in figure 4 [29]. Also shown in figure 4 is a prototype of the seat to evaluate said visibility. Riders from heights of 5'ft to 6'2" all stated they had no problems with visibility of the prototype. Once the fairing is attached more visibility testing will occur.

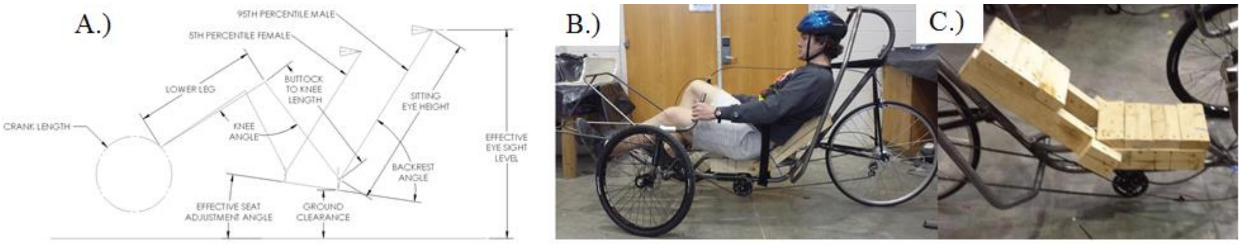

Figure 4. *Visibility Analysis and Testing A). Anthropometric layout B.) Rider visibility testing C.) Prototype Seat*

The design for the seat itself was initially made of fiberglass alone and it was thought to be rigid enough. Through developmental testing this was shown to be untrue after multiple layers of fiberglass would deform through minimal hand strength. To increase the rigidity first flat stock was tested and provided to be invalid. Building on this a seat substructure made of .5" OD 4130 steel tubing was created. After the fiberglass was attached to the substructure, using zip ties testing showed the seat was finally strong enough to not yield under rider weight. The development and testing method is shown in figure 5.

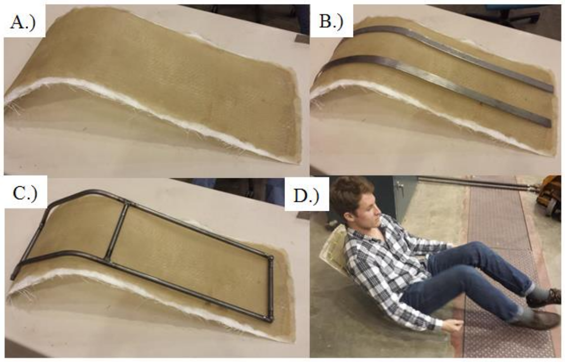

Figure 5. *Development and rigidity testing of the seat A.) Original concept B.) First concept for improved seat C.) Final improved concept D.) Seat strength testing method*

From the seat configuration there were some unanticipated benefits and failures that we learned from. Of the unanticipated benefits, the seat rails allow for protection of the drivetrain from the rider, it has made the chain path routing easier, and it has allowed easy placement of a jackshaft. In terms of learnings, while the seat rails provide flexing support to the main member, the connection areas to the RPS needed more flexing support and the seat rails were ineffective in this area.

Learnings

The failures in the seat rigidity helped defined the final concept of a tubing substructure after flat stock and simple composite failed to work. Thus it demonstrated the impact shapes have on strength. That being said the seat still slightly deflects when the rider's weight is applied. To resolve this telescoping stiffeners with be added add shown in figure 6. Compared to the other telescoping methods such as figure 2D, the incorporation of our telescoping stiffeners are innovative as well, because they do not require a fixture clamp or support. , while still allowing for full adjustability. Overall they will help support the seat in a triangle configuration as shown in figure 6. Adding the stiffener bars will alleviate stress on the skewers and the stress concentration holes on the seat rails where the mount is located. On another note, telescoping handlebars could be needed, because although anthropometric data may be assumed similar for people of different sizes, it is does not reflect the comfort of having bend arms at given angles. Lastly, a head rest is strongly encouraged for better overall rider support.

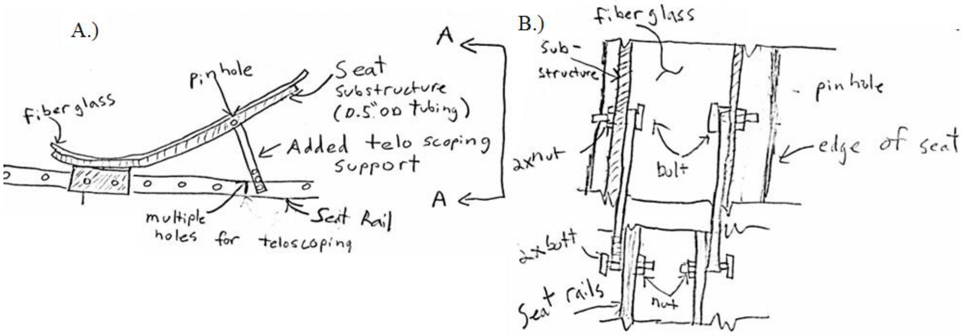

Figure 6. *Stiffening bar for rigidity improvements A.) Front view B.) Side view A-A*