Mechanical
Engineering
CAL POLY

Adaptive Tricycle

Final Design Review
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California Polytechnic State University,
San Luis Obispo

Sponsored by
California Children's Services

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Disclaimer

This document is the result of a school year long project performed by four mechanical engineering students. All information within this document was created by these four students and does not represent professional advice. Furthermore, as of March 20th, 2020, the spring quarter of Cal Poly, SLO has been moved to an online format due to the COVID-19 pandemic limiting the work that the team of student can make on the project. As a result, the scope of this document has been altered to apply to all conditions that can limit motor functions instead of completing the physical fabrication of the tricycle. While the original manufacturing plans are discussed, all further manufacturing has been canceled.

Abstract

This Final Design Review document describes the senior design project carried out by a team of four mechanical engineering students from California Polytechnic State University, San Luis Obispo in conjunction with California Children's Services for Savannah, a student at San Luis Obispo High School. The purpose of the project is to design an adaptive vehicle for Savannah that serves as a form of exercise and can be easily operated by her with little to no outside assistance. Background into Savannah's condition is provided as well as previous designs of similar adaptive tricycles, document standards and specifications which constrain design solutions, outline the scope of the project as well as the needs and wants of the end user as understood by the team, and develop a path towards the final design through description of the design process. The final design described in this document is centered around the user's strongest muscle group (her abdomen and back muscles) to provide all necessary tricycle functions. These functions include steering, powering and braking. In general, the steering mechanism will utilize bevel gears to actuate the front wheel of the tricycle, the powering system will be a ratcheting push bar that is harnessed to the user's torso, and the braking system will be a brake pad on the front wheel that is engaged by leaning back in the seat. This document contains our team's process for developing our final design, solid model of our final design, justification calculations, manufacturing plans and engineering drawings, and our schedule for completion of the final product. In addition, a summary of the effects of the COVID-19 pandemic on project completion is provided, including an outline of future documentation which will aid an outside party in development and completion of our intended design, as well as the team's revised project direction and scope.

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Figures and Tables

1.0 Introduction

Our team consists of four mechanical engineering students in our senior year at Cal Poly working to design an adaptive tricycle for a high school student as our senior project. Adaptive tricycle designs have been implemented for a variety of user needs, ranging from consumers with limited limb strength to amputees. While many of these adaptive tricycles can be universally used for consumers with similar limited capabilities, there are many cases in which a user cannot operate the vehicle due to their condition. These adaptive tricycles utilize alternative methods for operating the vehicle, including powering, steering, braking and user access. Typical adaptive tricycle interfaces include hand pedals for users with lower extremity disability or other alternate control interfaces. Savannah is a student at San Luis Obispo High School with arthrogryposis, which is a condition in which she has limited strength and mobility through her arms and legs as well as her hands and feet. Currently, she has an adaptive exercise tricycle that she is unable to operate on her own due to her limited limb use. We aimed to redesign her exercise vehicle to maximize her ability to use it on her own. The essential functions of the vehicle that we were aiming to optimize included entering and exiting the vehicle, powering the vehicle using Savannah's capabilities, steering the vehicle in a comfortable manner, and braking in an ergonomically comfortable way. This document serves as a final design review (FDR) which has continued from the content in our critical design review and includes general information on her condition, a brief description of her current tricycle, a summary of our team's objectives and design ideation process, and a detailed timeline of our design and analysis process, along with engineering justifications that serve as a proof of concept for each subsystem. These calculations are discussed in the concept justification section in this report and are detailed in the report appendices. The final design report details the final design that we planned to implement and test through a verification prototype and eventually in the final product. Testing plans are outlined along with updates to the timeline for completing the prototyping process and the manufacturing plan of the final design. Additionally, alternative documentation detailing the new project direction of a universal design is outlined, including the conclusions we drew from the testing and manufacturing we performed and suggestions for future design process improvement.

2.0 Background

Before developing a plan of action for designing a new tricycle, the team researched previous senior projects with similar goals, existing patents for adaptive tricycles, and scholarly journal articles reporting on design effectiveness and various design considerations for similar projects. Many senior projects in the past have been geared toward developing adaptive vehicles, ranging from racing bikes to leisure vehicles. Figure 1 includes two of the senior project designs that we researched for information on steering and seat accessibility functions. Due to the unique nature of our project, we were unable to find any current designs that match all the requirements for our end design, however several existing designs contained subsystems that were used as inspiration for our design.

The first senior project we researched was a single-arm recumbent tricycle designed for a former marine. While the project itself ended up using a single-arm mechanism to steer the vehicle, the designers' considerations from their concept development mentioned the possibility of a lean-to-steer handcycle. This vehicle uses a shaft that connects the seat to the front wheel to turn it, which could be a potential solution to the mechanism of the current tricycle that Savannah is unable to use. This, along with their implemented concept of lean-assist steering, which amplifies maneuvering capabilities done by hand by providing additional rotation by leaning, can be implemented and improved within our own design.

Figure 1. Right, adjustable open seating. Left, lean-to-steer mechanisms.

The second senior project of interest to our group was an adaptive adjustable tricycle built for disabled students in the Buena Park School District for physical therapy. What interested us was their adjustable seat, which included an aligner to easily ratchet up or down the seat. As accessibility is of high importance to our project, the frame and seat interface with the rider on this adaptable tricycle could be utilized in the redesign of her current tricycle.

In addition to researching senior project designs, we researched relevant patents that could aid in the final design of the power transmission system, steering and braking systems. Appendix A lists these patents and the main takeaways from them. Before we could implement any designs, we had to better understand the current vehicle, which is shown in Figure 2. The first steps we took when beginning this project was to get in close contact with Savannah and her primary caregivers. We paid a visit to Linda Wolff (her physical therapist) and William Walters (one of her teachers at her high school) to get some more preliminary information about the challenge. The goal of this information gathering was to fully understand what specific needs exist for Savannah regarding her tricycle and her ability to operate it. We wanted to take the time to listen to Savannah and see the issue through her eyes so that we can ensure that our work is concentrated on solving the right problems.

We were able to get access to the current Invacare Tricycle™ and investigate how it operates as well as the difficulties it may present. There are many qualities of the tricycle that make it more accessible to those with disabilities, for example, an easier method of shifting gears is currently in place; given these additions, though, there are still hindrances that are present and make it difficult, or even impossible for Savannah to properly use it and get exercise.

Figure 2. Savannah's current tricycle.

Upon performing a preliminary inspection of Savannah's current tricycle and her limitations, we discovered that she is easily able to maneuver from her electric wheelchair onto the tricycle because the wheelchair is higher than the tricycle seat. When attempting to get back onto the wheelchair from the tricycle, Savannah struggles to overcome the height change. Another issue that we noticed was that unless somebody is holding the tricycle stationary, it will roll away during mounting and dismounting and cause Savannah to fall. After noticing these issues, we moved on to her ability to operate the bike. We found that there were three main hardships that she had with using the bike. First, the bike is designed to be propelled purely with arm strength and since Savannah's arms cannot provide enough force to power the bike, the drive train must be redesigned. Second, the steering mechanism on the current tricycle requires Savannah to use both hands to maneuver which is not feasible for her. The steering also has too much resistance for her to overcome to steer. The team will have to customize the design to be more aligned with Savannahs capabilities. Last, the current braking system on the tricycle consists of a coaster brake and an emergency locking brake, both of which Savannah is unable to operate.

In our meeting with Ms. Wolff, we learned more about Savannah's condition, arthrogryposis. Ms. Wolff went over some basic ranges of motion that Savannah possesses and informed us of the causes and effects of arthrogryposis. From this initial meeting, we were able to begin research on Savannah's condition which was vital to understand the nature of her disability. In the next meeting, we were able to meet with Mr. Walters and Savannah where she demonstrated her typical exercises so that we could determine her ranges of motion. In terms of operating the bike, Savannah reportedly has three percent grip strength in her left hand and five percent in her right hand, meaning that the current method of operating the tricycle with hand pedals proves to be undesirable. Finally, we observed that Savannah has great core strength and balance, which could potentially be the focus of our solution to the powering and steering of the tricycle.

In this project we will be following Americans with Disabilities Act (ADA) standards when adapting this tricycle. The Americans with Disabilities Act sets the standard for ease of access to buildings and devices for mobility. For our tricycle design, we will need to follow guidelines as set by the Department of Justice and Department of Transportation for the vehicle to access and safely navigate sidewalks and other facilities. The tricycle will need to be operated only in facilities that support the final dimensions and specifications of the tricycle. The factors that facilities keep in mind are outlined in the Electronic Code of Regulations under Title 28, Section 36.311.

2.1 Arthrogryposis and Savannah

As mentioned previously, Savannah lives with Arthrogryposis Multiplex Congenita (typically referred to as arthrogryposis), and this condition renders her arms and legs without much usability. It is a condition that affects about three out of every 10,000 births and begins when the fetus is growing in the mother’s womb. The fetus’ limbs that are affected by arthrogryposis are stiff and not moving during an important developmental period. Due to the lack of movement of the limbs, it is nearly impossible for those with the condition to use them adequately (British Medical Journal). For Savannah specifically, the condition affects both her upper and lower limbs. She does have some use of her arms, but she does not have enough arm and grip strength to currently use the adapted tricycle effectively.

The purpose of the tricycle, as mentioned, is for Savannah to be more active and get more exercise than she currently gets. Lisa Wagner, in “Rehabilitation Across the Lifespan for Individuals with Arthrogryposis” says that an increase in bodily movement would not necessarily improve the condition of arthrogryposis, but it would still allow those with the condition to stay healthy in other aspects and allow them to interact with their environment more effectively. We plan to make a device that allows Savannah to have that exercise and interaction to increase her quality of life. The device is not meant to help her overcome her condition, but rather allow her to further strengthen the parts of her body that allow her to do daily tasks and provide a fun alternative to her current daily form of transportation. Creating a vehicle that she can power on her own accord and achieve physical fitness with is what we plan on creating.

3.0 Objectives

With the task at hand, it was very important for us to reach an agreement with Savannah, her teachers, and her sponsor on the scope of the project in relation to their desired outcomes from the project. Figure 3 outlines the boundary in which the user/vehicle interface design will be focused.

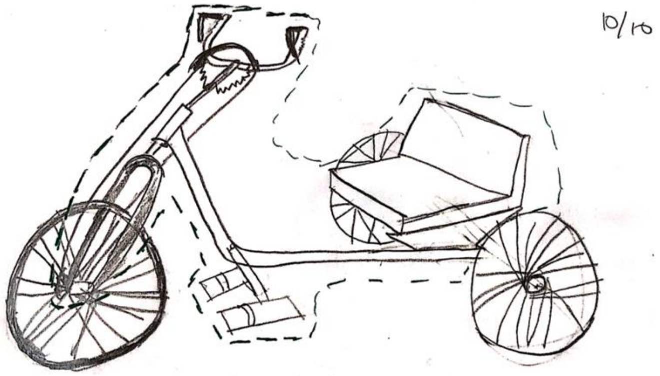


Figure 3. Boundary Drawing of the Adapted Tricycle.

The purpose of the boundary drawing was to physically represent the scope of our task at hand. By creating a boundary around the specific regions of the project that we are concerned with, we can clearly communicate our goals within our group, and to our sponsor. As shown in the drawing, our team is focused on the overall sizing of the bike to fit Savannah, the braking system, the steering system, and the power transfer system.

The “needs” and “wants” columns of Table 1 were determined through interviews with Savannah, Mr. Walters, and Ms. Wolff where we gained information on the tricycle and Savannah. Under the “needs” section are the requirements for this project that will stand as the bare minimum we must satisfy when presenting the final product. The “wants” section includes specifications that are intended to be included in the final product, but do not carry the same weight as the needs section. Certain items such as the “adjustable resistance for powering the tricycle”, which is meant for the purpose of strengthening Savannah’s core, may not be included if the final tricycle sufficiently satisfies the other categories.

Table 1. Adapted tricycle needs and wants table.

Needs	**Wants**
Power tricycle without extensive use of arms or legs	Raising or lowering the seat for ease of access
New steering mechanism	Maximizing exercise
Lightweight	Aesthetically pleasing
Large enough seat	Adjustable resistance to power the tricycle
Using the tricycle for exercise	
Implement a more reliable braking system	

3.1 Quality Function Development Description

We created a Quality Function Development (QFD) House of Quality chart, found in Appendix B, to categorize the functions of the tricycle and relate them to each other. There are factors that have positive relationships to each other, such as weight and power transmission. The positive relationship means that as the weight changes in one direction, the need for power transmission changes in that same way. The heavier the tricycle becomes; the more power transmission is necessary for an effective vehicle. There are some factors that have a negative relationship, an example of that being weight and top speed. An increase in weight leads to a higher time it takes for the tricycle to reach top speed. It is important to think about not only what factors are necessary for the tricycle to both perform well and be easy to use for Savannah, but it is also important to consider how these factors affect each other. These relationships can change the target values for each of the categories.

The House of Quality outlines which criteria we are looking for when designing the vehicle, as well as which target values we are aiming for. There are some nominal values that we aim to achieve, such as a value for weight, but there are also many qualitative specifications necessary in the final design, including Savannah's satisfaction with riding the tricycle and how easy it is for her to use it. These values will be determined by use and performance surveys that we plan to present to Savannah to see how the tricycle fits her and are some of the most important qualities of the tricycle that we plan to consider when designing and building.

3.2 Specifications Table

Table 2 tabulates the specifications and the requirements for the tricycle in order of most important to least important. The vehicle must satisfy these requirements within the mandatory tolerance in order to achieve a successful tricycle for Savannah to operate. Some specifications are not quantifiable, but rather qualitative, like the Ease of Use and Performance. These specifications are analyzed by Savannah's reaction and overall satisfaction with the tricycle, and those are the most important factors when designing and executing the adaptation of the tricycle. The tricycle itself has an overall pass/fail criterion of performance; if Savannah cannot use it or will not get good enough exercise from it, the tricycle has failed. If the more important specifications fail, the tricycle fails, while if the tricycle is a bit on the heavier side for her parents to transport, or aesthetics are not ideal, the tricycle can still accomplish the task.

Table 2. Tabulated design specifications for final design.

Spec #	Parameter Description	Requirement or Target	Tolerance	Risk	Compliance
1	Top Speed under own control	6 mph minimum	-	H	A, T
2	Ease of Use	Pass/Fail	-	H	A
3	Seat Design	Pass/Fail	-	H	I
4	Steering Performance	Pass/Fail	-	H	A
5	Time to Access	15 seconds	-	M	T
6	Braking Distance	Current Distance	1.5 feet	M	T
7	Weight	Current Weight	10 lb	M	T
8	Dimensions	Current Dimensions	1 foot each direction	M	I
9	Aesthetics	Pass/Fail	-	L	I
10	Time Until Top Speed	10 seconds	-	L	T

H = High, M = Medium, L = Low, A = Analysis, I = Inspection, T = Test

1. The top speed under own control is how fast the tricycle can move under only Savannah's power. If the top speed is too low, it might not be worth it for her to use it.
2. The Ease of Use will be determined by a series of questions we will ask Savannah; it is a way to represent how easy it is for her to use the tricycle.
3. The way the seat is designed is based on what works best for Savannah, regarding comfortability and operability.
4. Steering Performance is going to be analyzed in the same way as Ease of Use; we will ask Savannah how well the tricycle performs under her power.
5. Time to Access refers to how long it takes Savannah to enter and exit the tricycle.
6. The tricycle needs to have a safe braking distance so Savannah can be safe while operating it.
7. The weight is simply how much the tricycle weighs, and this affects portability in terms of lifting the tricycle into the bed of a pickup truck, which is primary mode of transport for the tricycle when moving it between distant locations.
8. The dimensions, like the weight, relate to the portability of the tricycle, and are moderately important when designing, specifically when transporting the tricycle.
9. Aesthetic appeal is a less necessary spec that is determined by how much Savannah likes the visual appearance of the new tricycle.
10. The Time Until Top Speed is how long it takes Savannah to reach the highest speed, she can make the tricycle go.

4.0 Concept Design

Now that our objectives have been established, we now approach the task of ideation and concept design. Through many activities of ideation and filtering of these ideas, we aim to develop more concrete design concepts, followed by a final preferred design concept. The ideation stage began with brainstorming and led to activities that not only filtered out the ideas that were not applicable, but also combined them with other ideas and aspects that would show how they worked as a cohesive unit. With the findings from these activities, our goal is to come up with a safe and effective design that is also feasible.

4.1 Concept Generation

With initial research completed and the scope of the project defined, we were ready to begin the ideation process. The process began with a functional decomposition exercise to generate ample ideas. Functional decomposition is a method in which the overall system is broken down into three or four subsystems to reveal the basic functions that are necessary to achieve the overall goal, which in our case is to exercise Savannah. Figure 4 demonstrates the basis for the functional decomposition method. The chart begins at the top with the overall goal of this project and is further broken down with how we plan on achieving the goal as you move down the chart. Moving up the chart explains the reason as to why we are executing the certain action. For instance, one of the branches read: Steer tricycle, turn wheels, apply force. The "apply force" subsection explains how we plan on turning the wheels, while the "turn wheels" subsections explains why we want to apply a force.

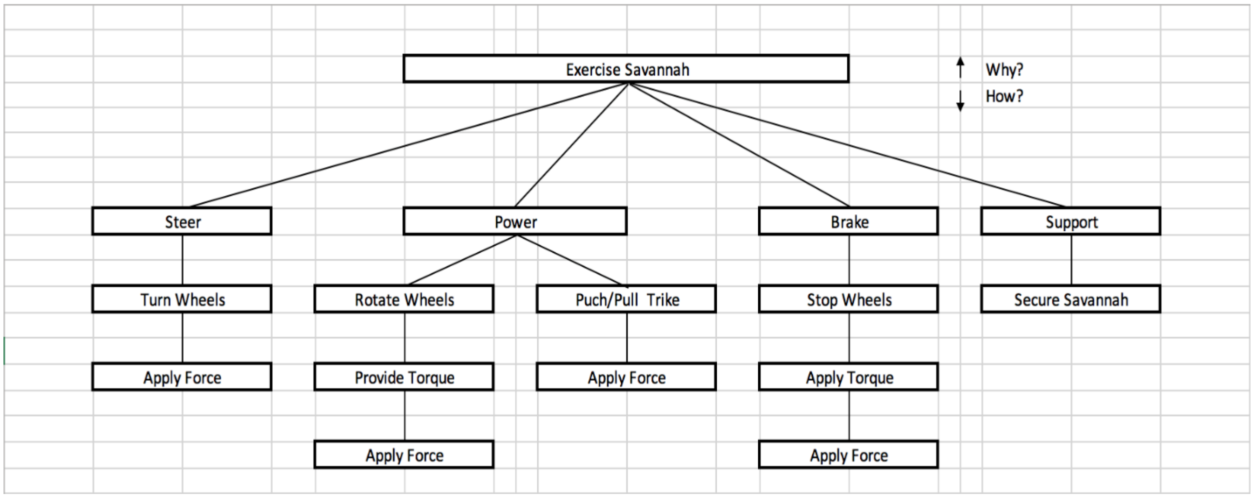


Figure 4. Functional Decomposition Chart.

When making this chart, our group determined four main subsystems: powering, steering, braking, and seating. Once we would reach the most basic task for executing each subsystem we would then begin to produce as many ideas as possible. This resulted in around 20-30 ideas for each of the subsystems. This process encouraged our team to think outside of the box rather than restraining ourselves to our initial solutions, with an emphasis on eliminating the team's personal bias toward any given design when brainstorming ideas. A list of the ideas produced from this method are included in Appendix C, which also includes the Pugh Matrices from our idea selection process. Once the brainstorming phase was over, the top five ideas for each subsystem were chosen by the group by determining the more feasible ideas which were further analyzed through idea selection techniques.

4.2 Idea Selection

With the top five ideas for each subsystem, we constructed four Pugh Matrices, which are meant to compare each idea with the existing design to reveal all strengths and weaknesses of each aspect of the tricycle; the aspects we included are Braking, Steering, Powering, and Supporting. Following the creation of the Pugh Matrices, we tabulated the top three ideas of each matrix in a morphological table. The morphological table allowed us to create combinations from the varying ideas of each function to create five different tricycle design concepts. The list of combinations created by the morphological table are listed in Appendix D. Figure 5 displays the first of these concepts, a design that incorporates a leaning back mechanism for braking, lifting or pushing a bar for steering, using a bar for powering, and including a seatbelt for support.

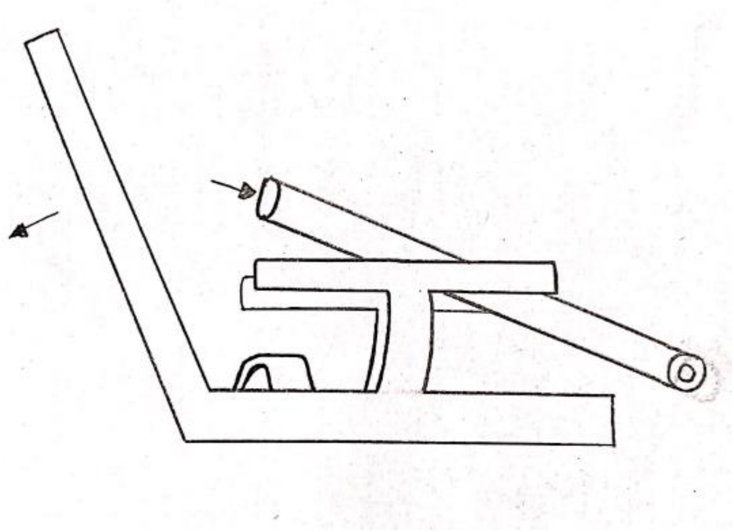


Figure 5. Concept 1 drawing.

The drawing for the first concept illustrates a leaning back motion in order to provide braking for the tricycle. The seatbelt is presented as a means of securing Savannah to the seat. Meanwhile, the bars acting as the arms of the seat that can be used to steer the tricycle. This steering mechanism performs a similar function to that of the lean to steer mechanism in the sense that Savannah will be leaning to the left or to the right to steer the tricycle. However, moveable armbars could be simpler to implement onto an existing tricycle rather than modifying a chair to move backwards, forwards, and sideways. The lean to steer mechanism is demonstrated in Figure 6, which is a drawing of the third concept. Concept 3 includes a hand pedal for braking, a lean to steer seat, a rowing machine mechanism for powering, and a seatbelt to secure Savannah.

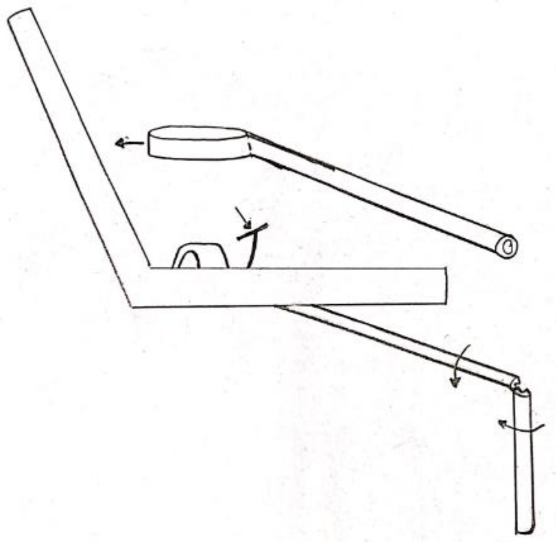


Figure 6. Concept 3 drawing.

The lean to steer mechanism in the drawing for concept 3 is demonstrated by the two linkages attached beneath the seat. The leaning motion of the seat will be translated from the upper bar to the vertical bar through the use of bevel gears. The bevel gears will be able to transfer the rotation caused by the leaning of the seat into rotation of the vertical bar, which can be used to turn the wheels of the tricycle to the left or to the right. The hand pedal illustrated on the side of the seat represents the braking mechanism for the tricycle, where Savannah would need to push or rest her arm on a pedal to initiate braking. This method of braking will need to take into consideration the minimal amount of force that Savannah could apply to the pedal using her arms. As for powering, Savannah's waist would be strapped to a rod which can be pulled by Savannah in a manner similar to that of a rowing machine in order to power the wheels. Finally, the seat belt is also used in this design to secure Savannah to the seat. Figure 7 demonstrates the design for concept 4, which includes a hand pedal for braking, lifting or pushing a bar for steering, a rowing machine mechanism for powering, and straps to secure Savannah.

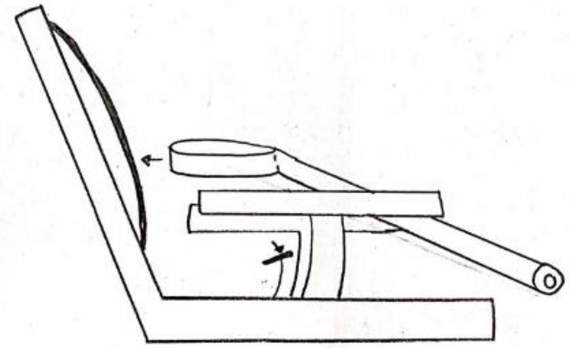


Figure 7. Concept 4 drawing.

Concept 4 features a mixture of some of the mechanisms seen in concept 1 and concept 3 except with the introduction of seat straps to secure the rider. The seat itself is no longer used to power, steer, or brake the tricycle, meaning that this design would feature minimal alterations to the seat, a design choice that could be favorable. Including the hand pedal for concept 4 introduces the same concern as for the hand pedal in concept 3. Furthermore, despite the minimal changes to the seat, the addition of multiple, separate components could lead to a problem in keeping all the extra mechanisms from interfering with each other or from coming into contact with Savannah while being operated.

As for concepts 2 and 5, the combinations for these two proved to be difficult to illustrate, which served as an indication to us that perhaps the overall concepts themselves would not be feasible to create if a simple drawing was too difficult to demonstrate. While these two concepts include similar methods of steering and powering compared to the other three concepts, such as the lean to steer and push bar mechanism, it was the frontal pad brake mechanism that proves to be difficult to incorporate in both concept 2 and concept 5. The front pad brake is meant to be a flat plate that Savannah would be able to lean forward into to apply a braking force, similar to that of the hand pedal, except this pad would be activated with Savannah's chest rather than her arms. Due to the disagreement of the subsystems, this was considered when comparing the five concepts to one another.

These concepts were compared by means of a Weighted Decision Matrix (WDM). A WDM is meant to take our design concepts and see how well each of them satisfy an area of need as previously mentioned in the QFD House of Quality. The WDM results revealed that design 3 was the best fit design for us, given that it best satisfied our necessary criteria. We then compared the results of the WDM with what our team felt would be the best design and found that the matrix resulted in physically implausible combinations of mechanical components.

While we have determined separate functionalities of the tricycle that best suit Savannah's physical capabilities and have a theoretical concept of the overall design which can incorporate all four functionalities that we aim to include into a single tricycle, we have yet to create a complete concept model which contains all of the functions. Size limitations of the tricycle have prevented complete implementation of the concept functions, which we plan to resolve within the coming weeks. However, each function can be separately described in terms of functionality. As a result, we settled on our general design to be a lean-to-steer, pushing a ratcheting bar to power, push pedal to brake, and a seat (seatbelt with arm bars).

We made the decision to disregard the WDM results and move forward with this new idea because after taking a closer look at the current tricycle and how it functions we realized that the combinations of some of these design concepts were quite impossible to create. For example, one of the concepts was implementing both a front brake pad as well as a ratcheting bar to power. These two components would obviously take up the same space, so there was no reason to consider some of these ideas from our ideation process. But, with that, we decided on the concept stated at the end of the previous paragraph because that takes not only function into account, but spatial attributes as well, making it the most desired design concept.

4.3 Concept Description and Justification

With each subsystem defined, we then moved on to developing clear models to demonstrate how each mechanism will satisfy the needs of Savannah. It is also important to identify how each mechanism is tailor-made specifically for her needs and why the logistics behind each mechanism is achievable and functional. The following concepts for each subsystem will provide the basis for our design moving forward.

The steering device will utilize a gearing ratio that will ultimately result in the desired reaction of the tricycle's front wheel in response to Savannah's leaning to the left or right on her seat. The leaning motion will twist the steering axle therefore manipulating the set of bevel gears interlocked at a 90-degree angle which will then actuate the front wheel. Figure 8 depicts a computer-aided drafting (CAD) model that demonstrates how a twisting motion of the seat will achieve the desired result. The vertical member represents the pre-existing steering column of the tricycle, which will be press fitted with a bevel gear to minimize the amount of new parts and materials we will need to add to the steering system. Since Savannah cannot control most existing steering mechanisms due to her limited use her arms and upper body strength, this solution will allow her to use her core strength to steer as a viable alternative.

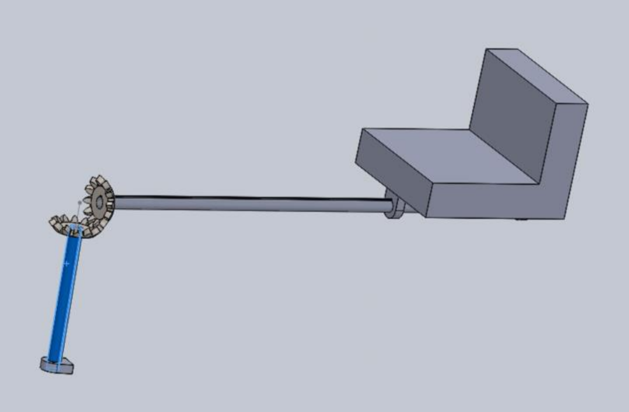


Figure 8. Conceptual CAD model of steering system.

For the power transmission system, we considered a padded, rigid bar that Savannah can push on with her upper body. This applied axial force would in turn drive two ratcheting gears, which are directly attached to the rear wheels, on each side of the tricycle to transfer the axial force into the desired rotational motion of the rear wheels. In other words, this mechanism would allow Savannah to operate the tricycle much like a wheelchair. The only difference is that the push bar would translate the force into a rotational motion instead of directly pushing the wheels. Figure 9 shows a basic solid model of the setup of the system. The crossbar of the model is what would be padded so that Savannah can push into it with her upper body, and the orange gears would be attached to the drive train to turn the rear wheels. This design is intended to utilize Savannah's abdominal strength since she has demonstrated to us that this is her strongest muscle group. The implementation of the push bar mechanism will be the function by which Savannah will be able to power the tricycle, although the transmission of her pushing motion to the wheels has been modified in the final design upon further force analysis.

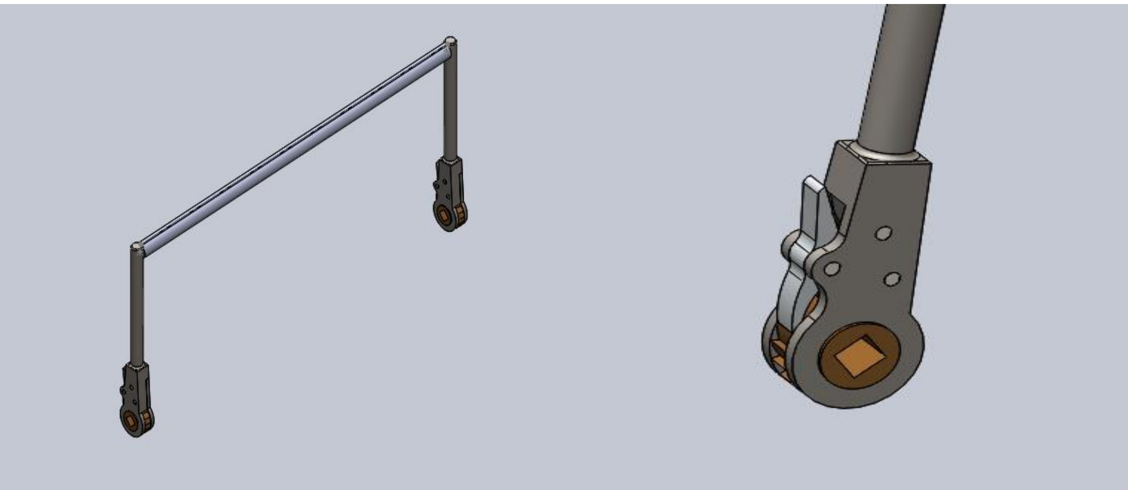


Figure 9. Rigid push bar CAD model used to translate axial force into torque.

Our solution to the tricycle's braking system initially utilized a standard coaster brake, illustrated in Figure 10. The only alteration that we would make is, instead of turning foot pedals backwards to engage the brake (which is the way standard bikes use coaster brakes) the brake would be modified to activate when Savannah leans backwards. An initial iteration for this concept included pushing back on her seat rest to activate two coaster brakes but this was not implemented due to the spacing of tricycle components and the lack of seat back support as a result. This allows her torso to be the source of steering, powering and braking for the tricycle without overcomplicating the user interface for operation. This, along with a simple harness for Savannah to assist in her pulling the bar back to her original position after each push, will constitute the essential design changes that will be made to allow her to control the tricycle entirely on her own. After more analysis, we found that the coaster brake would be impossible to use on the tricycle due to the severe lack of allowable rotational motion between powering and braking the tricycle. The coaster brake does not allow the rider to return to their original position and power from that position, due to the worm gear within the coaster brake having to move past its original position to begin powering after braking has been performed. We plan to implement cable brakes in our final design rather than the original coaster brakes since we can continue using backwards leaning motion to engage the brake. Using a cable brake allows the leaning back to directly implement a brake force on the tricycle, with no constrictions of allowable rotating motion that were present with the coaster brake design.

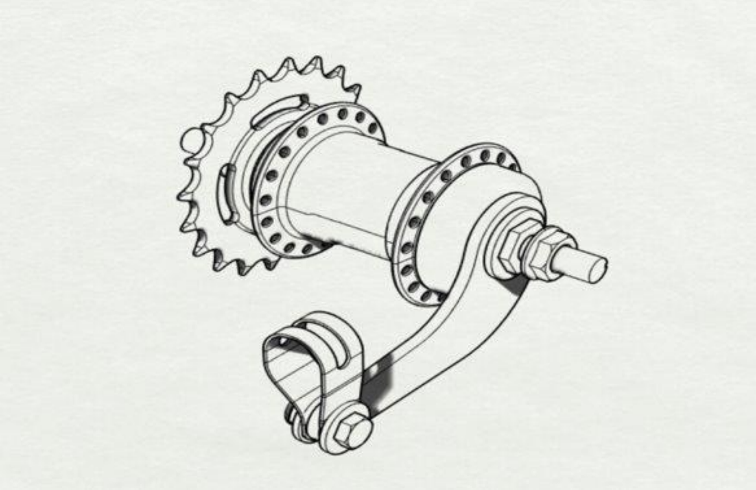


Figure 10. 3D drawing of a typical coaster brake.

Since the current tricycle has a complex steering and driving system located completely in the front of the vehicle and will not be used in the final design, major modifications must be made to the tricycle if our subsystem designs are to be implemented. Since this is the case, we have also researched other tricycles that are cheaper and more readily modifiable in case we determine that the magnitude of the changes we would apply would be too great to justify performing on the current tricycle. Potential modifications to a tricycle include, but are not limited to, cutting off the steering column to make room to implement the lean-to-steer mechanism, welding support shafts to the original frame of the tricycle to hold the steering column and drivetrain, and drilling into the frame of the tricycle to bolt or pin drivetrain components to the tricycle.

4.4 Preliminary Analysis/Tests and Challenges

When inspecting and analyzing the force needed to power the tricycle, it was important to focus on gear ratios with respect to the radii of the gears and/or lever arms, (the gear radii can be measured/manufactured on the adapted tricycle, and the lever arm comes from the to-be-installed power bar, as previously mentioned). To do this, one team member used estimations for weight and the coefficient of static friction in order to find the necessary output force for movement. With this value, a graph was made to demonstrate the necessary ratio of gear and lever arm radii, and an input force that is needed based on changing that ratio. With the installation of the power bar, it will be easier to find both a feasible gear ratio and a necessary force input needed from Savannah. The calculations for force input/output and the graph demonstrating their relationship with the gear ratio can be found in Appendix E.

Steering analysis was fundamentally different than the analysis done to determine the necessary force inputs for the powering system. The focus for steering was aimed toward the tilt angle necessary to effectively turn the front wheel through the steering column. While analysis has not been done to determine tipping point of the seat based on Savannah's weight and core strength limits, a conservative tilt angle of 15 degrees to the left or right is used as a system parameter and a wheel turn angle of 45 degrees to the left or right will be used as the desired wheel turning capabilities. These parameters were determined by riding a bicycle and testing the maximum comfortable leaning angle and turn angle while cruising on a flat paved road at an approximate speed of 10 mph. Similarly, to the powering analysis, a gear ratio of 3:1 will be implemented between the bevel gears to ensure that the limits of tilt and turn angles match, as Appendix F details. Further analysis will be necessary to ensure that Savannah will be able to consistently tilt the seat without overexerting herself or tipping. A potential solution considered to prevent Savannah from leaning too far and falling out of her seat when steering was to add a bar attached to the rigid support shaft parallel to the steering shaft that the seat sits on. By positioning this bar such that it contacts the seat and rigidly supports the seat at the maximum leaning angle to both the left and right side, the rider will be unable to exceed the determined maximum angle and can hold the maximum lean angle more easily without overexerting their core.

Additionally, we took account of the forces necessary to bring the tricycle to a complete stop within the predetermined distance of 1.5 ft. Estimations were made in the calculation of these forces, such as the combined weight of the tricycle and Savannah and a riding speed of 10 mph. The calculation of the braking force necessary to bring the tricycle to a stop was done by calculating the force required to produce the work energy that would bring the kinetic energy of the tricycle to zero, as Appendix G demonstrates in the first half of the calculations. Further testing will be required to determine if Savannah can apply the necessary force to apply the brakes with her leaning back movement. Given demonstrations of Savannah's core strength, we believe she will be able to provide the minimum force, although with the braking mechanism being a large safety concern, physical strength tests with Savannah had to be conducted. Based on these tests, it was determined that Savannah's core strength is more than sufficient to brake the tricycle effectively.

With all these designs and design considerations, there are risks, challenges, and variables that come along with them. We have attached a Design Hazard Checklist (Appendix H) that lists common design hazards and possible dangers when creating a mechanical design. In the checklist, we realized that the main dangers that our design presents are things like high acceleration and deceleration, large moving masses, falling hazard, the possibility of misuse, and the need for a stop button.

When dissecting these design hazards, we thought about the easiest ways to negate or solve these potential hazards with devices or tools that would work cohesively with our overall design. To solve the hazards of high acceleration and deceleration and large moving masses, we found that strapping the user into the tricycle would greatly reduce the chances of harm due to the change in speed of the masses. To prevent dangers of falling and potential misuse, we plan to teach Savannah how to properly operate the vehicle, hopefully negating these potential hazards. Regarding the need for an emergency stop, we plan to have an effective braking system that can bring the tricycle to a quick and safe stop.

As with most vehicles, these potential hazards are quite common. Due to the commonality of hazards, we found it to be a rather straightforward approach when analyzing solutions. The use of straps, proper teaching and instructions, and an efficient and safe braking system was the most effective and logical route when making our design as safe as possible. Our emphasis is on the proper training of Savannah for operation of the tricycle, which can be counterintuitive, especially when compared to traditional bicycle operation.

We plan to test our final design against the design specifications that we have previously determined in order to gauge how well our final product meets our end user's wants and needs compared to our desired results. While most of our specifications are pass/fail criteria to be judged by Savannah, such as seat design, ease of use and aesthetics, there are a few measurable specifications that will need to be confirmed through analysis by the team. Top speed under a rider's control as well as braking distance will be analyzed by having a team member ride the tricycle on a flat road. The rider will attempt to accelerate up to the maximum speed they can achieve and then attempt to brake as quickly as the tricycle will allow upon reaching a pre-determined checkpoint. Top speed as well as time to top speed will be measured by a speedometer phone application attached to the rider which will begin recording upon the rider's start. The braking distance will be judged by another team member standing at the checkpoint with a measuring tape who will measure the distance from the checkpoint to the stopped tricycle parallel to the tricycle's driving path. Weight and dimensions will be measured using a scale and a measuring tape. The final test of time to access will be performed by Savannah while a team member times the duration of her exiting her scooter and entering the tricycle. As of now, we have determined no need for preliminary calculations to fulfill any of the design specifications we have set in place.

5.0 Final Design

Following additional analysis and parts research, our group has finalized a design plan that outlines the steps necessary to adapt the tricycle. Major design changes made since the concept ideation phase of the project will be outlined in the following sections of the report. Additionally, this section includes the dimensions and materials of parts that we will incorporate into the final design of the adapted tricycle. All the decisions that we have made are based on engineering principles and analysis that proves that our finalized design will satisfy our design specifications, including force analyses, geometric relationships, and material mechanics.

5.1 Design Description

As previously mentioned, the tricycle's design is comprised of three subsystems: the powering, braking, and steering subsystems. Each subsystem was first analyzed separately to determine ideal functionality before being implemented within the entire tricycle design.

Powering

The powering subsystem consists of the power bar (which is directly harnessed to Savannah), two crank arms that are each connected to one side of the power bar on one end and to one of the two crank sprockets on the other, the free driving sprockets on the rear wheels, and the two chains connecting the drive sprockets to the rear sprockets. This layout is shown in Figure 11.

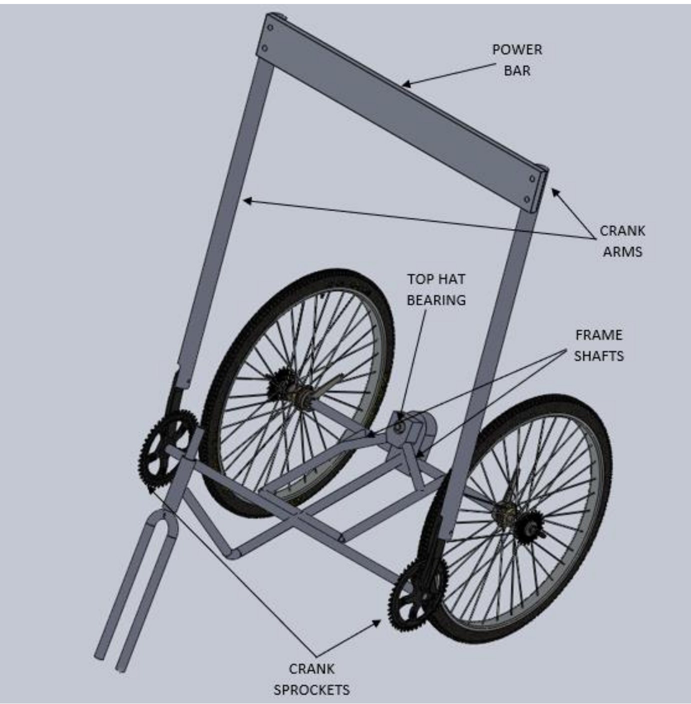


Figure 11. CAD model focusing on powering subsystem.

Braking

The braking system is integrated within the powering mechanism since both subsystems utilize the power bar interface in order to operate. The only difference in how they are activated is the direction in which Savannah pushes – forwards or backwards. The braking subsystem itself uses a cable and caliper brake system from a standard bicycle as shown in Figure 12. The cable will be attached directly to the front of the power bar so that when Savannah pulls back on the power bar the cable will tension and thus activate the brake pads on the rim of the front wheel. When Savannah pushes forward to power the tricycle, the brake cable is not tensioned and therefore will not influence the tricycle's operation. This solution allows our team to keep the desired activating motion from Savannah without interfering with the powering mechanism of the tricycle like the coaster brake design did.

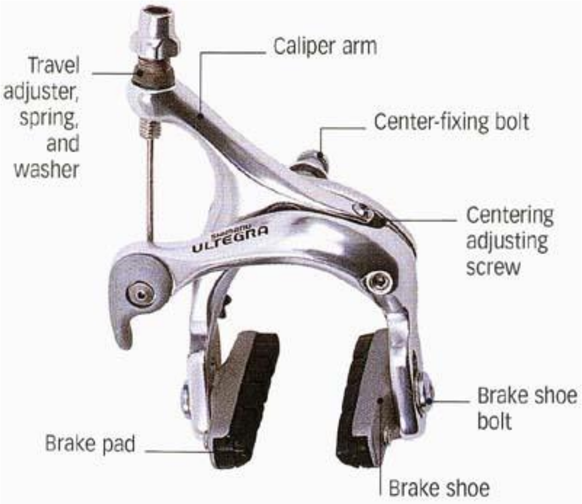


Figure 12. Bike Caliper Brakes

Steering

The steering subsystem consists of the tricycle seat from the given original tricycle, a rotating shaft, bevel gears, a top hat bearing, and supporting structural members. The rotating shaft will be clamped directly to the seat so that the steering shaft will rotate as the seat leans with Savannah's body. The steering shaft is supported by a rigid 'T'-shaft (the support shaft) that is welded to the frame and will rotate within the top part of the support member which will have sleeve bearings press fitted inside so that the steering shaft is free to rotate. At the rear of the vehicle, two support members that are welded onto the frame house a top hat bearing that will fit inside of the steering shaft with a clearance of .008" so that the steering shaft will be supported and allowed to rotate freely with minimal vibrations due to the small clearance fit, as shown in Figure 13. The front wheel steering will be controlled by two bevel gears that will translate the seat's leaning motion into the actuation of the front wheel. In other words, as Savannah leans to the left the front wheel will turn the bike to the left accordingly. The bevel gears have been selected to have a 3:1 ratio in order to translate a 15 degree lean in the seat into a 45 degree front wheel actuation. In order to set a maximum range that the seat can lean, we plan to use the current tricycle's existing design which is a spring that connects the tricycle's front wheel to the frame which provides elasticity to the steering. These components will be either fastened together with screws or welded together; this will be addressed in the manufacturing plan section later in the document.

Figure 13. Close-up of top hat bearing (left) and steering shaft (right)

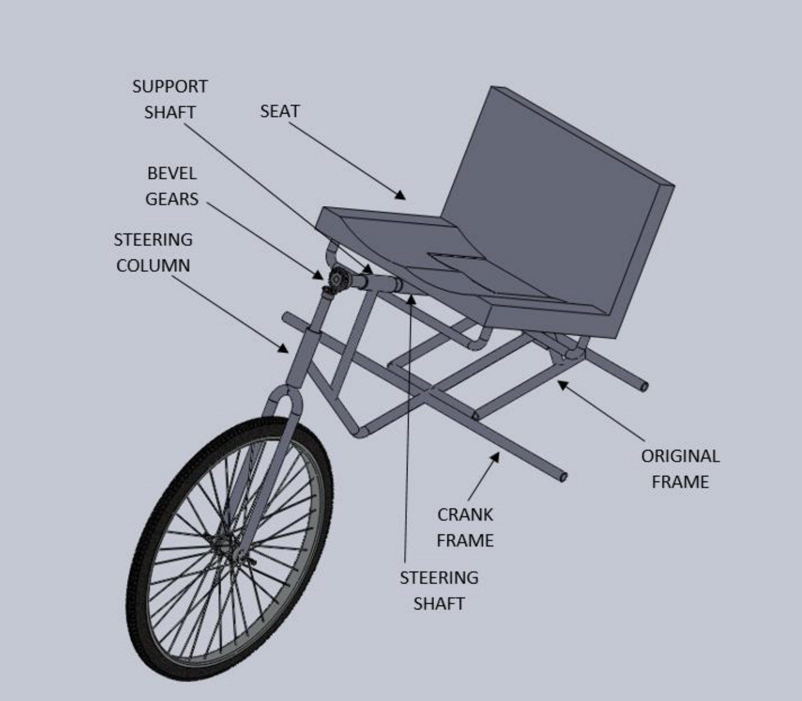


Figure 14. CAD model focusing on steering system and its associated frame components.

We went through a Failure Modes and Effects Analysis, located in Appendix K to inspect various potential failures ranging from the tricycle braking, to the seat being uncomfortable for Savannah, and assigned numbers from 1-10 (1 being the least important, 10 being the most important) for the following categories: severity (how detrimental it is), occurrence (how often it may occur), and detection (how difficult it would be to detect). We multiplied these factors together to come up with an overall score for the priority of the possible failure.

A score of 100 typically warrants a need for improvement of the aspect; none of our scores came out to above 100, so it is safe to say that we do not need to create action plans to lower the priority of failure aspect. Our highest score, though, was for the possibility of the welds breaking. We plan on outsourcing the welding on the tricycle to a Cal Poly Mustang 60 Shop Technician to ensure that the welds are much safer than if one of our team members were to do it. The tricycle is to be inspected before each ride to detect possible failures before they occur. We hope to adapt the tricycle in a way that limits the overall failure possibilities and ensures the safety of Savannah, as well. Regarding maintenance, though, if a weld or fastener breaks, the best method of repair would be to make another weld in place of the original or replace the fastener that broke.

5.2 Design Justification

The final design decisions came from engineering calculations, tests, and geometric limitations of the tricycle. In particular, the configuration of the Invacare Tricycle^{TM} determined the sizing and location of the crank arm, sprockets, and bevel gears. We sized the crank arm to be at a comfortable chest height for Savannah which we measured directly on Savannah. The diameters of the crank arm members were determined by a stress analysis shown in Appendix F**.** The force input to the center of the rectangular pad was determined by a test set up to estimate Savannah's core strength. In this assessment, we asked Savannah to pull on various weights using her core strength, where she demonstrated her ability to pull approximately 60 pounds using her core. Meanwhile, our team performed an additional test that determined the maximum forward lean angle that would be most comfortable for her. This test drove our decision to size the drive and free sprockets with a 3 to 1 ratio to get the most rotation in the wheels from as little leaning as possible while keeping the size of the sprockets reasonable. This analysis was supported using the equation found in Appendix E from a free body diagram analysis to determine whether the sprocket ratio would be enough to overcome static friction given Savannah's force input.

We also developed a simple structural prototype to verify that our powering design would work. To do this we sourced two different types of bicycles, one with a braking system that was separated from the drive train and another with a coaster brake (braking system is integrated into the drive train). The difference in the two designs revealed a flaw in our initial design. We learned that if a coaster brake is used, then the drive train cannot power the tricycle forward because the crank arms must rotate 360 degrees so that the coaster brake does not engage. However, with the other bike design, caliper brake installed separate from the drive train, the crank arm is free to operate in any range of angles without engaging the brake thus making it the ideal design for our application. In this case, Savannah would be free to ratchet the drive train with her torso free on constraint. As a result of this discovery, we decided to install a caliper brake on the front wheel that would be operated by a tensioned cable that would attach to the front of the push bar. This set up would allow Savannah to brake by pulling her torso back as originally intended.

As for the steering subsystem, the length of the steering shaft was determined according to the distance between the preexisting steering column and the rear end of the frame where the top hat bevel gear housing will be welded. The diameter of the shaft was determined through a shear-moment analysis, shown in Appendix F, where various shear forces and bending moments along the shaft were calculated. These calculations were then used to size the diameter of the shaft for a solid and hollow tube configuration. Ultimately, the hollow tube configuration proved to be the more cost-effective option. Previous analyses of the bevel gear ratios hold as the 3 to 1 ratio ensures a comfortable maximum leaning angle of 15 degrees for Savannah while the front wheel turns a maximum of 45 degrees.

Finally, the braking subsystem underwent the most noticeable change in our design since our PDR document. While the initial justifications verified the use of a coaster brake in our design, our structural prototype disapproved the usage of coaster brakes. Our structural prototype is meant to demonstrate the functionality of one or more components of our design. Initially, our prototype was meant to demonstrate the functionality of our crank arm subsystem, although we decided to construct a prototype that included wheels with a coaster brake hub. As we proceeded with testing the structural prototype, we noticed that as the crank arm would be turned back to engage the coaster brake hub, the arm itself was unable to return to its initial position and would have to be pushed farther forward each time the arm was pulled back. This discovery immediately invalidated the use of a coaster brake. Instead, after consulting bike technicians, we decided to include a cable and caliper brake. Since the current tricycle already contains a front wheel with a caliper brake, we simply need to attach a cable to the crank arm that connects to the caliper brake. Savannah would still be able to activate the braking mechanism with the same leaning back motion as she would have with the coaster brake design.

6.0 Manufacturing & Testing Plan

A detailed manufacturing plan can be found in Appendix L, and the Indented Bill of Materials (iBOM) can be found in Appendix M; these documents display what materials we purchased, where we purchased them, how we planned on implementing them together in our final design. In the iBOM, it is evident that we bought most our materials from McMaster-Carr because it has the widest variety of raw materials that were presented with data that we were able to conduct mechanical analysis with. Outside of using McMaster-Carr, we planned to buy the other materials at the "Bike Kitchen," a local shop that sells bike materials at a low cost.

After purchasing materials, we planned on outsourcing the welding on the frame to a Cal Poly Mustang 60 Shop Technician in order to maximize the structural integrity of the final design. Other than welding, we would have performed all machining operations on our own. All non-welded components would have been fastened together based on the calculated loads on each member. The attachment methods for each component are listed in Table 3. Using fasteners would have still allowed the load bearing on the lever arms and other components while minimizing the complexity of the manufacturing process. Components that must be attached are listed below along with the fastening method.

Table 3. Summary of fastening methods for component attachments.

Components	Fastening Method
Crank arms and power bar	1/4-20 Bolt (two locations)
Crank sprockets and crank arms	1/4-20 Bolt
New and old frame members	Weld (Low carbon steel)
Support shaft and frame	Weld (Low carbon steel)
Support shaft, bearings and steering shaft	Press fit
Bevel gears and steering shaft/column	Press fit
Seat and steering shaft	C-clamp

Most manufacturing processes that would have been performed other than assembling or welding components together are simple cuts on a cold saw. Much of the hollow tubing that we planned to purchase would have been cut to a length necessary to keep the tricycle steering system in line along the steering shaft. Fine trimming would have then been done to ensure precision in sizing components. The only other operation that would have been done is drilling clearance holes into the power bar and crank arms in order to bolt them together.

6.1 Assembly

Since there is a variety of fastening methods in place between tricycle components, priority is given to critical manufacturing assembly processes that have future processes reliant on them. For instance, the steering assembly requires bearings to be concentric with each other between the front and rear of the vehicle, so the components that are included in the steering assembly would have been fastened first, beginning with press fitting the bevel gears on the steering shaft and column, then press fitting bearings to the steering shaft, press fitting the support shaft to those bearings, and finally clamping the seat to the steering shaft via C-clamps, which are designed to reduce vibration during steering while maintaining a secure connection between the seat and steering shaft, such that they will rotate together. This then allowed the Shop Technician to weld any new frame components to the steering assembly, which in turn allowed us to make fine adjustments to the frame, including cutting the new front frame components to length in order for the steering column and steering shaft to line up properly before welding the new and old frame components together.

From there, the powering system would have been formed, beginning by welding the new crank frame members to the original frame, then press fitting bearings onto the crank frame and finally press fitting the crank sprockets onto the bearings. From there, the crank arms would have been bolted to the crank sprockets and bolted to the power bar, connecting the drive system. The chains would have likely been needed to be on the crank sprockets and wheel sprockets before press fitting the crank sprocket in order to properly tension the chain after assembly. Once the steering and drive systems were completely fastened, the braking system would have been implemented by attaching a caliper brake to the front wheel and running a brake cable from there to the powering bar by clamping it to the steering column and running it up to the powering assembly, where it would have been fastened to the top of one of the crank arms.

The execution of assembly should have taken place over the course of about 20 days. This time frame accounts for delays regarding the Shop Tech's free time as well as organizational hurdles and shipping delays with McMaster-Carr. The welding is minimal and was expected to be completed in one session for the Shop Tech, given that there were no weld defects or component meshing issues, such as improper weld location or misaligning parts after welding. The fasteners were to be installed by our team, which should take approximately one hour per subsystem. Most of the time between welding and fastening would be spent ensuring that components are properly fastened to each other through load testing and trimming parts if necessary to maintain concentricity along the steering system axis and ensure proper sizing of components relative to Savannah's body measurements. Chain and brake tensioning would also take place over multiple sessions, as it is an iterative process of tensioning and testing to optimize powering and braking performance.

6.2 Testing Expectations

We planned on testing performance aspects of the newly adapted tricycle, as opposed to testing smaller components of the tricycle. The specifications we planned to test are shown in Table 2. Anything from the time it took Savannah to enter and exit the tricycle, to the time it took Savannah to get to the top speed of the tricycle, to the top speed of the tricycle itself. This project was meant to focus on the usability of the tricycle for Savannah, so we planned on testing the aspects of the tricycle that are most closely related to Savannah's usability of the tricycle.

6.3 Manufacturing & Testing Recommendations

There are many things a team should look out for when dealing with the purchasing and manufacturing and testing of an adapted tricycle. Things like purchasing cost, manufacturing outsourcing cost, time taken to manufacture the tricycle, and proper testing procedures are some of the important aspects of these processes. When purchasing parts, it is important for a team to find a material supplier that has a wide range of options, like McMaster-Carr. We chose them as a supplier because they had reasonable pricing for the material, as well as a great deal of choices for sizing and material. Following this, it is important to find a manufacturer, such as a welder, (if the team chooses not to do the welding) and find one that falls within the proposed budget for the project. Along with these, considering the time it takes to manufacture the tricycle is very important, because manufacturing often takes a great deal more time than initially expected. Following these intermediate decisions, a team adapting a tricycle such as this should plan on testing the most important aspects of the tricycle and analyze how these test results factor into user experience.

7.0 Design Verification Plan

There were a handful of specifications we kept in mind when ideating the adapted tricycle; these specifications are shown in Table 2. Following the creation of these specifications, we created a test plan to verify the specifications with the design, shown in Appendix J as the Design Verification Plan. We assigned an acceptance criterium to each specification, followed by an assigned team member that would test an individual criterium once the verification prototype is complete. This decision was made because a majority, if not all, specifications can only be tested when the final prototype is complete, and many of the specifications are dependent on Savannah's ability to use the tricycle. We will use this test plan to determine whether the specifications are met and the design is acceptable.

The specifications mentioned are as follows: top speed under Savannah's own control, ease of use, seat design, steering performance, time to access the seat, braking distance, weight, dimensions, aesthetics, time until top speed. These specifications account for both the needs and wants of Savannah, as she is the primary and/or sole user of the tricycle. Each test, whether it is measuring the time until the top speed, time to access, or braking distance, all require being in the presence of Savannah and being at a location where operation of the tricycle is acceptable, most likely a track and field location either at SLO High School or Cal Poly.

One of the most important numerical data tests is the time until top speed for the tricycle. We will measure how long it takes for Savannah to reach top speed, as well as how fast the top speed is. This will require a track, stopwatch, and a radar gun/speedometer. We will take the data for these values and perform data analysis consisting of uncertainty propagation to find accurate and true values for these tests to see if they are acceptable. Many of these specification test acceptances, though are numerically intensive, essentially rely on how Savannah chooses to accept them. The overall tricycle is being adapted for her, so her decision on whether each aspect of the tricycle is acceptable is of upmost importance.

8.0 New Project Scope and Results

Before our team completed the winter quarter of 2020, we detailed out plans to execute manufacturing and begin machining. Due to the closure of Cal Poly's campus, and therefore the machine shops, our team is unable to complete any further manufacturing. Therefore, this section of the document will describe the new deliverables of our project as well as our reasoning for the changes that we have made relative to the given situation. Ultimately, we have settled on a broadened problem statement for our group with the aim of providing access to the information that we developed throughout this school year to as many people as possible. Our hope is that our findings from this project can be adapted to any individual that has similar needs as Savannah regardless of his or her specific condition. We have settled on developing the information that we have learned in this project so that it will be beneficial to any individual with limited limb use which could include cerebral palsy, muscular dystrophy, and Parkinson's disorder.

As a result, we will aim to complete two last deliverables before the end of the school year. The first will be completing this document as a final design review (FDR) with all the details necessary for any third party to fabricate our design and adapt it for all types of limb limitations.

The second deliverable for our group will be a separate document that will serve as a concise source of information pertaining to how what we have learned can be applied to all torso operated tricycles. Our goal is to document our findings in a way that is easily interpreted by non-technical people.

8.1 Ideation for a New Deliverable (CHANGE TITLE OF SUBSECTION)

With a new scope set for the project, we proceeded to consider new approaches in presenting this project as a universal design. Over the span of multiple meetings with our project advisor there were several ideas considered in creating a supplemental deliverable for the project in place of a final prototype. One of the ideas considered was a step by step guide that would be posted to a website such as WikiHow or Instructables on how to modify any preexisting tricycle to become a core-powered exercised device. The idea behind this approach is to have an easily accessible guide for the public; however, since no one in the team had prior knowledge in creating instructional guides for those sorts of websites, we felt that more effort would be directed in the formatting of the guide rather than the content of the guide. As such, the group ultimately determined that our efforts would be made more efficient in a different approach.

The group proceeded with the idea of creating something similar to a step by step guide, although it was to be created as a separate document that could be uploaded to any easily accessible website. The newly created document utilizes the same concept of portraying a universal design of Savannah's adapted tricycle, except now the group can be more focused on the content of the guide rather than the formatting of the guide that would only apply to one particular website. In this way, we feel that the new document accomplishes our ultimate goal of portraying our design process in such a way that anyone could repeat this design with their own tricycle.

Ultimately, no major design changes or further analysis was performed in the creation of the universal design report. Additionally, due to the halt in manufacturing, no further design changes were necessary. Rather, the same methods used in the original design process for Savannah's tricycle were explained in the document to aid the reader in determining the necessary modifications to be made for the tricycle being built. Further explanation of the document in its entirety is covered in the following section.

8.2 Universal Design Report Deliverable

The universal design report acts as a separate document that does not directly reference the FDR, although it does include information mentioned in this report. Furthermore, the document will begin with a background section that includes information mentioned within the background section of this report. This is done to give readers the necessary information for the use of building an adapted tricycle. Next, the overview section of the report will describe an outline of the universal design report itself. The information included within this section provides a brief overview of the final design section within the FDR. With this information in mind for the reader, the building portion of the step by step guide begins. Potential material selection for the build is discussed, with the reader selecting material based on the analysis performed within the

FDR when designing Savannah’s tricycle. Finally, the report outlines the manufacturing and assembly of the varying subsystems, similar to that of the manufacturing process for Savannah’s tricycle. The primary difference is that the universal design report is modified in a way to accommodate for variations in manufacturing and assembly for other tricycles.

9.0 Project Management

The remainder of this project was meant to be focused on the building of the final design outlined in this report. Specifically, purchasing the necessary materials for the verification prototype will take immediate priority following the delivery of this report. We had received $750 in funding provided by the Baker-Koob Grant to help pay for the materials and had recently been approved $350 from the Cal Poly Mechanical Engineering Student Fee Allocation Committee (ME-SFAC) proposal. Our group was proactive in purchasing the materials to allow for ample build time for the remainder of the project. Fortunately, the parts being purchased for the structural prototype could be reused in the final prototype as our team sees fit.

With a finalized design and manufacturing plan, we moved forward in finally adapting the tricycle. Certain tests were still needed to be conducted by our team to ensure that the verification prototype will be safe for Savannah to use, and once Savannah’s safety had been ensured, we were to ask her to express her satisfaction with our prototype and its ease of use. The final prototype was meant to be presented in the Senior Project Expo towards the end of the 2020 spring quarter, where our tricycle was to be placed on display along with other senior projects for the public to view.

As previously mentioned, we were unable to get the manufacturing of the tricycle completed due to the pandemic. This also meant that we were unable to complete any testing on the tricycle as well as get any feedback from Savannah. Since no manufacturing was completed and no testing results were achieved, our group has instead changed our scope of the project and created a broader view of what needs to be done when adapting a tricycle. We aim to give background, direction, and recommendations to those who are looking to adapt a tricycle for someone in a similar situation as Savannah.

10.0 Conclusions & Recommendations

This document serves as a contract between our team and the sponsor over the end goals of this project. The information collected through research has led to an in-depth ideation process and later development of many design possibilities, of which have been narrowed down to one finalized design. The next step in the process was to begin assembling our verification prototype and test it against our specifications before assembling our final design, but due to unforeseen circumstances, manufacturing and testing of the final design prototype was unable to be completed.

Instead, we aim to assist any who wish to adapt their own tricycle in order to serve a similar purpose to that of ours. We went through many rounds of ideation that consisted of what we believed to be great methods of operation of completion for the tricycle, but we had realized that these methods were not achievable. Of these things were the implementation of the coaster brake; due to limited motion of the tricycle, a coaster brake would have been impossible to implement. With that, our group realized how difficult taking apart a tricycle and welding and fastening altered parts on to the tricycle truly is. We realized that manufacturing takes a great deal more time than anticipated, leading to a shortened timeline of operation for the completion of the design.

This document now serves as a guide to those who wish to adapt and edit an existing tricycle to meet the needs of someone that resembles the needs of Savannah. Through the trials and tribulations of our group’s process, we hope to give guidance to those with little to no manufacturing experience, like ourselves. Considering the hurdles that come with purchasing, manufacturing, and testing is imperative to the overall design implementation, and can lead to an extended process, but also can lead to a more efficient design in the end.

References

"Arthrogryposis Multiplex Congenita." *British Medical Journal (Clinical Research Edition)*, vol. 283, no. 6283, 1981, pp. 2–3. *JSTOR*, www.jstor.org/stable/29502700.

Bolton, Jasper et al. "Adaptive Adjustable Tricycle," *Cal Poly Senior Project*, 2018.

Borsotti, Alex, Sean Liston and Ryan Westermann. "Single Arm Recumbent Bicycle." *Cal Poly Senior Project*, 2018.

Invacare. "Invacare Top End Excelerator Handcycle." *Invacare Product Catalog - Invacare Top End Excelerator Handcycle*, invacare.com.

Rastoder, Eldar, et al. "Interview with Linda Wolff." 7 Oct. 2019.

Rastoder, Eldar, et al. "Interview with William Walters and Savannah." 14 Oct. 2019.
U.S. Government. "28 CFR § 36.311 - Mobility Devices." *Legal Information Institute*, Legal Information Institute, www.law.cornell.edu/cfr/text/28/36.311.

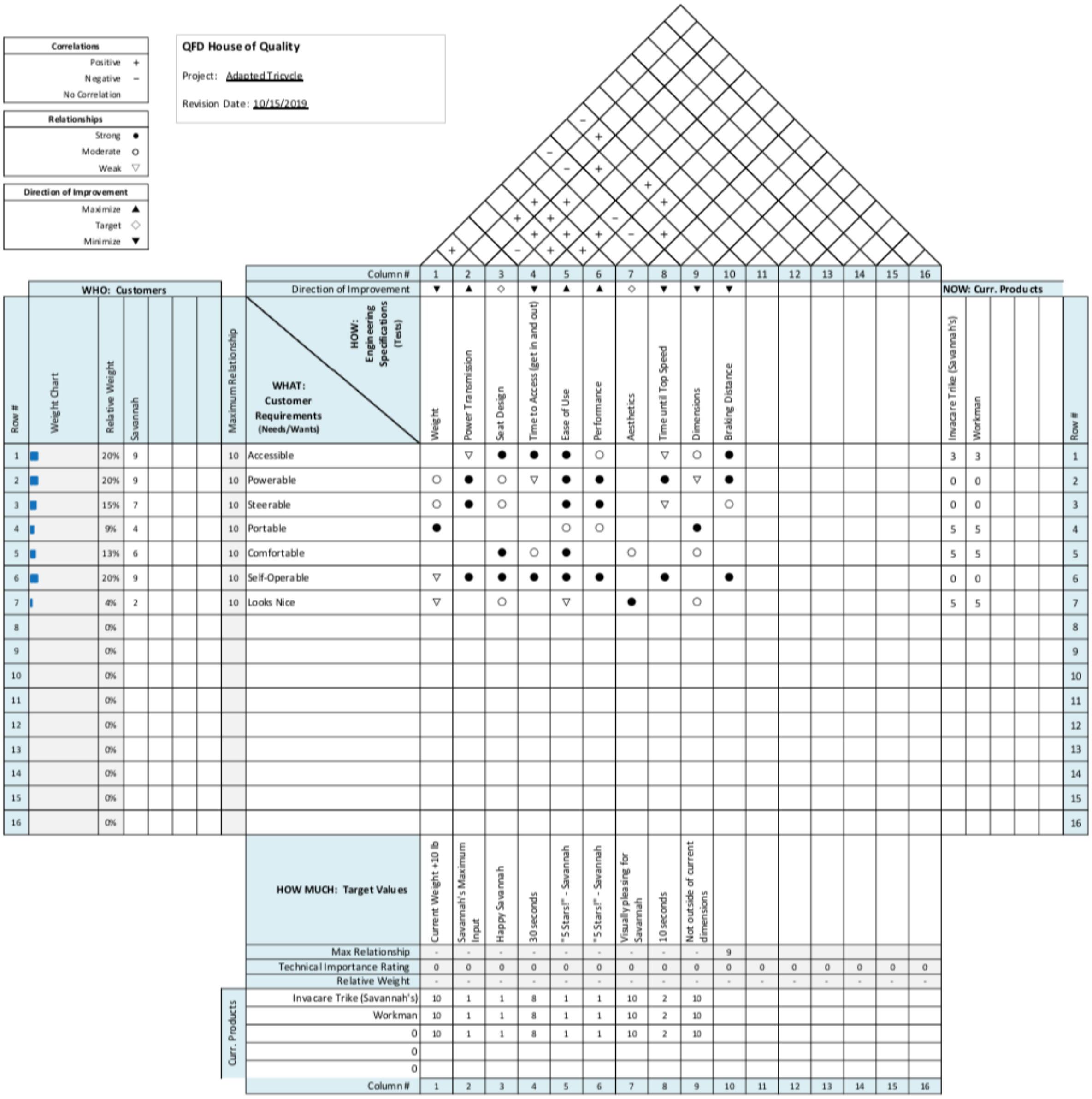
Wagner, Lisa V., et al. "Rehabilitation across the Lifespan for Individuals with Arthrogryposis." *American Journal of Medical Genetics Part C: Seminars in Medical Genetics*, vol. 181, no. 3, 2019, pp. 385–392., doi:10.1002/ajmg.c.31729.

Yanchulis, Dave. "United States Access Board." *About the ADA Standards*, www.access-board.gov/guidelines-and-standards/buildings-and-sites/about-the-ada-standards.

Appendix A – Patent List

1. Special needs adaptive tricycle. Turner, U.S. patent 20100331149A1. This patent presents an adaptive tricycle that is fitted with an extra wheel on the rear side of the tricycle. The steering mechanism of this tricycle could be a potential solution for the steering problem on the current tricycle.
2. Tricycle for handicapped individuals. Richard Vanore, U.S. patent 4152005A. This patent presents a tricycle that is very similar to the current Invacare tricycle. The tricycle utilizes power generated through turning the hand pedals, and this will provide more information on the current tricycle's configuration.
3. Resistance apparatus for exercise equipment. Wilkinson, et al. U.S. patent 5476431A. This patent presents an elastic apparatus that is used for exercise equipment to add resistance to workouts. This information could be useful in implementing an adjustable resistance system in our final product.
4. Human powered land vehicle. Stout, U.S. patent 4705284A. This patent presents a tricycle with a lowered seat in a "tadpole" configuration with two wheels in the front of the tricycle and on rear wheel. This configuration could be considered in our final design if a new tricycle is needed. Other information on a braking and steering mechanism is also provided.
5. Bed attached swivel socket crane lift assembly. Ramsey, U.S. patent 5918328A. This patent presents a device that helps maneuver people with disabilities in and out of bed using a back and forth mechanism on the back rest of the seat. This particular mechanism could be considered as a means of helping Savannah with back and forth sit-up movements, which are a mode of function being considered to use to power the tricycle.
6. Arm actuated brake lever for quadriplegic. Lofgren, et al. U.S. patent 20150210346A1. This patent presents a brake lever for an adapted tricycle that is activated through the movement of the hand or wrist. While Savannah does not possess much grip strength or wrist movement to operate this particular device, this device can be modified to better accommodate Savannah and her strengths.
7. Extendable handcycle pedal. Invacare Corp, U.S. patent 20030075002A1. This patent presents the hand cycle pedal currently used on Savannah's Invacare tricycle. The hand pedal can be further studied to understand how the hand pedal configuration works and provides motion to the wheels.

Appendix B – House of Quality



Correlations
Positive +
Negative –
No Correlation

Relationships
Strong ●
Moderate ○
Weak ▽

Direction of Improvement
Maximize ▲
Target ◇
Minimize ▼

QFD House of Quality

Project: Adapted Tricycle

Revision Date: 10/15/2019

	WHO: Customers																								NOW: Curr. Products					
								Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16						
								Direction of Improvement	▼	▲	◇	▼	▲	▲	◇	▼	▼	▼												
Row #	Weight Chart	Relative Weight	Savannah				Maximum Relationship	HOW: Engineering Specifications (Tests) WHAT: Customer Requirements (Needs/Wants)	Weight	Power Transmission	Seat Design	Time to Access (get in and out)	Ease of Use	Performance	Aesthetics	Time until Top Speed	Dimensions	Braking Distance							Invacare Trike (Savannah's)	Workman				Row #
1	▮	20%	9				10	Accessible		▽	●	●	●	○		▽	○	●							3	3				1
2	▮	20%	9				10	Powerable	○	●	○	▽	●	●		●	▽	●							0	0				2
3	▮	15%	7				10	Steerable	○	●	○		●	●		▽		○							0	0				3
4	▮	9%	4				10	Portable	●				○	○			●								5	5				4
5	▮	13%	6				10	Comfortable			●	○	●		○		○								5	5				5
6	▮	20%	9				10	Self-Operable	▽	●	●	●	●	●		●		●							0	0				6
7	▮	4%	2				10	Looks Nice	▽		○		▽		●		○								5	5				7
8		0%																												8
9		0%																												9
10		0%																												10
11		0%																												11
12		0%																												12
13		0%																												13
14		0%																												14
15		0%																												15
16		0%																												16

	HOW MUCH: Target Values	Current Weight +10 lb	Savannah's Maximum Input	Happy Savannah	30 seconds	"5 Stars!" - Savannah	"5 Stars!" - Savannah	Visually pleasing for Savannah	10 seconds	Not outside of current dimensions							
	Max Relationship	-	-	-	-	-	-	-	-	-	9						
	Technical Importance Rating	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Relative Weight	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Curr. Products	Invacare Trike (Savannah's)	10	1	1	8	1	1	10	2	10							
	Workman	10	1	1	8	1	1	10	2	10							
	0	10	1	1	8	1	1	10	2	10							
	0																
	0																
	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Appendix C – Decision Matrices

Function Ideas

Steering	Powering	Braking
Steering Wheel	Power Bar	Lean Back Brake
Lean To Steer	Controller	Rope Pull Brake
Twist To Steer	Rowing Machine	Side Hand Pedal
Rope Pull	Increasable Resistivity	
Controller	Twist Body	
Lift/Push Bar	Torsion Spring	
	Conveyer Belt	
	Tilt-Sensor	
	Ratchet	

Braking

	Hand Brake	Lean Back Brake	Rope Pull Brake	Side Hand Pedal	Front Pad Brake
Accessible	S	+	+	+	+
Comfortable	S	S	-	S	S
Self-Operable	S	+	+	+	+
Looks Nice	S	S	-	S	-
Positive Impact	S	+	+	+	+
Feasible	S	+	+	+	+
	DATUM				

Steering

	Steering Wheel	Twist To Steer	Lean To Steer	Lift/Push Bar	Controller
Accessible	S	+	+	S	+
Functional	S	+	+	+	+
Comfortable	S	-	-	S	+
Looks Nice	S	S	S	S	+
Feasible	S	-	-	-	-
	DATUM				

Powering

	Hand Pedals	Lean Forward	Rowing Machine	Power Bar	Seat Itself
Accessible	S	-	+	-	+
Powerable	S	+	+	+	+
Comfortable	S	S	-	S	+
Self-Operable	S	+	-	+	S
Looks Nice	S	S	S	S	+
Clearly Communicated	S	-	+	S	S
Feasible	S	S	S	S	-
	DATUM				

Support

	Seatbelt	Sliding Seat	Straps	Bucket Seat	Side Blocks
Accessible	S	-	S	S	-
Heavy	S	-	S	-	-
Comfortable	S	-	S	+	-
Safe	S	S	S	+	+
Feasible	S	S	S	+	+
	DATUM				

Appendix D – Morphological Table and Resulting Function Combinations

Morphological Table

	Braking	Steering	Supporting	Powering
I	Lean Back Brake	Lean To Steer	Seatbelt	Rowing Machine
II	Side Hand Pedal	Lift/Push Bar	Bucket Seat	Power Bar
III	Front Pad Brake	Twist To Steer	Straps	Lean Forward

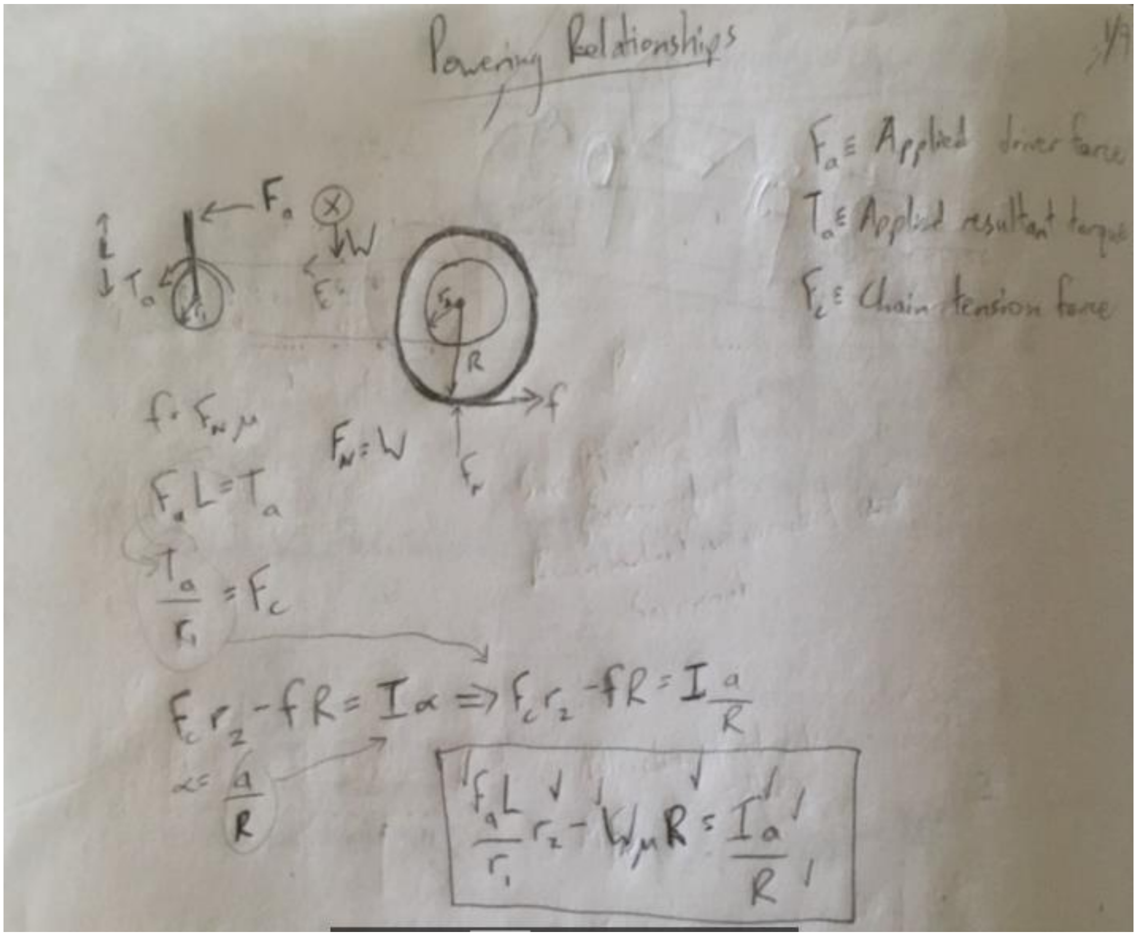
Combinations

	Braking	Steering	Supporting	Powering
#1	Lean Back (I)	Lift/Push Bar (II)	Seatbelt (I)	Power Bar (II)
#2	Front Pad Brake (II)	Lean To Steer (I)	Straps (III)	Power Bar (II)
#3	Side Hand Pedal (II)	Lean To Steer (I)	Seatbelt (I)	Rowing Machine (I)
#4	Side Hand Pedal (II)	Lift/Push Bar (II)	Straps (III)	Rowing Machine (I)
#5	Front Pad Brake (II)	Lean To Steer (I)	Seatbelt (I)	Power Bar (II)

Weighted Decision Matrix

		Options									
		1		2		3		4		5	
Criteria	Weighting	Score	Total	Score	Total	Score	Total	Score	Total	Score	Total
Weight	3	5	15	5	15	5	15	5	15	5	15
Power Transmission	4	7	28	7	28	8	32	8	32	7	28
Seat Design	4	8	36	9	36	8	32	9	36	8	32
Time to Access	4	5	20	5	20	5	20	5	20	5	20
Use Survey	5	-	-	-	-	-	-	-	-	-	-
Performance Survey	5	-	-	-	-	-	-	-	-	-	-
Aesthetics	2	7	8	4	8	7	14	7	14	4	8
Time to Top Speed	1	5	5	5	5	5	5	5	5	5	5
Dimensions	2	7	8	4	8	7	14	7	14	4	8
			120		120		132		136		116

Appendix E – Power Analysis



Powering Relationships

1/9

$F_a \equiv$ Applied driver force

$T_a \equiv$ Applied resultant torque

$F_c \equiv$ Chain tension force

$f = F_N \mu$

$F_N = W$

$F_a L = T_a$

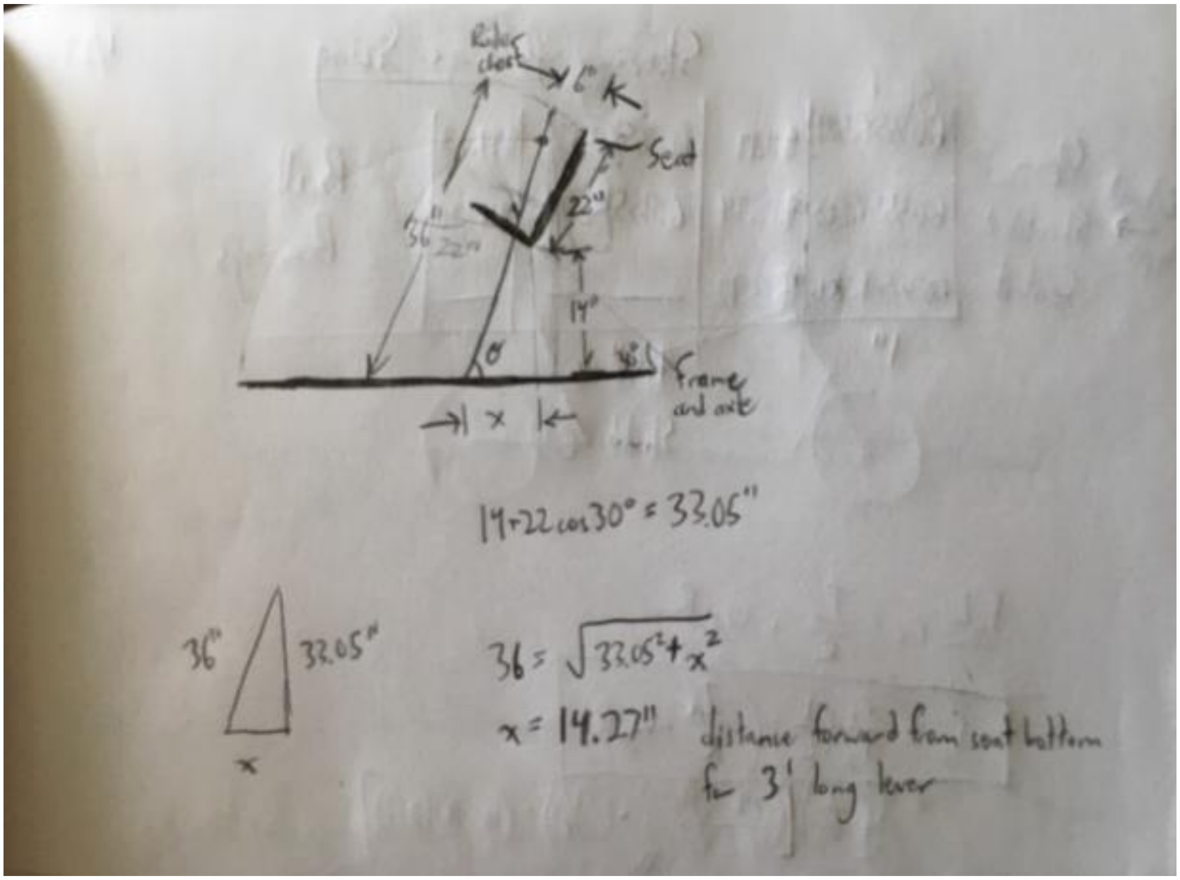
$\frac{T_a}{r_1} = F_c$

$F_c r_2 - fR = I\alpha \Rightarrow F_c r_2 - fR = I\frac{a}{R}$

$\alpha = \frac{a}{R}$

$$\boxed{\frac{F_a L}{r_1} r_2 - W \mu R = \frac{I a}{R}}$$

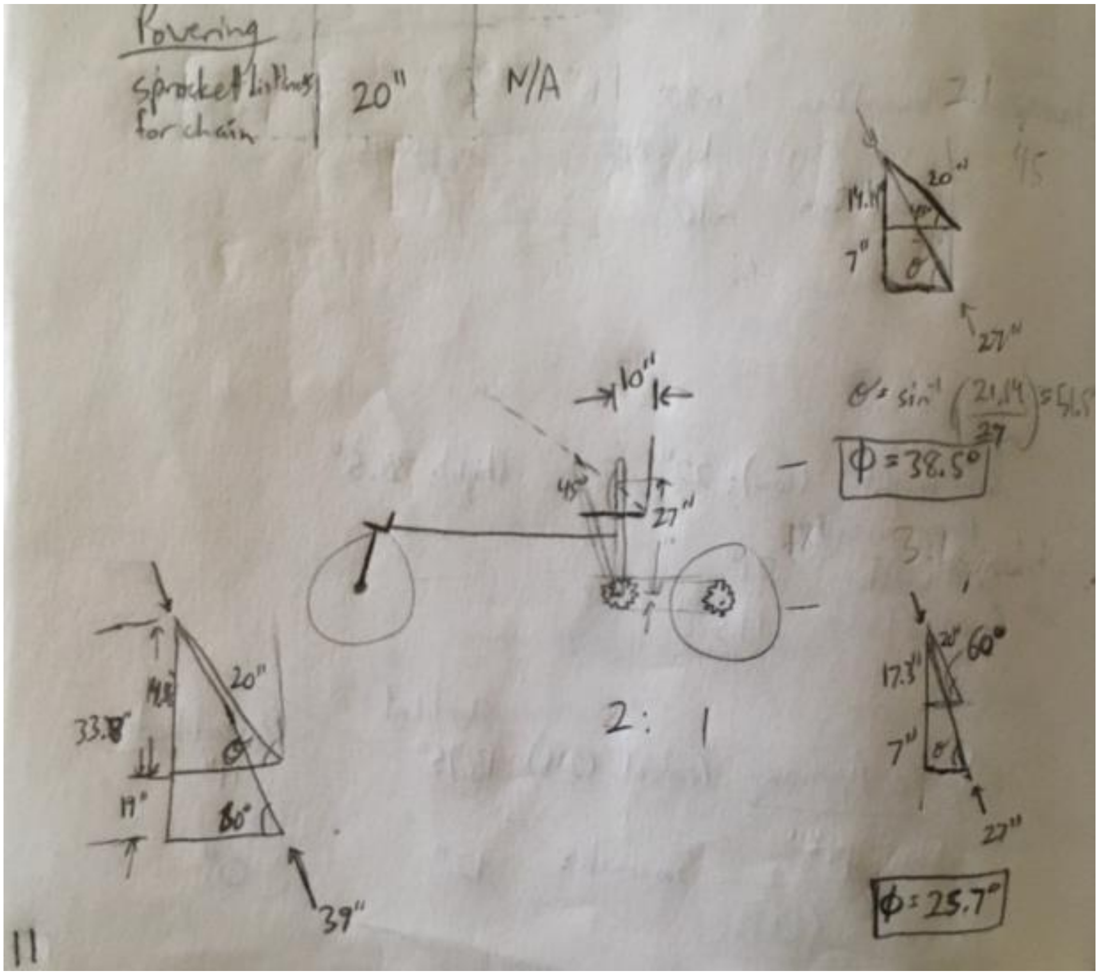
Appendix F – Component Sizing Calculations



$14 + 22\cos 30° = 33.05"$

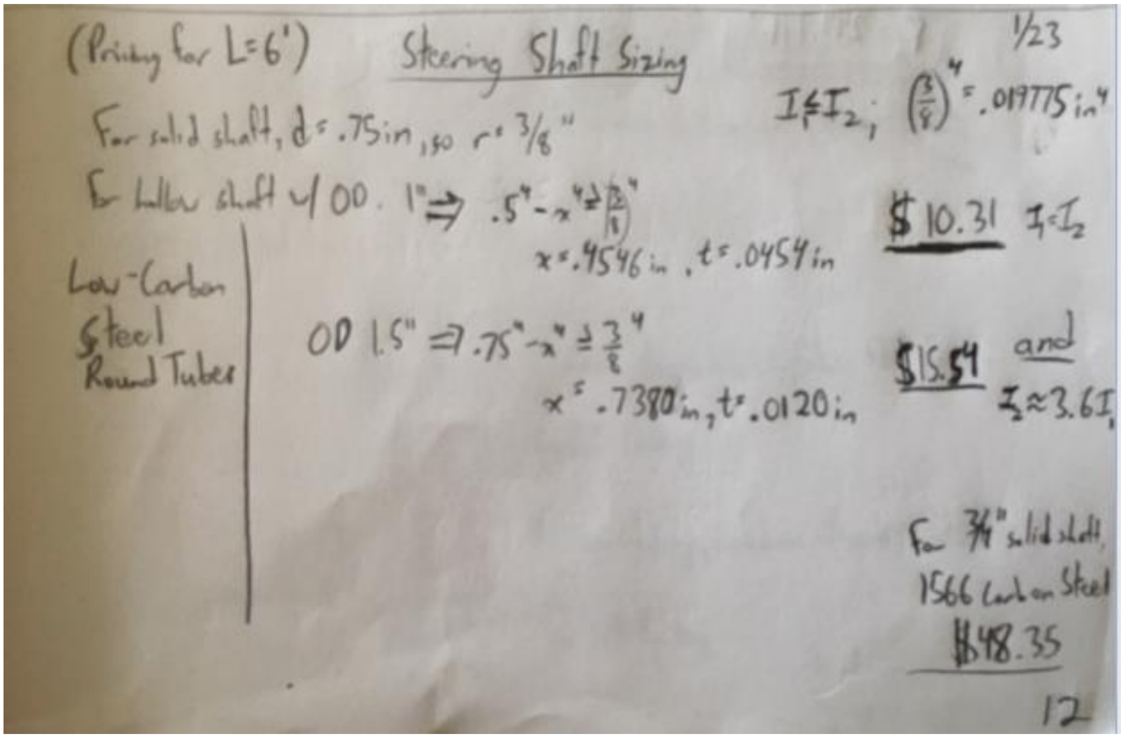
$36 = \sqrt{33.05^2 + x^2}$

$x = 14.27"$ distance forward from seat bottom for 3' long lever



Powering		
sprocket listings for chain	20"	N/A

11



(Pricing for L=6')

Steering Shaft Sizing

1/23

For solid shaft, d = .75in, so r = 3/8"

$I_1 \leq I_2$; $\left(\frac{3}{8}\right)^4 = .019775\,in^4$

For hollow shaft w/ OD. 1" ⇒ $.5^4 - x^4 \geq \left(\frac{3}{8}\right)^4$

$x = .4546\,in$, $t = .0454\,in$

$10.31 $I_1 = I_2$

Low-Carbon Steel Round Tubes

OD 1.5" ⇒ $.75^4 - x^4 \geq \frac{3}{8}^4$

$x = .7380\,in$, $t = .0120\,in$

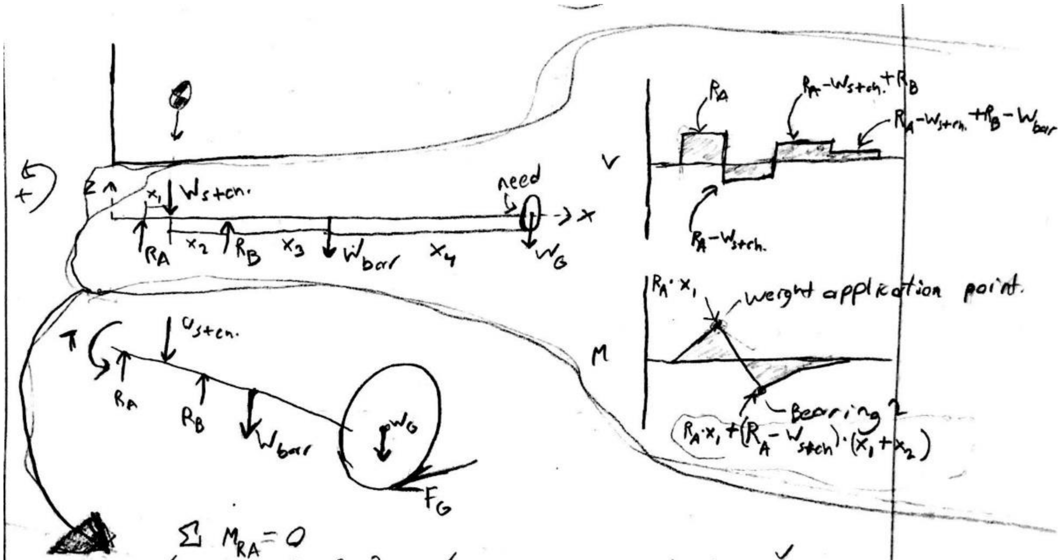
$15.54 and $I_2 \approx 3.6 I_1$

For 3/4" solid shaft, 1566 Carbon Steel

$48.35

12

SHEAR MOMENT ANALYSIS



$$\Sigma M_{RA} = 0$$

$$-\overset{\checkmark}{W_{s+ch.}} \cdot \overset{?}{x_1} + \overset{?}{R_B} \cdot (\overset{?}{x_1} + \overset{?}{x_2}) - \overset{\checkmark}{W_{bar}} \cdot (\overset{?}{x_1} + \underbrace{x_2}_{\checkmark} + x_3) - \overset{\checkmark}{W_G} (\overset{?}{x_1} + \overbrace{x_2 + x_3 + x_4}^{\checkmark}) = 0$$

$$R_B = \frac{W_{s+ch} x_1 + W_{bar} (x_1 + x_2 + x_3) + W_G (x_1 + x_2 + x_3 + x_4)}{x_1 + x_2}$$

$$\Sigma F_z = 0$$

$$R_A - W_{s+ch.} + R_B - W_{bar.} - W_G = 0$$

$$R_A = W_{s+ch} + W_{bar} + W_G - R_B$$

LEVER ARM ANALYSIS

DEFLECTION

$$\delta = \frac{PL^3}{3EI}$$

$\delta = 0.125 \text{ in}$

$P = 30 \text{ lb}$

$L = 36 \text{ in}$

$E = 10^7 \frac{\text{lb}}{\text{in}^2}$

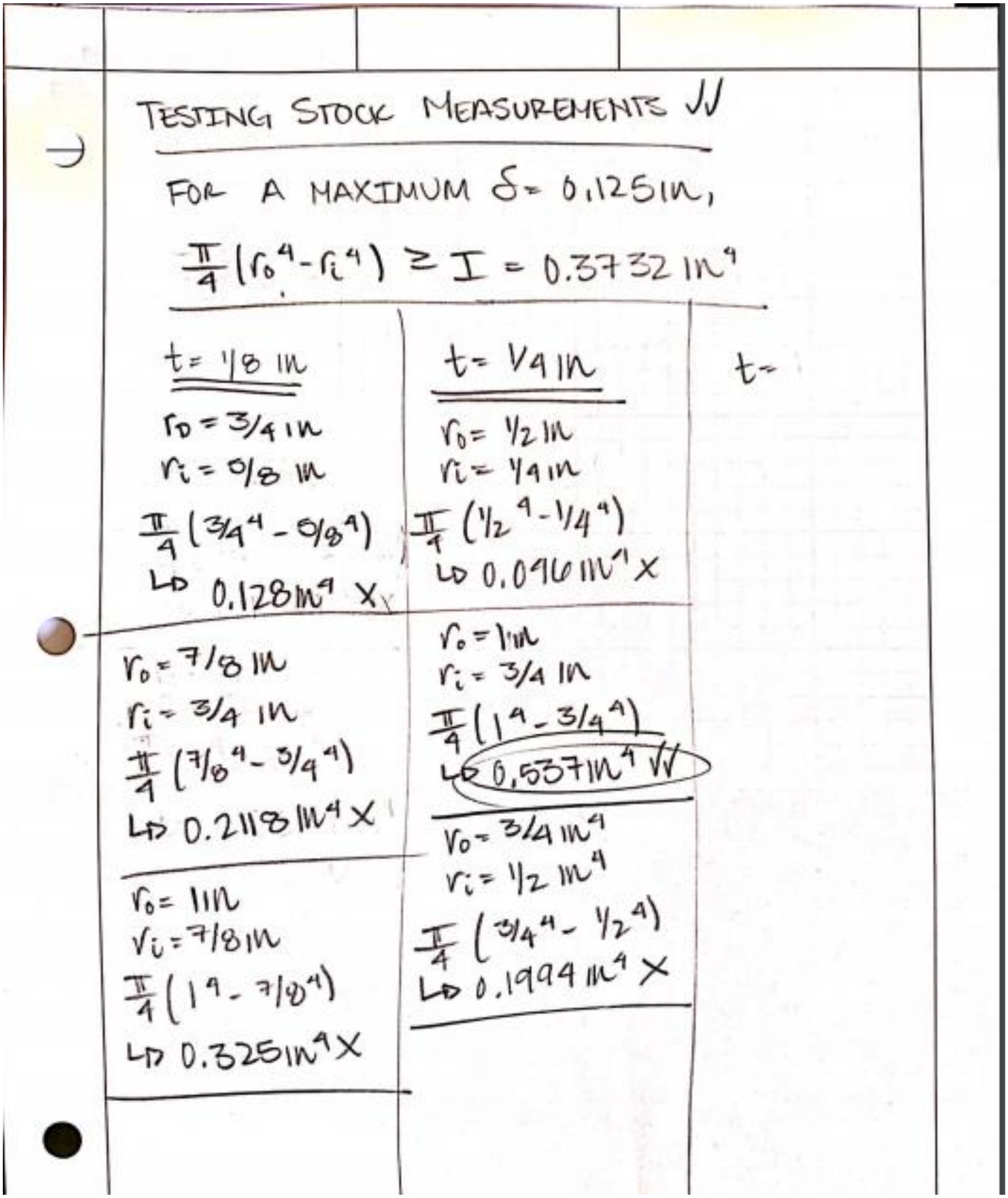
SOLVE FOR I

$$I = \frac{PL^3}{3E\delta}$$

$$I = \frac{(30 \text{ lb})(36 \text{ in})^3}{3(10^7 \frac{\text{lb}}{\text{in}^2})(0.125 \text{ in})} \left[\frac{\text{lb} \cdot \text{in}^3}{\frac{\text{lb}}{\text{in}^2} \text{in}}\right] \rightarrow [\text{in}^4]$$

$$\underline{I = 0.3732 \text{ in}^4}$$

$$I = \frac{\pi}{4}(r_o^4 - r_i^4)$$



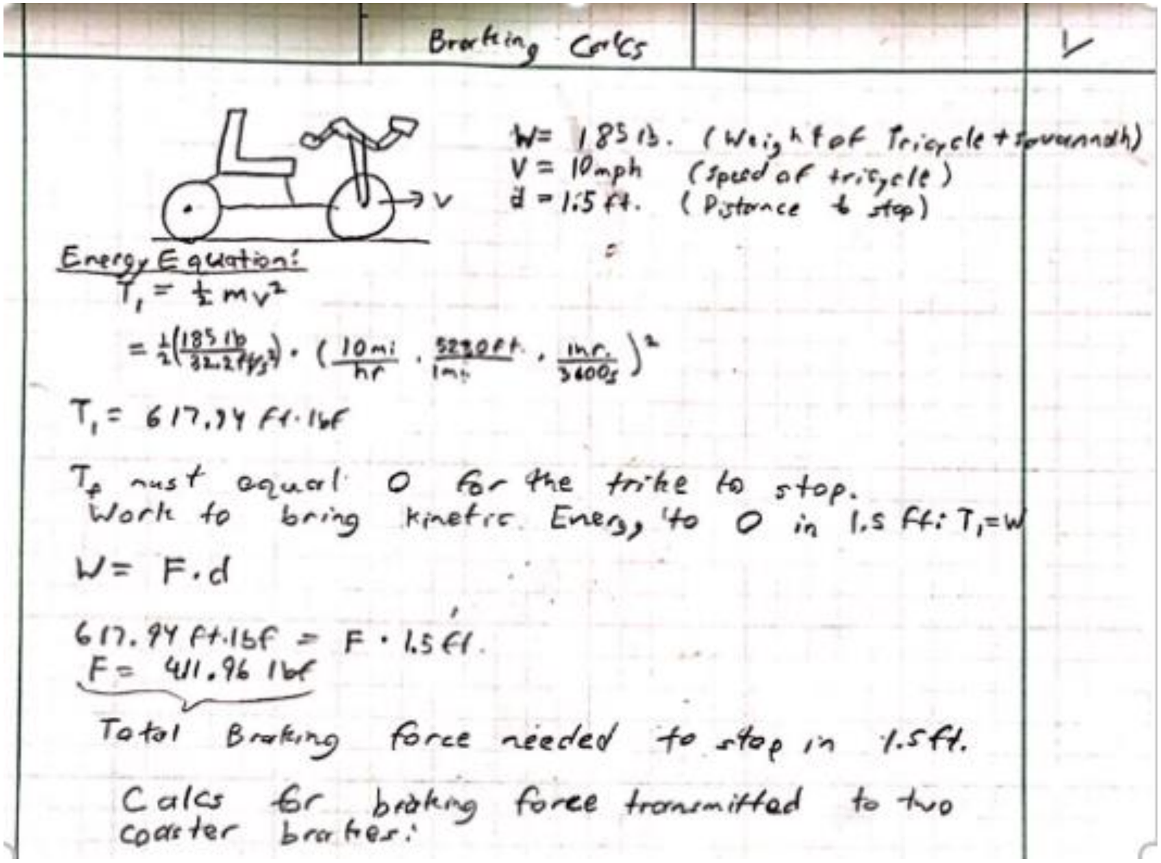
TESTING STOCK MEASUREMENTS ✓✓

FOR A MAXIMUM $\delta = 0.125$ in,

$\frac{\pi}{4}(r_o^4 - r_i^4) \geq I = 0.3732$ in^4

$t = 1/8$ in	$t = 1/4$ in	$t =$
$r_o = 3/4$ in $r_i = 5/8$ in $\frac{\pi}{4}(3/4^4 - 5/8^4)$ ↳ 0.128 in^4 X	$r_o = 1/2$ in $r_i = 1/4$ in $\frac{\pi}{4}(1/2^4 - 1/4^4)$ ↳ 0.096 in^4 X	
$r_o = 7/8$ in $r_i = 3/4$ in $\frac{\pi}{4}(7/8^4 - 3/4^4)$ ↳ 0.2118 in^4 X	$r_o = 1$ in $r_i = 3/4$ in $\frac{\pi}{4}(1^4 - 3/4^4)$ ↳ $\boxed{0.537 \text{ in}^4}$ ✓✓	
$r_o = 1$ in $r_i = 7/8$ in $\frac{\pi}{4}(1^4 - 7/8^4)$ ↳ 0.325 in^4 X	$r_o = 3/4$ in^4 $r_i = 1/2$ in^4 $\frac{\pi}{4}(3/4^4 - 1/2^4)$ ↳ 0.1994 in^4 X	

Appendix G – Braking Calculations



Braking Calcs ✓

$W = 185\ lb.$ (Weight of Tricycle + Savannah)
$V = 10\ mph$ (Speed of tricycle)
$d = 1.5\ ft.$ (Distance to stop)

Energy Equation:

$$T_1 = \frac{1}{2} m v^2$$

$$= \frac{1}{2}\left(\frac{185\ lb}{32.2\ ft/s^2}\right) \cdot \left(\frac{10\ mi}{hr} \cdot \frac{5280\ ft.}{1\ mi} \cdot \frac{1\ hr.}{3600\ s}\right)^2$$

$$T_1 = 617.94\ ft \cdot lbf$$

T_f must equal 0 for the trike to stop.
Work to bring kinetic Energy to 0 in 1.5 ft: $T_1 = W$

$$W = F \cdot d$$

$$617.94\ ft \cdot lbf = F \cdot 1.5\ ft.$$

$$\underbrace{F = 411.96\ lbf}$$

Total Braking force needed to stop in 1.5 ft.

Calcs for braking force transmitted to two coaster brakes:

Appendix H – Design Hazard Checklist

DESIGN HAZARD CHECKLIST

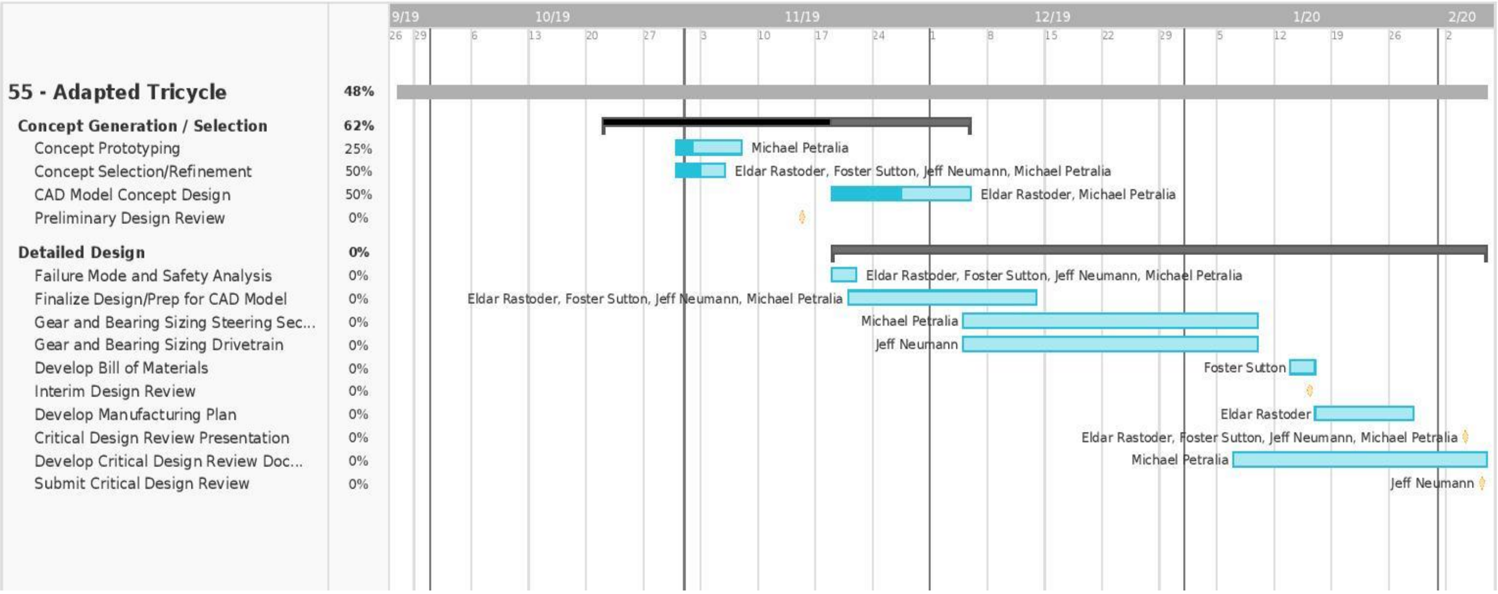
Team: __Savannah's Pit Crew (55)_____________ Advisor: ____Sarah Harding____ Date: ___11/6/19___

Y	N	
☐	⦸	1. Will the system include hazardous revolving, running, rolling, or mixing actions?
☐	⦸	2. Will the system include hazardous reciprocating, shearing, punching, pressing, squeezing, drawing, or cutting actions?
⦸	☐	3. Will any part of the design undergo high accelerations/decelerations?
⦸	☐	4. Will the system have any large (>5 kg) moving masses or large (>250 N) forces?
☐	⦸	5. Could the system produce a projectile?
⦸	☐	6. Could the system fall (due to gravity), creating injury?
☐	⦸	7. Will a user be exposed to overhanging weights as part of the design?
☐	⦸	8. Will the system have any burrs, sharp edges, shear points, or pinch points?
☐	⦸	9. Will any part of the electrical systems not be grounded?
☐	⦸	10. Will there be any large batteries (over 30 V)?
☐	⦸	11. Will there be any exposed electrical connections in the system (over 40 V)?
☐	⦸	12. Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases?
☐	⦸	13. Will there be any explosive or flammable liquids, gases, or small particle fuel as part of the system?
☐	⦸	14. Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design?
☐	⦸	15. Will there be any materials known to be hazardous to humans involved in either the design or its manufacturing?
☐	⦸	16. Could the system generate high levels (>90 dBA) of noise?
☐	⦸	17. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use?
⦸	☐	18. Is it possible for the system to be used in an unsafe manner?
⦸	☐	19. For powered systems, is there an emergency stop button?
☐	⦸	20. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
High accelerations or decelerations.	The user will be strapped into the tricycle in order to improve safety based on the acceleration and deceleration concerns.	2/1	
Large masses or forces.	The tricycle itself is more than 5 kg and will be moving along with the user. The harness, as mentioned above, can help hinder the hazards at hand.	2/1	
Falling due to gravity.	As with any tricycle or bicycle, people have the chance of falling and getting hurt. To reconcile this, we plan on teaching Savannah how to properly use the tricycle and strongly recommend a helmet for crash protection.	4/1	
Used in an unsafe manner.	We hope that anyone using the tricycle will use it properly, and without taking it to dangerously high speeds, in order to remain safe. To help with this, we plan to keep the possible flat ground top speed below 10 mph.	2/1	
Stop button.	There will not be a stop button, but there will be a braking mechanism in place to bring the tricycle to a safe stop.	2/1	

Appendix I – Gantt Chart



Appendix J – Design Verification Plan & Report

Report Date	February 7, 2020		Sponsor	California Children's Service			Component/Assembly	
TEST PLAN								
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES TESTED		TIMING	
						Quantity	Type	Start date	Finish date
1		Measure the top speed of the trike while Savannah is powering it	8 mph	Foster	VP	1	PV	4/21/20	
2		Measure how easy the trike is for Savannah to use	P/F	Jeff	VP	1	PV	4/21/20	
3		Test how comfortable the seat design is for Savannah	P/F	Jeff	VP	1	PV	4/21/20	
4		Test how easy/efficiently the trike steers	P/F	Michael	VP	1	PV	4/21/20	
5		Measure the time it takes for Savannah to access the trike	15 seconds	Michael	VP	1	PV	4/21/20	
6		Measure the braking distance Savannah typically creates	Current Distance	Eldar	VP	1	PV	4/21/20	
7		Measure the overall weight of the trike	Current Weight + 25 lb	Eldar	VP	1	PV	4/21/20	
8		Measure the dimensions of the trike	Current Dimensions + 1 ft upward	Jeff	VP	1	PV	4/21/20	
9		Test how aesthetically pleasing the trike is to Savannah	P/F	Michael	VP	1	PV	4/21/20	
10		Measure the time to top speed of the trike while Savannah is operating it	10 seconds	Foster	VP	1	PV	4/21/20	

Appendix K – Failure Modes and Effects Analysis

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurrence	Current Detection Activities	Detection	Priority
Braking Tricycle	Brake does not engage	Cannot stop tricycle- could lead to accident	9	1. Coaster brake fails/breaks	1.) Stress analysis on brakes 2. Fatigue analysis on brakes 3. Maintenance of brakes and tires	1	1.) User test brakes before every ride session	2	18
		Cannot stop tricycle- could lead to accident	9	1. Too much resistance applying brake 2. Savannah cannot administer the brake (outside of her physical capabilities)	1.) Testing Savannah's physical capabilities 2.) In depth planning of component orientation 3.) Low resistance on chair lean	1	1.) Have Savannah test prototype of bike to see if she can administer the brakes with her core strength	2	18
	Bike brakes too hard or not hard enough	"a.)Cannot stop tricycle in time - leads to accident b.)Abrupt stop leads to jerking motion - could injure user"	9	"1. Too much brake power 2. Too little brake power"	1.) Braking power analysis on coaster brakes	1	1.) Performance testing on ease of applying brakes, tested with Savannah	2	18
Support Savannah	Seat doesn't fit Savannah	Cannot operate tricycle	5	Seat not designed with user in mind	get body measurements of Savannah	1	Check if Savannah can get into seat prototype	1	5
	Too stiff	Uncomfortable to sit	3	Seat not designed with user in mind	Choose comfortable material	1	Sit on material ourselves	1	3
	Shape isn't ergonomic	Uncomfortable to sit	3	Seat not designed with user in mind	Design seat around Savannah	1	Have Savannah sit in prototype	1	3

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurrence	Current Detection Activities	Detection	Priority
	Material cannot support passenger load	Breaks or permanently deforms seat	7	Material selected is too weak	Preliminary load calculations of passenger sitting on seat	2	Place load comparable to Savannah on seat	1	14
	Seat belt too tight	uncomfortable to drive	3	Insufficient seat belt length	get body measurements of Savannah	1	Check seat belt length	1	3
	Fasteners break	shear loads or cyclical loading	5	Insufficient fastener strength	Preliminary load calculations	1	Confirm that fasteners are unchanged after test run	2	10
Steer tricycle	uncomfortable range of motion	steering angle range is too great	6	improper gear ratio to steering column	preliminary turning angle calculations	3	measure ratio of rack and pinion turning	1	18
	shaft material failure	shaft deforms/breaks	7	high shear loads	preliminary load calculations	3	test drive tricycle	2	42
	bevel gears fail	steering column doesn’t translate motion	5	gears selected too weak	preliminary load calculations	3	test drive tricycle	2	30
Power tricycles	uncomfortable range of motion	cannot create sufficient power for tricycle	8	bar is placed too far from rider	get body measurements of Savannah	3	test drive tricycle	1	24
	push bar breaks	cannot power tricycle	5	Material selected is too weak	preliminary load calculation	3	apply comparable force to push bar	1	15
	insufficient mechanical advantage	cannot effectively power tricycle	5	Lever arm too short	preliminary load calculations	3	prototype lever arm torque translation	3	45
General	material corrodes	components break	5	material selective is too corrosive	research material properties before selection	2	Long-term analysis of material strength decay	3	30
	Welds break	tricycle falls apart	7	materials aren't readily weldable	research material properties before selection	3	Long-term analysis of material strength decay	3	63

Appendix L– Manufacturing Plan

	Component	Quantity	Status	Plan for production
STEERING	Bevel Gear Rack	1	Purchase	Press fit to steering shaft
	Bevel Gear Pinion	1	Purchase	Press fit to steering shaft
	Steering Shaft	1	Raw Material	Cut with cold saw and press fit to bearings
	Seat Sleeve Bearings	5	Purchase	Press fit to steering shaft and to support shaft
	Support Shaft	1 (1 ft)	Modify from Purchase	Cut with cold saw and press fit to bearings, welded to frame, clamped to Seat Plate
POWERING AND BRAKING	Drive Sprocket	2	Purchase	Fastened to Crank Arms and Lower Support Shaft
	Free wheels (wheel, coaster brake and sprocket)	2	Purchase	Use fastener to attach rigid portion of wheel to frame
	Chain	2 (15 ft ea)	Purchase	Attach to both sprockets
	Crank Arm	2 (3 ft ea)	Modify from Purchase	Fasten to Drive Sprocket
	Power Bar	1	Modify from Purchase	Fasten to Crank Arms
SEAT ASSEMBLY	Seat	1	From Current Product	Fasten to Seat Plate
	Seat Plate	1	Modify from Purchase	Fasten to Plate Clamps
	Plate Clamps	2 (5 pack)	Purchase	Fasten to Seat Plate
FASTENERS	Screws	1	Purchase	Use as Fasteners for multiple parts
	Nuts	1	Purchase	Use as Fasteners for multiple parts
FRAME	Old tricycle frame	1	Modify From Current Product	Cut with cold saw and possibly re-weld to modify frame to fit tricycle
	Support Shaft	1 (3 ft)	Purchase	Weld to current frame

Appendix M – Indented Bill of Materials

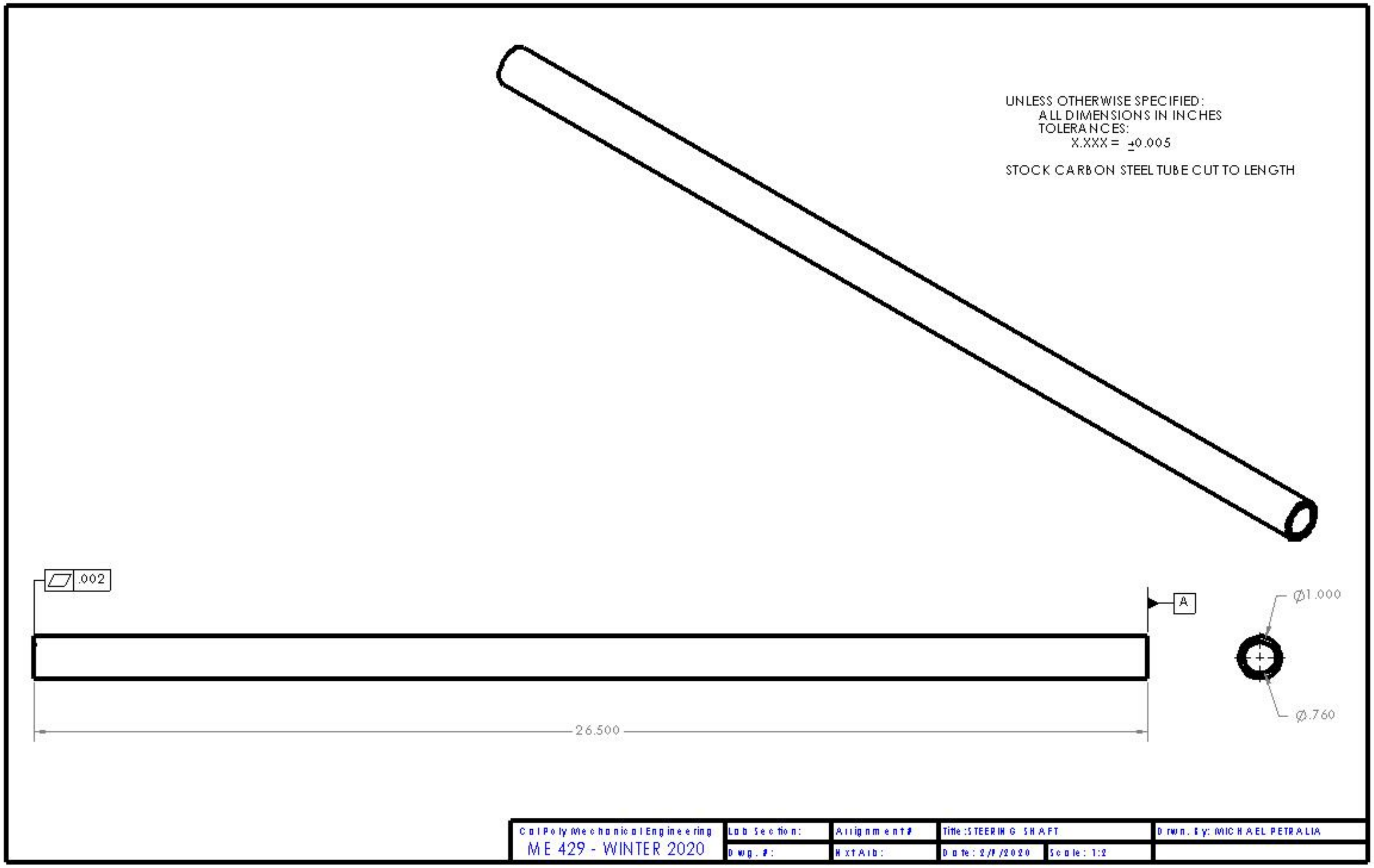
Adaptive Tricycle

Indented Bill of Material (iBOM)

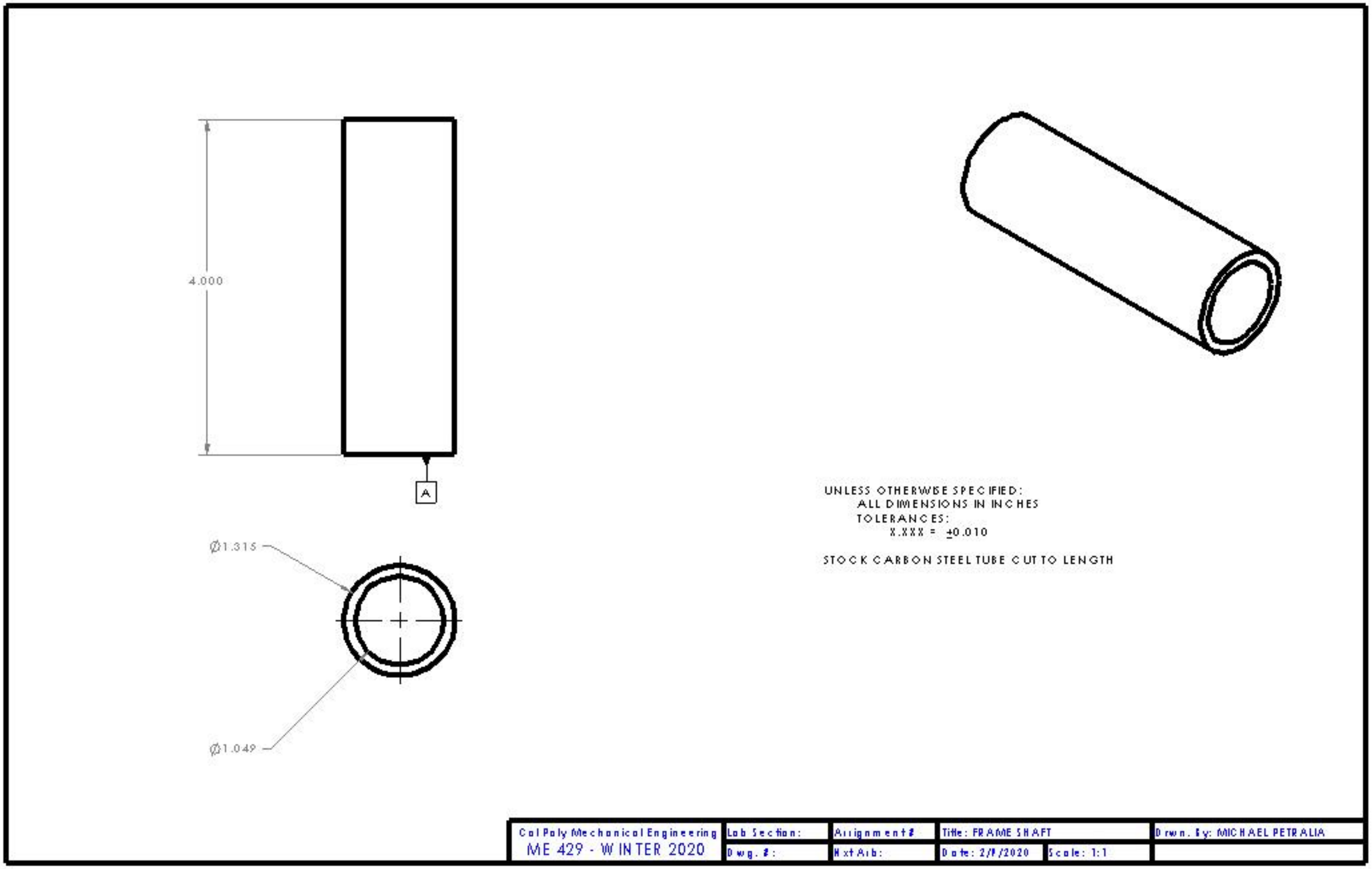
Assembly Level	Part Number	Description				Qty	Cost	Ttl Cost	Source	More Info
		Lvl0	*Lvl1*	*Lvl2*	*Lvl3*					
0	100000	Final Assy							------	
1	110000		Steering Assembly						------	
2	111000			Bevel Gear Rack		1	42.42	42.42	McMaster	6529K22
2	112000			Bevel Gear Pinion		1	29.76	29.76	McMaster	6529K15
2	113000			Steering Shaft		1	20.51	20.51	McMaster	7767T371
2	114000			Seat Sleeve Bearings		3	2.79	8.37	McMaster	6391K423
				Top Hat Bearing		1	1.46	1.46	McMaster	6338K423
2	115000			Support Shaft		1	27.34	27.34	McMaster	7767T53
2				Frame Shaft		2	109.35	218.7	McMaster	7767T53
1	120000		Powering Assembly						------	
2	121000			Drive Sprocket		2	22.71	45.42	McMaster	2737T264
2	122000			Free Wheel		2	20.00	40.00	Bike Kitchen	Price isn't final
2	123000			Chain		2	10.00	20.00	Bike Kitchen	Price isn't final
2	124000			Crank Assembly					------	
3	124100				Crank Arm	2	57.84	115.67	McMaster	9056K13
					Sprocket Bearing	2	7.92	15.84	McMaster	60355K507
3	124200				Power Bar	1	24.77	24.77	McMaster	9246K461
1	125000		Seat Assembly						------	
2	125100			Seat		1	0.00	0.00	Current Seat	
2	125200			Seat Plate		1	0.00	0.00	Current Seat	
2	125300			Plate Clamps (5 pack)		2	7.65	15.30	McMaster	3177T16
1	191000		Screws (10 pack)			1	7.87	7.87	McMaster	93306A546
1	192000		Nuts (100 pack)			1	8.22	8.22	McMaster	90670A029
					Total Parts	**27**		**641.65**	**Total Cost**	

Appendix N – Detail Drawings for Modified Parts

Steering Shaft



Support Shaft

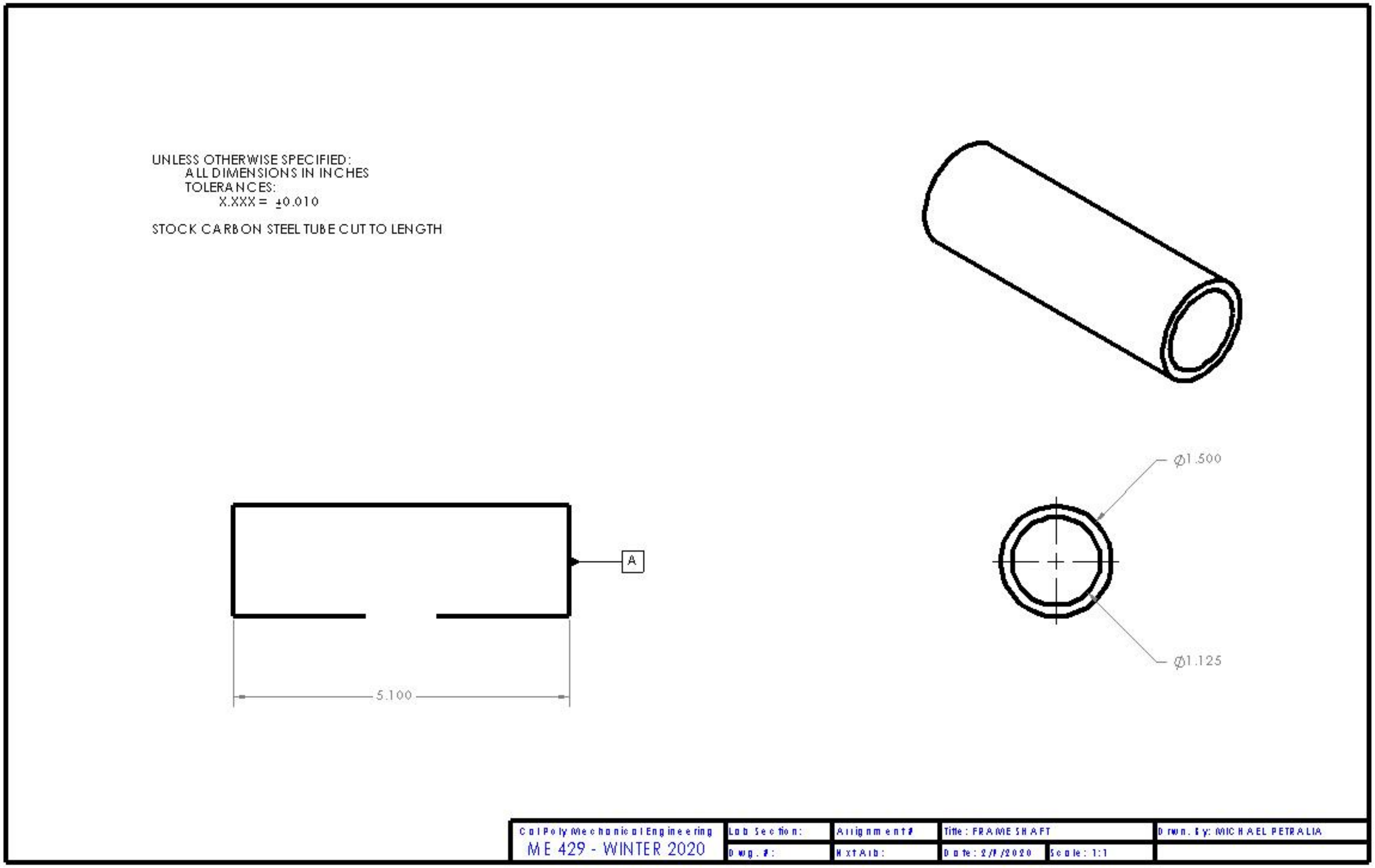


UNLESS OTHERWISE SPECIFIED:
ALL DIMENSIONS IN INCHES
TOLERANCES:
X.XXX = ±0.010

STOCK CARBON STEEL TUBE CUT TO LENGTH

Cal Poly Mechanical Engineering ME 429 - WINTER 2020	Lab Section:	Assignment#	Title: FRAME SHAFT		Drwn. By: MICHAEL PETRALIA
	Dwg. #:	Nxt Asb:	Date: 2/[illegible]/2020	Scale: 1:1	

Frame Shaft

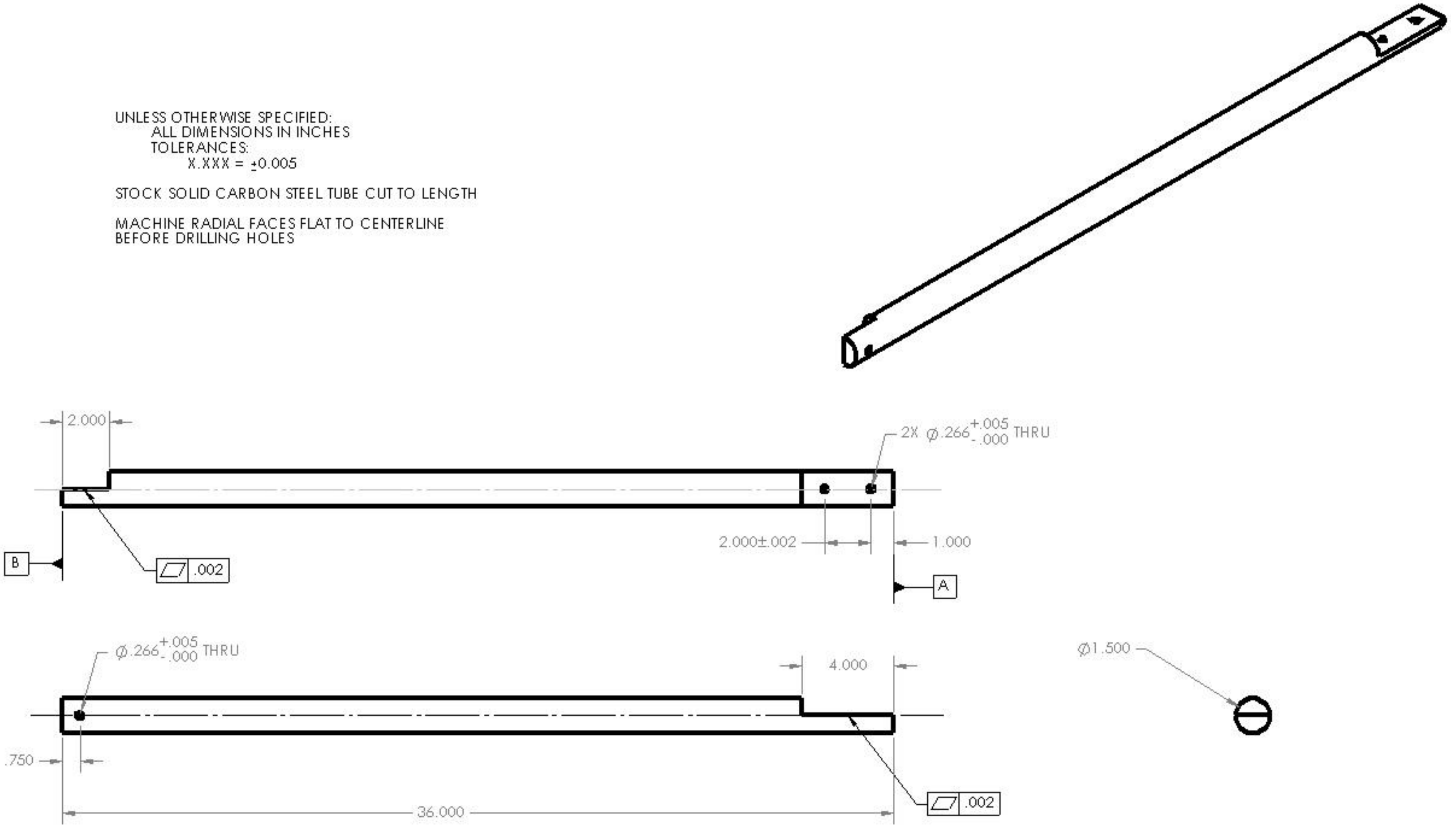


UNLESS OTHERWISE SPECIFIED:
ALL DIMENSIONS IN INCHES
TOLERANCES:
X.XXX = ±0.010

STOCK CARBON STEEL TUBE CUT TO LENGTH

Cal Poly Mechanical Engineering ME 429 - WINTER 2020	Lab Section:	Assignment#	Title: FRAME SHAFT		Drwn. By: MICHAEL PETRALIA
	Dwg. #:	Nxt Asb:	Date: 2/7/2020	Scale: 1:1	

Crank Arm



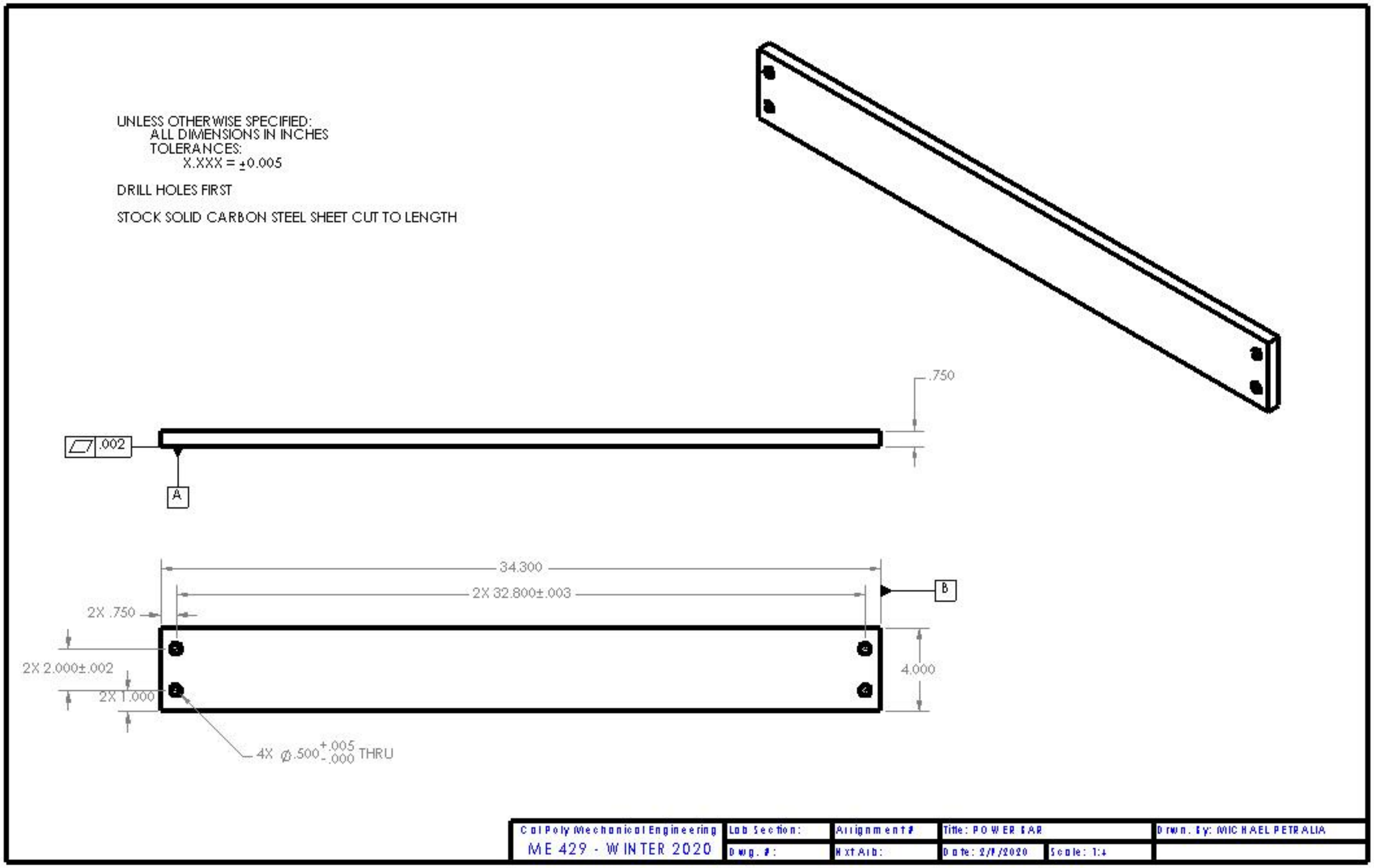
UNLESS OTHERWISE SPECIFIED:
ALL DIMENSIONS IN INCHES
TOLERANCES:
X.XXX = ±0.005

STOCK SOLID CARBON STEEL TUBE CUT TO LENGTH

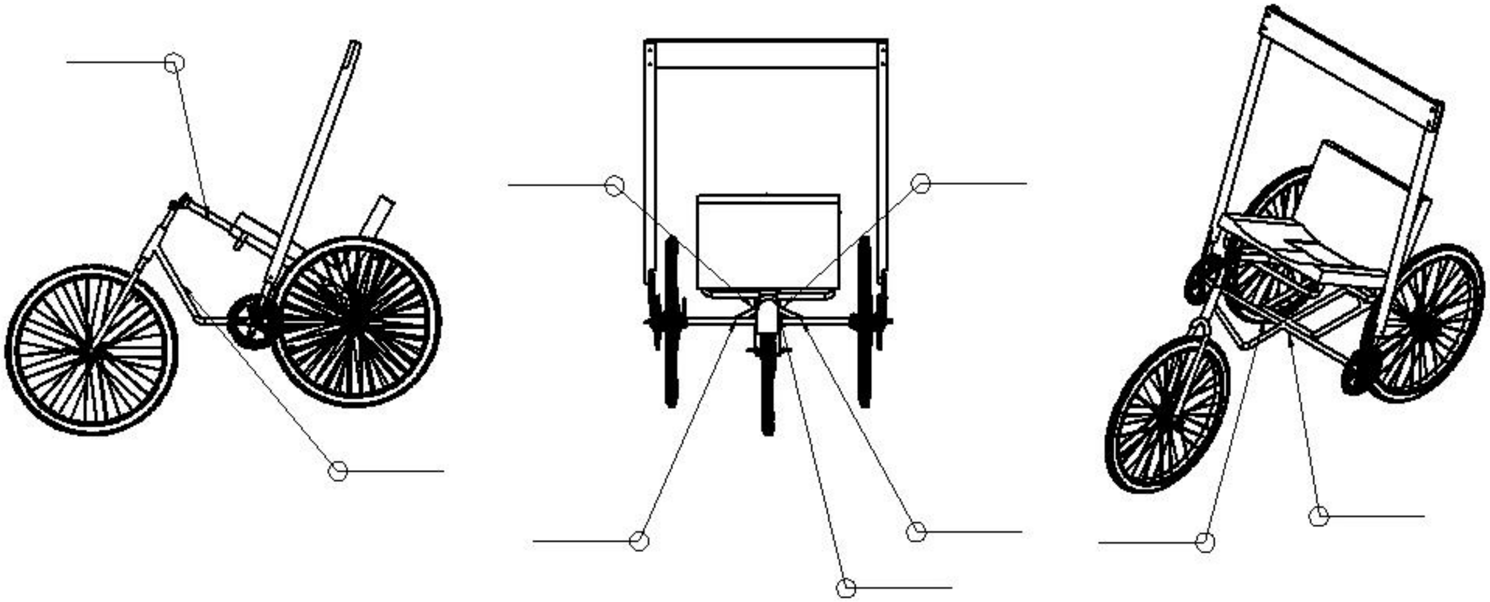
MACHINE RADIAL FACES FLAT TO CENTERLINE BEFORE DRILLING HOLES

Cal Poly Mechanical Engineering ME 429 - WINTER 2020	Lab Section:	Assignment #	Title: CRANK ARM	Drwn. By: MICHAEL PETRALIA
	Dwg. #:	Nxt Asb:	Date: 2/9/2020 / Scale: 1:4	

Power Bar


UNLESS OTHERWISE SPECIFIED:
ALL DIMENSIONS IN INCHES
TOLERANCES:
X.XXX = ±0.005
DRILL HOLES FIRST
STOCK SOLID CARBON STEEL SHEET CUT TO LENGTH
.002
A
.750
34.300
2X 32.800±.003
B
2X .750
2X 2.000±.002
2X 1.000
4.000
4X Ø.500 +.005 -.000 THRU
Cal Poly Mechanical Engineering
ME 429 - WINTER 2020
Lab Section:
Assignment#
Title: POWER BAR
Drwn. By: MICHAEL PETRALIA
Dwg. #:
Nxt Asb:
Date: 2/7/2020
Scale: 1:4

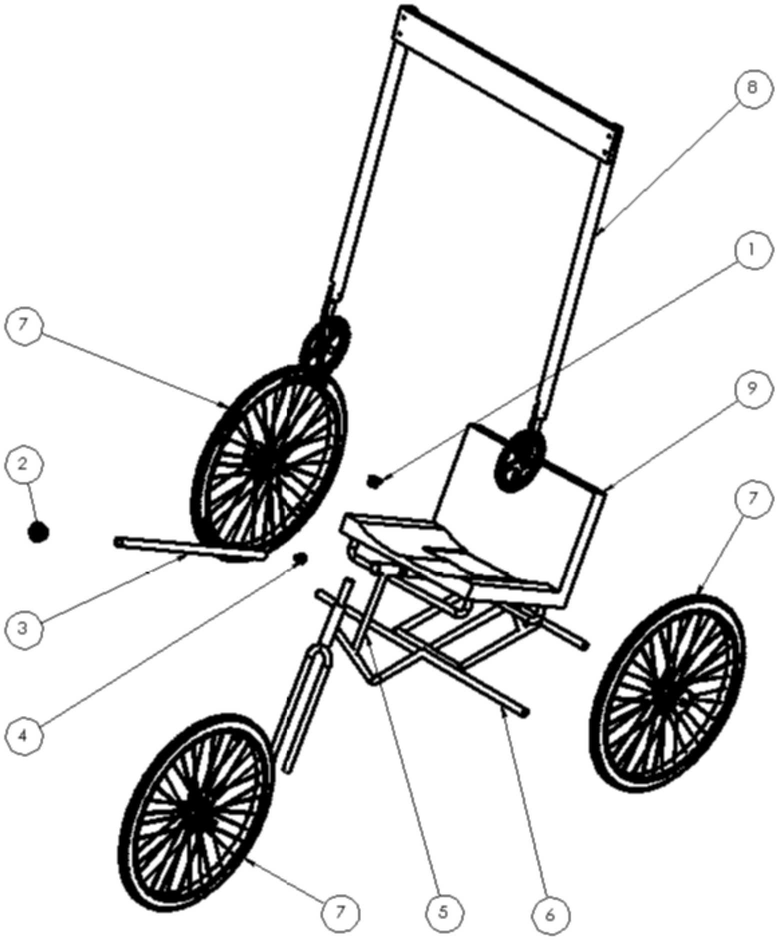
Weld Callouts



Cal Poly Mechanical Engineering	Lab Section:	Assignment#	Title: TRICYCLE ASSEMBLY WELDS		Drwn. By: MICHAEL PETRALIA
ME 429 - WINTER 2020	Dwg. #:	Nxt Asb:	Date: 2/7/20	Scale: 1:15	

Tricycle Assembly Exploded View

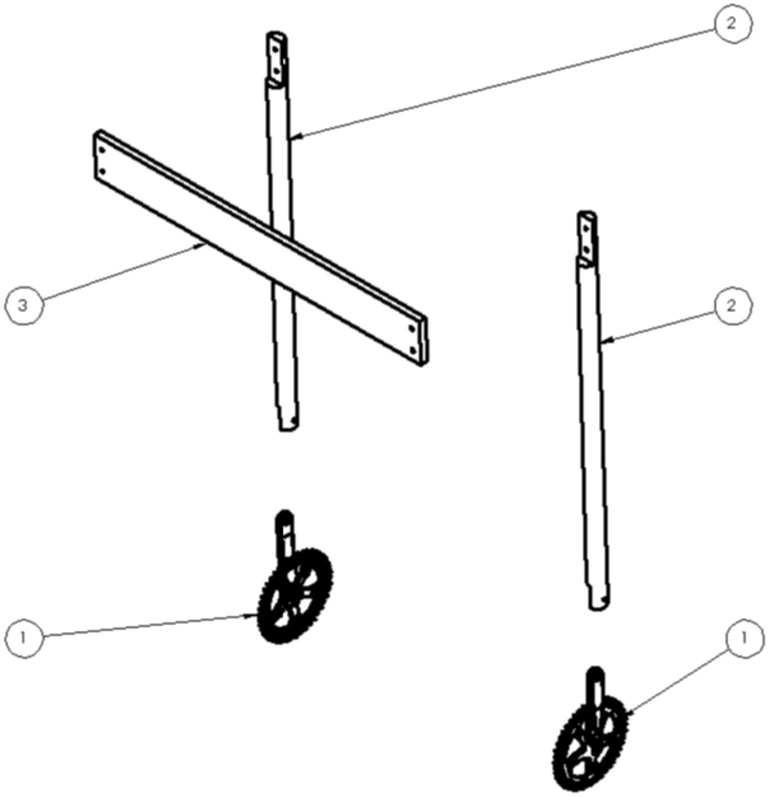
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	111000	BEVEL GEAR RACK	1
2	112000	BEVEL GEAR PINION	1
3	113000	STEERING SHAFT	1
4	114000	TOP HAT BEARING	1
5	115000	SUPPORT SHAFT	1
6	116000	FRAME SHAFT	1
7	122000	24 INCH FREE WHEEL	3
8	124000	CRANK ASSEMBLY	1
9	125000	SEAT ASSEMBLY	1



Cal Poly Mechanical Engineering	Lab Section:	Assignment #	Title: TRICYCLE EXPLODED VIEW	Drwn. By: ELDAR RASTODER
ME 430 - SPRING 2020	Dwg. #:	Nxt Asb:	Date: 5/13 Scale: 1:12	Chkd. By:

Po

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	121000	DRIVE SPROCKET	2
2	124100	CRANK ARM	2
3	124200	POWER BAR	1



Cal Poly Mechanical Engineering	Lab Section:	Assignment #	Title: CRANK ASSEMBLY	Drwn. By: ELDAR RASTODER
ME 430 - SPRING 2020	Dwg. #:	Nxt Asb:	Date: Scale:1:8	Chkd. By: ME STAFF

Appendix O – Specification Sheets for Bill of Materials

Bevel Gear Rack

6529K22

Metal Miter Gear

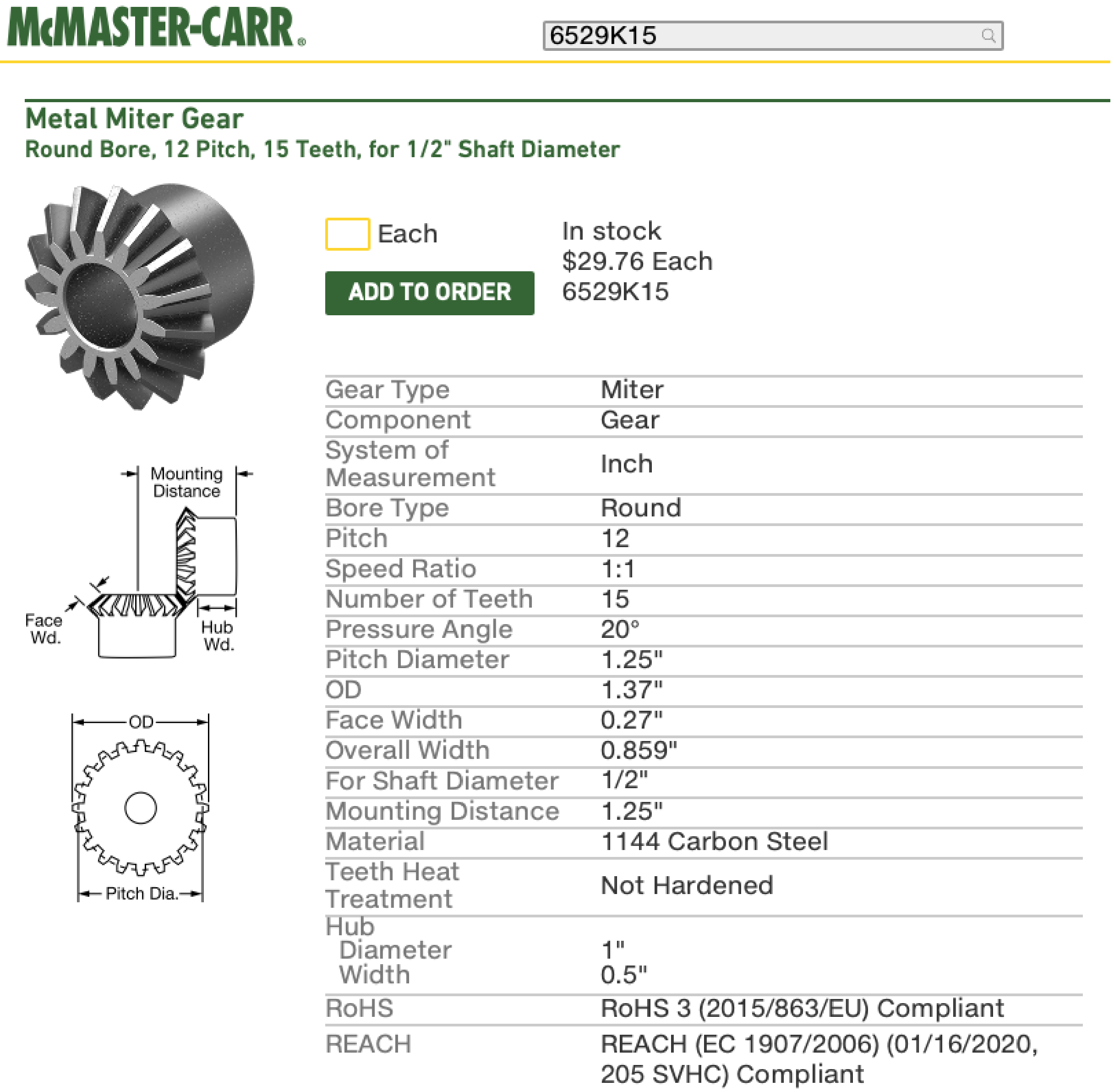
Round Bore, 12 Pitch, 24 Teeth

☐ Each

In stock
$42.42 Each
6529K22

Gear Type	Miter
Component	Gear
System of Measurement	Inch
Bore Type	Round
Pitch	12
Speed Ratio	1:1
Number of Teeth	24
Pressure Angle	20°
Pitch Diameter	2"
OD	2.12"
Face Width	0.43"
Overall Width	1.219"
For Shaft Diameter	1/2"
Mounting Distance	1.875"
Material	1144 Carbon Steel
Teeth Heat Treatment	Not Hardened
Hub	
Diameter	1.5"
Width	0.688"
RoHS	RoHS 3 (2015/863/EU) Compliant
REACH	REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant

Bevel Gear Pinion



Metal Miter Gear

Round Bore, 12 Pitch, 15 Teeth, for 1/2" Shaft Diameter

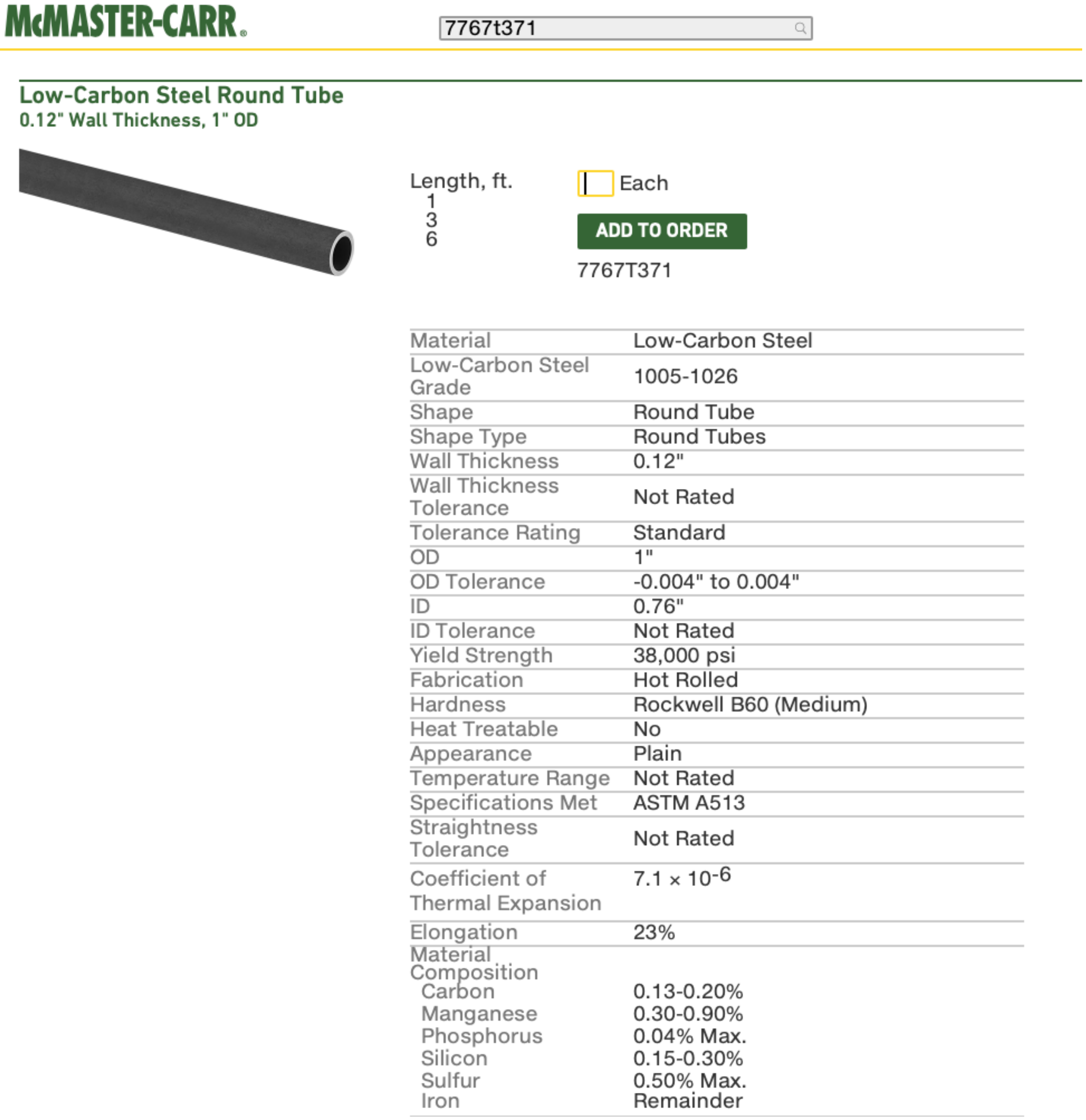
☐ Each

ADD TO ORDER

In stock
$29.76 Each
6529K15

Gear Type	Miter
Component	Gear
System of Measurement	Inch
Bore Type	Round
Pitch	12
Speed Ratio	1:1
Number of Teeth	15
Pressure Angle	20°
Pitch Diameter	1.25"
OD	1.37"
Face Width	0.27"
Overall Width	0.859"
For Shaft Diameter	1/2"
Mounting Distance	1.25"
Material	1144 Carbon Steel
Teeth Heat Treatment	Not Hardened
Hub	
Diameter	1"
Width	0.5"
RoHS	RoHS 3 (2015/863/EU) Compliant
REACH	REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant

Steering Shaft



Low-Carbon Steel Round Tube

0.12" Wall Thickness, 1" OD

Length, ft.
1
3
6

☐ Each

7767T371

Material	Low-Carbon Steel
Low-Carbon Steel Grade	1005-1026
Shape	Round Tube
Shape Type	Round Tubes
Wall Thickness	0.12"
Wall Thickness Tolerance	Not Rated
Tolerance Rating	Standard
OD	1"
OD Tolerance	-0.004" to 0.004"
ID	0.76"
ID Tolerance	Not Rated
Yield Strength	38,000 psi
Fabrication	Hot Rolled
Hardness	Rockwell B60 (Medium)
Heat Treatable	No
Appearance	Plain
Temperature Range	Not Rated
Specifications Met	ASTM A513
Straightness Tolerance	Not Rated
Coefficient of Thermal Expansion	7.1×10^{-6}
Elongation	23%
Material Composition	
Carbon	0.13-0.20%
Manganese	0.30-0.90%
Phosphorus	0.04% Max.
Silicon	0.15-0.30%
Sulfur	0.50% Max.
Iron	Remainder

Seat Sleeve Bearings

Oil-Embedded Bronze Sleeve Bearing

for 1" Shaft Diameter and 1-1/8" Housing ID, 1" Long

In stock
$2.79 Each
6391K423

System of Measurement	Inch
Bearing Type	Plain
Plain Bearing Type	Sleeve
For Load Direction	Radial
Material	SAE 841 Bronze
For Shaft Diameter	1"
ID	1"
ID Tolerance	0" to 0.001"
For Housing ID	1 1/8"
OD	1.127"
OD Tolerance	0" to 0.001"
Length	1"
Length Tolerance	-0.005" to 0.005"
Dynamic Radial Load Capacity	2,000 lbs. @ 60 rpm
Lubrication	Lubricated
Lubrication Method	Embedded
Lubricant	SAE 30 Oil
For Shaft Type	Round
Shaft Mount Type	Slip Fit
Temperature Range	-35° to 300° F
RoHS	RoHS 3 (2015/863/EU) Compliant
REACH	REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant

Top Hat Bearing

Oil-Embedded Flanged Sleeve Bearing
for 1/2" Shaft Diameter and 3/4" Housing ID, 3/4" Long

In stock
$1.46 Each
6338K423

System of Measurement	Inch
Bearing Type	Plain
Plain Bearing Type	Flanged
For Load Direction	Combined Radial and Thrust
Material	SAE 841 Bronze
For Shaft Diameter	1/2"
ID	0.501"
ID Tolerance	0" to 0.001"
For Housing ID	3/4"
OD	0.752"
OD Tolerance	0" to 0.001"
Length	3/4"
Length Tolerance	-0.005" to 0.005"
Flange OD	1"
Flange Thickness	1/8"
Dynamic Radial Load Capacity	750 lbs. @ 120 rpm
Dynamic Thrust Load Capacity	930 lbs. @ 120 rpm
Lubrication	Lubricated
Lubrication Method	Embedded
Lubricant	SAE 30 Oil
For Shaft Type	Round
Shaft Mount Type	Slip Fit
Temperature Range	-35° to 300° F
RoHS	RoHS 3 (2015/863/EU) Compliant
REACH	REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant

Support & Frame Shafts

Low-Carbon Steel Round Tube

0.188" Wall Thickness, 1-1/2" OD

Length, ft.
1
3
6

☐ Each

7767T53

Material	Low-Carbon Steel
Low-Carbon Steel Grade	1026
Shape	Round Tube
Shape Type	Round Tubes
Wall Thickness	0.188"
Wall Thickness Tolerance	Not Rated
Tolerance Rating	Oversized
OD	1 1/2"
OD Tolerance	0" to 0.005"
ID	1 1/8"
ID Tolerance	Not Rated
Yield Strength	45,000 psi
Fabrication	Cold Worked
Heat Treatment	Stress Relieved
Hardness	Rockwell B60 (Medium)
Heat Treatable	No
Appearance	Plain
Temperature Range	Not Rated
Specifications Met	ASTM A513
Straightness Tolerance	Not Rated
Coefficient of Thermal Expansion	7.1×10^{-6}
Elongation	23%
Material Composition	
Carbon	0.13-0.20%
Manganese	0.30-0.90%
Phosphorus	0.04% Max.
Silicon	0.15-0.30%
Sulfur	0.50% Max.
Iron	Remainder

Drive Sprocket

Roller Chain Sprocket
for ANSI 25 Chain, 36 Teeth, for 3/4" Shaft Diameter

With Keyway

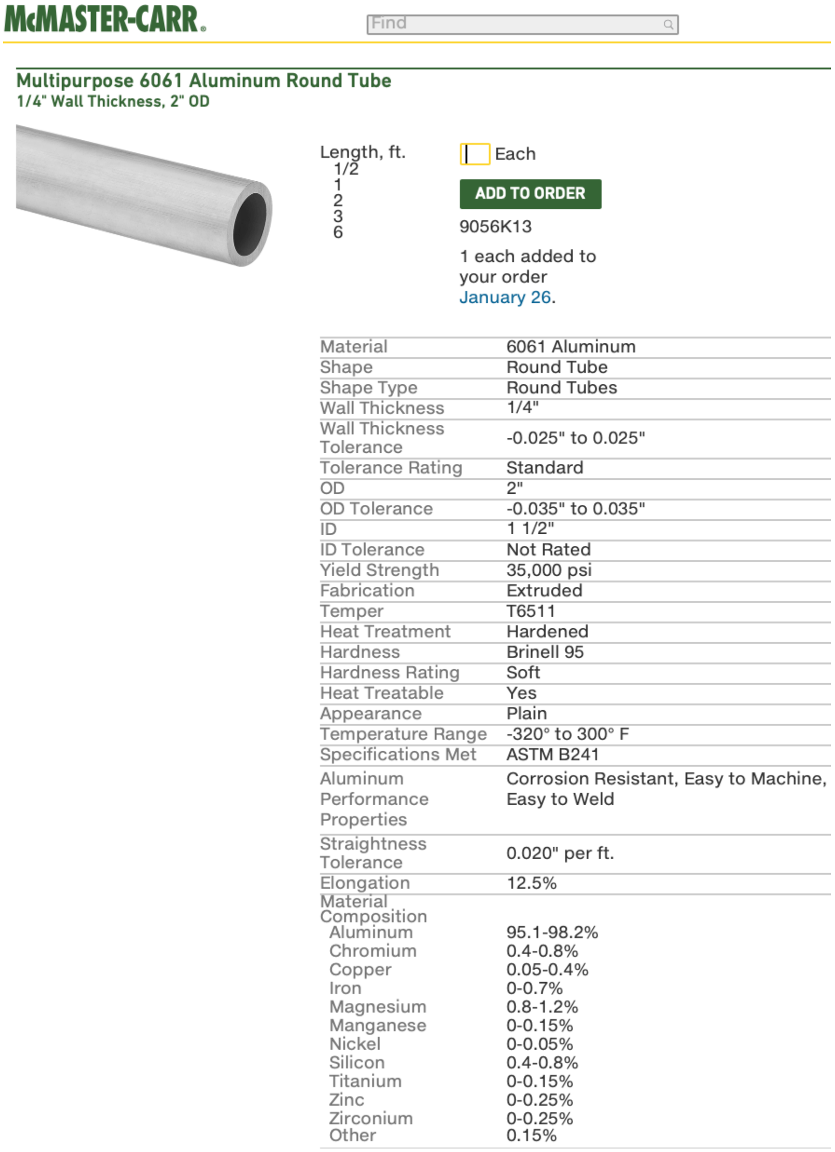
☐ Each

In stock
$22.71 Each
2737T264

Sprocket Type	Standard
Bore Type	Finished
For Roller Chain Strand Type	Single
For Roller Chain Standard	ANSI
For Roller Chain Trade Size	25
Pitch	1/4"
Number of Teeth	36
For Shaft Diameter	3/4"
Shaft Mount Type	Set Screw
For Shaft Type	Keyed
ID	3/4"
OD	3.01"
Overall Width	3/4"
Hub Diameter	1 1/2"
Keyway Width Depth	 3/16" 3/32"
Material	Steel
Includes	Two Set Screws
RoHS	RoHS 3 (2015/863/EU) Compliant
REACH	REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant
Country of Origin	United States

Mount these sprockets onto your shaft and secure with a set screw—no machining necessary.

Crank Arm



Multipurpose 6061 Aluminum Round Tube

1/4" Wall Thickness, 2" OD

Length, ft.
1/2
1
2
3
6

☐ Each

ADD TO ORDER

9056K13

1 each added to your order January 26.

Material	6061 Aluminum
Shape	Round Tube
Shape Type	Round Tubes
Wall Thickness	1/4"
Wall Thickness Tolerance	-0.025" to 0.025"
Tolerance Rating	Standard
OD	2"
OD Tolerance	-0.035" to 0.035"
ID	1 1/2"
ID Tolerance	Not Rated
Yield Strength	35,000 psi
Fabrication	Extruded
Temper	T6511
Heat Treatment	Hardened
Hardness	Brinell 95
Hardness Rating	Soft
Heat Treatable	Yes
Appearance	Plain
Temperature Range	-320° to 300° F
Specifications Met	ASTM B241
Aluminum Performance Properties	Corrosion Resistant, Easy to Machine, Easy to Weld
Straightness Tolerance	0.020" per ft.
Elongation	12.5%
Material Composition	
Aluminum	95.1-98.2%
Chromium	0.4-0.8%
Copper	0.05-0.4%
Iron	0-0.7%
Magnesium	0.8-1.2%
Manganese	0-0.15%
Nickel	0-0.05%
Silicon	0.4-0.8%
Titanium	0-0.15%
Zinc	0-0.25%
Zirconium	0-0.25%
Other	0.15%

Sprocket Bearing

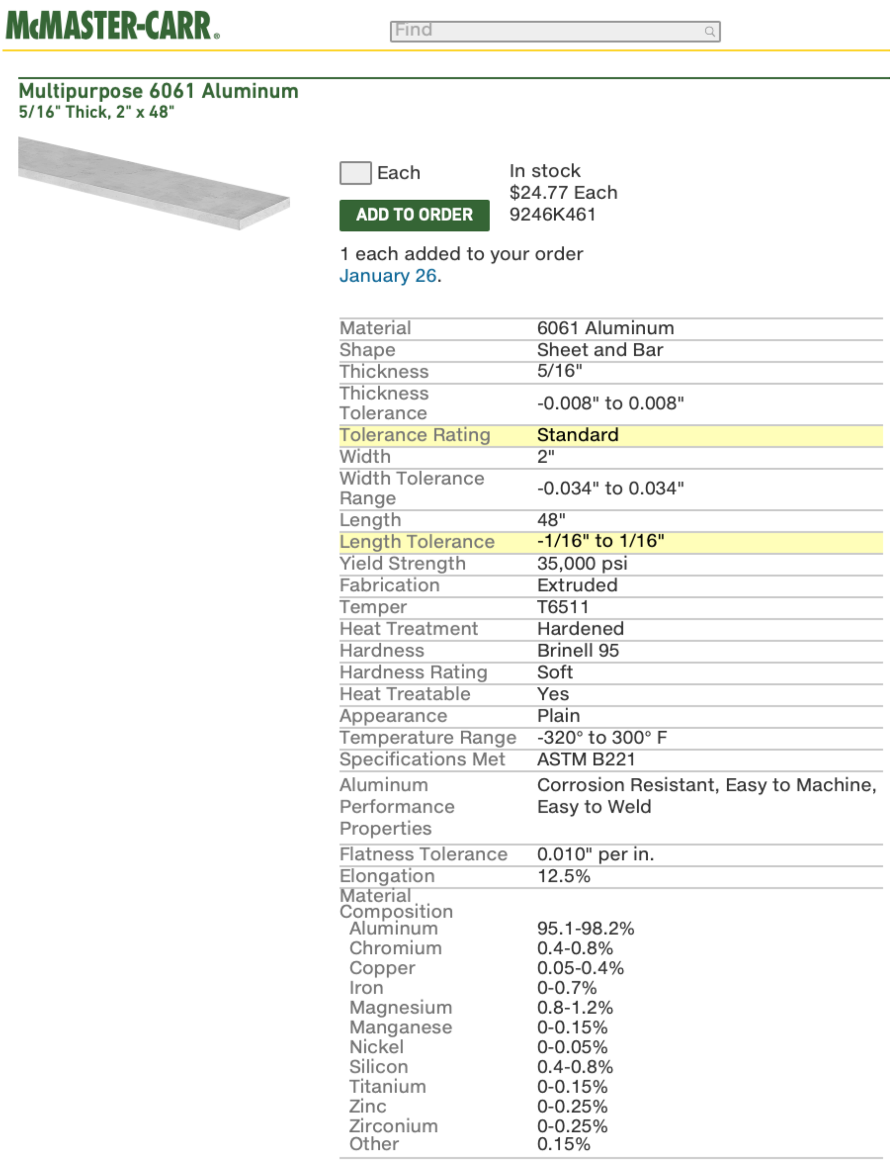
Ball Bearing

Open, Trade Number R12, for 3/4" Shaft Diameter

In stock
$7.92 Each
60355K507

Bearing Type	Ball
For Load Direction	Radial
Construction	Single Row
Seal Type	Open
Inner Ring Type	Standard
Ball Bearing Type	Standard
Trade No.	R12
For Shaft Type	Round
For Shaft Diameter	3/4"
ID	0.75"
ID Tolerance	-0.0004" to 0"
For Housing ID	1 5/8"
OD	1.625"
OD Tolerance	-0.0005" to 0"
Width	5/16"
Width Tolerance	-0.005" to 0"
Ring Material	Steel
Ball Material	Steel
Cage Material	Steel
Radial Load Capacity, lbs.	
Dynamic	1,750
Static	1,000
Maximum Speed	17,000 rpm
Lubrication	Required
Shaft Mount Type	Press Fit
Temperature Range	-20° to 230° F
ABEC Rating	ABEC-1
Radial Clearance Trade No.	C3
Radial Clearance	0.0005" to 0.0011"
RoHS	RoHS 3 (2015/863/EU) Compliant
REACH	REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant

Power Bar



Multipurpose 6061 Aluminum
5/16" Thick, 2" x 48"

☐ Each

In stock
$24.77 Each
9246K461

1 each added to your order
January 26.

Material	6061 Aluminum
Shape	Sheet and Bar
Thickness	5/16"
Thickness Tolerance	-0.008" to 0.008"
Tolerance Rating	Standard
Width	2"
Width Tolerance Range	-0.034" to 0.034"
Length	48"
Length Tolerance	-1/16" to 1/16"
Yield Strength	35,000 psi
Fabrication	Extruded
Temper	T6511
Heat Treatment	Hardened
Hardness	Brinell 95
Hardness Rating	Soft
Heat Treatable	Yes
Appearance	Plain
Temperature Range	-320° to 300° F
Specifications Met	ASTM B221
Aluminum Performance Properties	Corrosion Resistant, Easy to Machine, Easy to Weld
Flatness Tolerance	0.010" per in.
Elongation	12.5%
Material Composition	
Aluminum	95.1-98.2%
Chromium	0.4-0.8%
Copper	0.05-0.4%
Iron	0-0.7%
Magnesium	0.8-1.2%
Manganese	0-0.15%
Nickel	0-0.05%
Silicon	0.4-0.8%
Titanium	0-0.15%
Zinc	0-0.25%
Zirconium	0-0.25%
Other	0.15%

Plate Clamps

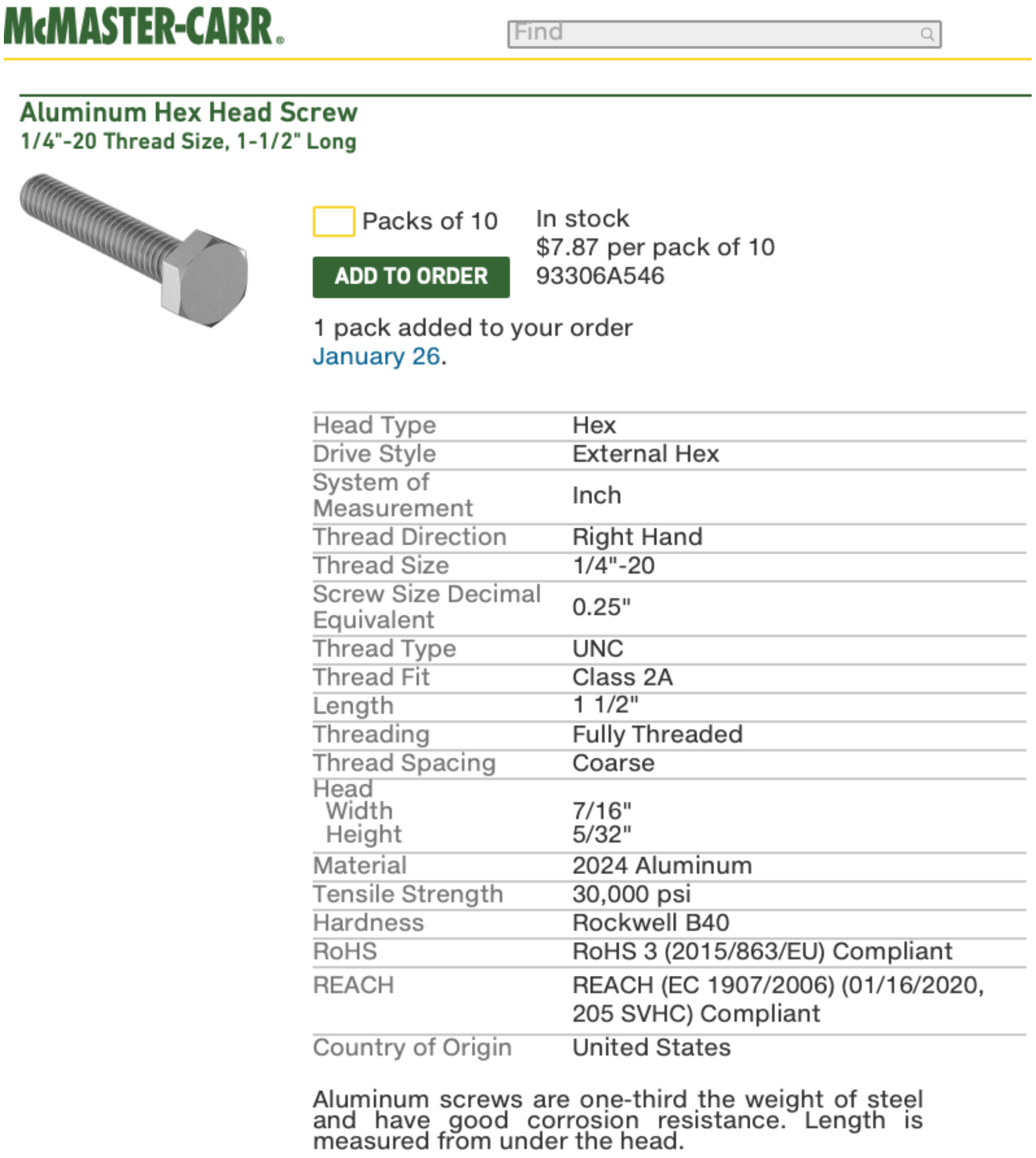
Snug-Fit Vibration-Damping Loop Clamp

Aluminum with Neoprene Rubber Cushion, 1" ID

☐ Packs of 5

In stock
$7.65 per pack of 5
3177T16

Mount Type	Screw On
For Number of Lines	1
Number of Mounting Points	1
Material	Aluminum
Cushion Material	Neoprene Rubber
ID	
Inch	1"
Metric	25 mm
For Conduit Trade Size	
EMT	3/4
For Copper Tube Size	3/4
Cushion Color	Black
Capacity	Not Rated
Center-to-Center Length	1"
Length	1 7/8"
Width	1/2"
Height	1 5/16"
Thickness	1/16"
Mounting	
Fasteners Included	No
Hole Diameter	13/64"
Temperature Range	-40° to 210° F
For Use Outdoors	Yes
Specifications Met	MS21919
RoHS	Not Compliant
REACH	REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant



Aluminum Hex Head Screw

1/4"-20 Thread Size, 1-1/2" Long

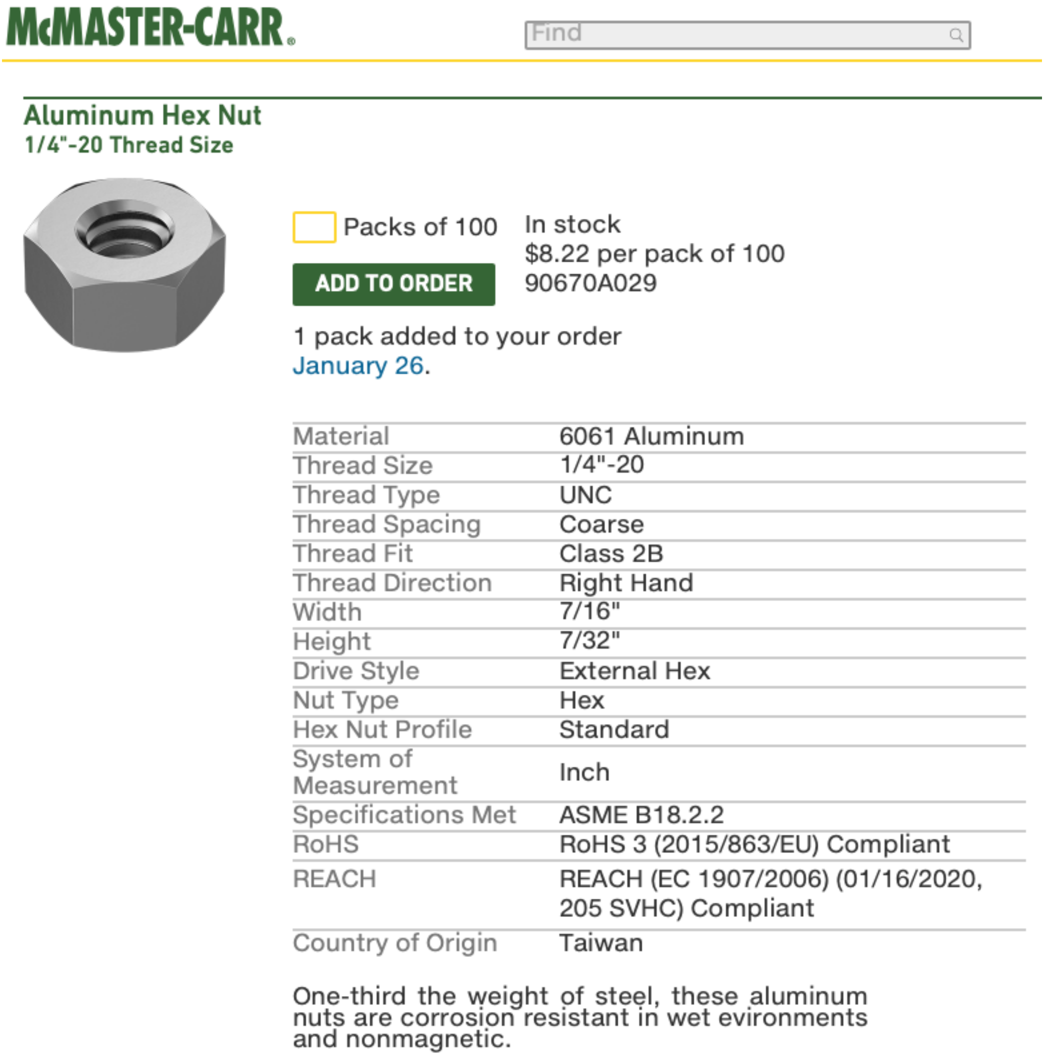
☐ Packs of 10

In stock
$7.87 per pack of 10
93306A546

1 pack added to your order
January 26.

Head Type	Hex
Drive Style	External Hex
System of Measurement	Inch
Thread Direction	Right Hand
Thread Size	1/4"-20
Screw Size Decimal Equivalent	0.25"
Thread Type	UNC
Thread Fit	Class 2A
Length	1 1/2"
Threading	Fully Threaded
Thread Spacing	Coarse
Head Width Height	 7/16" 5/32"
Material	2024 Aluminum
Tensile Strength	30,000 psi
Hardness	Rockwell B40
RoHS	RoHS 3 (2015/863/EU) Compliant
REACH	REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant
Country of Origin	United States

Aluminum screws are one-third the weight of steel and have good corrosion resistance. Length is measured from under the head.



Aluminum Hex Nut

1/4"-20 Thread Size

☐ Packs of 100

In stock
$8.22 per pack of 100
90670A029

1 pack added to your order
January 26.

Material	6061 Aluminum
Thread Size	1/4"-20
Thread Type	UNC
Thread Spacing	Coarse
Thread Fit	Class 2B
Thread Direction	Right Hand
Width	7/16"
Height	7/32"
Drive Style	External Hex
Nut Type	Hex
Hex Nut Profile	Standard
System of Measurement	Inch
Specifications Met	ASME B18.2.2
RoHS	RoHS 3 (2015/863/EU) Compliant
REACH	REACH (EC 1907/2006) (01/16/2020, 205 SVHC) Compliant
Country of Origin	Taiwan

One-third the weight of steel, these aluminum nuts are corrosion resistant in wet evironments and nonmagnetic.

Adaptive Tricycle

Universal Design Report

Spring 2020

California Polytechnic State University,
San Luis Obispo

Sponsored by
California Children's Services

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Table of Contents

Background

Our senior project was initially geared towards adapting a hand-powered tricycle into a core-powered tricycle, however, the COVID-19 pandemic halted manufacturing plans, despite our group having a full working design. We have created an informative guide to demonstrate the findings from our senior project along with a step-by-step process on how a common adult tricycle can be adapted into a push-bar tricycle. Creating this sort of tricycle would prove beneficial for any individual who has limited used of their upper or lower limbs, or even for any able-bodied person looking for a quality core exercise.

Overview

This section acts as a brief outline for the reader to understand the further sections in this document. Firstly, the material selection section will discuss the materials necessary to complete this project. Sections identifying the major subsystems of the adapted tricycle design were included for the ease of distinguishing various components of the assembly. A deliberation of the results from multiple design iterations is included in the results section to support subsystem design decisions, while subsequent sections describe analysis to justify final decisions. Finally, the step by step guide and recommendations section is outlined at the end of this document for the reader to follow. It is important that the reader should already possess an existing tricycle or be prepared to purchase a tricycle for the completion of this design as this guide does not cover how to build a tricycle from scratch. Any tricycle that can comfortably fit an adult's body will suffice. Figure 1 depicts the tricycle we adapted for this project.

Figure 1. An example of a potential tricycle that could be used for this project.

Further things to take note of are some limitations that this design contains or does not take into consideration, including that the design is ultimately intended for the adaptation of a tricycle specified for one user, although the design could be operated by anyone with a similar body type to our intended user. This aspect must be taken into consideration before any tricycle assembly has begun.

Material Selection

There were two primary constraints for selecting the materials for the adapted components of the tricycle: the ability to weld the new component to the frame (only steel components could be welded to the steel frame) and the weight of the components. If the component being attached to the tricycle was not being welded, we chose to use Aluminum 6061 since it was the most lightweight and strong material. If the component had to be welded, we would use choose carbon steel. An example of this is shown by our decision to use stock carbon steel tubing for our support members, and stock aluminum to build the push bar system since it could be fastened to the drive train without welding.

Following these two basic constraints, we then used the material choices to complete the necessary calculations to determine the dimensions of each component, such as the diameter of the crank arms and the thickness of the power bar. We implemented equations and theories from earlier material and stress analysis courses, along with the component material properties, to analyze and determine the correct sizing of each component.

Subsystem Breakdown

The three major subsystems of the tricycle were the powering, steering, and braking subsystems, all of which must be implemented cohesively for the tricycle to be operated properly and comfortably.

The primary components in the power subsystem are the driving sprocket, the crank arms, and the power bar, all of which are labeled in Figure 2 below. The power subsystem consists of a large driving sprocket attached to the main wheels of the tricycle. Following this, crank arms are attached to the sprocket, and then to the power bar. This connection of the power bar to the drive sprocket with crank arms creates a longer lever arm, giving the user more torque for the given input force. The crank arms are hollow aluminum tubes connected to both sides of the middle-resting power bar, which is where the input driving force is given. After researching similar tricycle projects, using the crank arms and power bar to power the tricycle was the most feasible design to implement onto the tricycle.

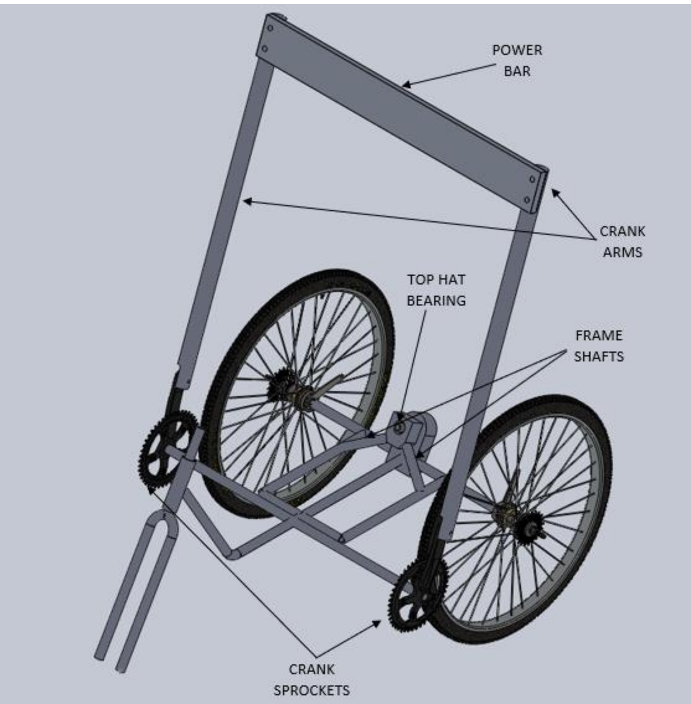

Figure 2. CAD model focusing on powering subsystem.

The steering subsystem consists of the seat, the supporting shaft, the steering shaft, a torsional spring, steering shaft, and bevel gears, which are indicated in Figure 3. The seat is meant to be comfortable for the user as well as be able to rotate on the shaft that connected to the main frame of the tricycle, supporting the seat. Encasing the steering shaft is the support shaft, allowing the seat to rotate around it by inserting sleeve bearings between the two shafts. With these components comes a torsional spring attached to the steering shaft, and this component translated a torsional force to the steering shaft that brings the seat to the middle, straight steering position. To translate the steering motion of the shaft to the front wheel, bevel gears were chosen, since they translate rotational motion at a 90° angle to each other. The bevel gear set is connected to the front wheel steering column and steering shaft, translating the rider's leaning rotation motion to turn the front wheel. This method of rotational translation is the simplest and most efficient idea available.

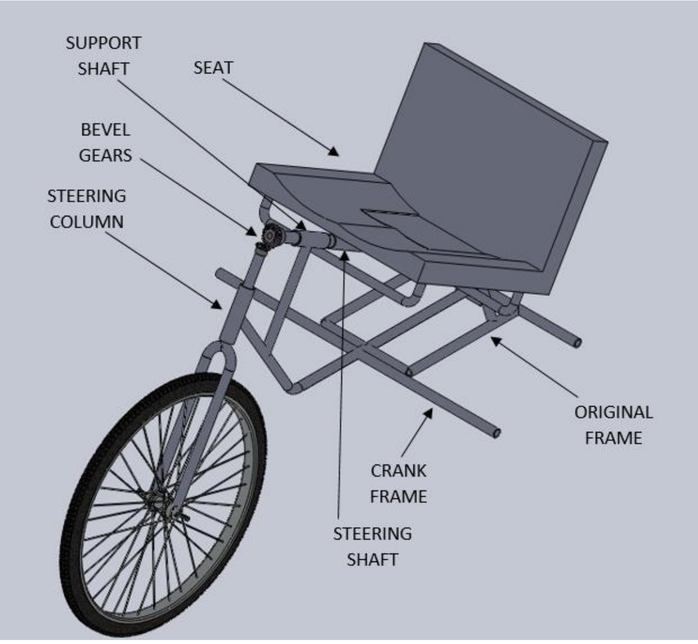

Figure 3. CAD model focusing on steering system and its associated frame components.

The final subsystem necessary to operate the tricycle is the braking subsystem, which consists of a wire-activated caliper brake mechanism connected to the crank arms, which in turn are connected to the user via a strap. The braking force is inputted by pulling the strap that sits around the user. Pulling the strap backward translates the force to the crank arms and activates the wire braking mechanism that then stops the vehicle. The wire braking mechanism was chosen over the previous decision of using coaster brakes, because the range of motion of the user was extremely limited, rendering the coaster brakes unusable. The wire braking mechanism allows for a pulling force to activate the tricycle, making it the most optimal choice for braking.

System Integration

Each subsystem within the overall design of the tricycle was chosen and refined based on its ability to operate efficiently relative to the other subsystem operations. To this extent, we designed the subsystems such that there were no redundancies in operator motion. The powering system utilizes forward pushing while the steering system relies on lateral leaning and the braking system is engaged by backward leaning and pulling, so no singular motion can engage more than one subsystem at a time. Each subsystem's operational capacity, however, is reliant on its position relative to the other subsystems and the rider. The steering system is located centrally in the tricycle, since the steering shaft must be able to rotate the rider, seat, and front wheel without interfering with the powering and braking subsystems. The power bar, which is the primary component that the rider interacts with for the powering system, is designed around the front half of the steering shaft to prevent interference with any rotating steering components, including the rider. Since a caliper brake is used with a tensioned cable to engage it, the powering system and braking system are both attached to the power bar and crank arm subassembly. Pushing to power the tricycle will create more slack in the brake cable, preventing it from engaging, while backwards leaning to engage the brakes will be in the opposite direction of motion necessary to power the tricycle. By positioning the subsystems as we did, riders can comfortably engage any of the subsystems just as operators of a traditional tricycle would.

Design Results

Our final design is a direct result from several iterations of prototyping throughout the school year. Beginning with our ideation phase and ending with our verification prototype, we verified our choices with engineering calculations and simple prototypes to. The most notable thing that we learned from prototyping was from speaking with a Cal Poly shop tech who helped us find out a significant problem with our drive train design. We then sourced two types of bicycles, one with a braking system that was separated from the drive train and another bike with a coaster brake (braking system is integrated into the drive train). The difference in the two designs revealed a flaw in our initial design. We learned that if a coaster brake is used, then the drive train cannot power the tricycle forward because the crank arms must rotate 360 degrees so that the coaster brake does not engage. However, with the other bike design, a caliper brake installed separately from the drive train, the crank arm is free to operate in any range of angles without engaging the brake thus making it the ideal design for our application. We did not run into any significant trouble with verifying our design outside of this instance. As a result, our design proved that it could be operated without the use of any limbs which is the main design constraint of the project besides safety.

Other than the setback with our drive train, we were confident that our design would operate as intended because of the work we did with our solid model, engineering calculations, and prototyping. For our engineering calculations, we made justifications by using principles from the mechanics of materials, such as deflection calculations, in order to solve for the sizing of our parts. We also performed a dynamic analysis on the drive train and the brakes to determine the required force inputs from the user. However, without building a full-scale prototype and running tests to verify its functionality we could never be fully confident that the tricycle would perform as it was designed. These tests would measure the top speed under the user’s own control, ease of use, steering performance, time to access the seat, braking distance, weight, dimensions, aesthetics, time until top speed. The objective of these tests is to ensure that the tricycle is a safe and effective way to provide exercise to the user. Before our team wrapped up winter quarter, we had detailed out plans to execute manufacturing as well as begun a small amount of machining. Since we had done enough analysis to size our parts, we planned to rely on learning more about the legitimacy of our design through trial and error during the manufacturing and testing phase. Unfortunately, due to the closure of Cal Poly's campus, and therefore the machine shops, our team was rendered unable to complete any further manufacturing.

Tricycle Assembly Guide

Our adaptive tricycle assembly was originally designed with one unique user in mind, but the design can be altered slightly to apply to a wide range of users. Table 1 lists the critical components and materials purchased for our group's own specific project. The sizing, material, and quantity of various parts will change with each project's design, which is why engineering analysis is crucial to determining the components necessary to adapt a range of tricycles.

Table 1. Critical components and dimensions our group used for our design.

Part Name	Description	Dimension 1	Dimension 2	Quantity
Steering Shaft	Low-Carbon Steel Round Tube	0.12" Wall Thickness	1" OD	6 feet
Bevel Rack	Metal Miter Gear, Round Bore	1/2" Shaft Diameter 12 pitch	24 teeth	1
Bevel Pinion	Metal Miter Gear, Round Bore	1/2" Shaft Diameter 12 Pitch	15 Teeth	1
Push Bar	Multipurpose 6061 Aluminum	5/16" Thick	2" x 48"	1
Top Hat Bearing	Oil-Embedded Flanged Sleeve Bearing and	for 1/2" Shaft Diameter	for 3/4" Housing ID	1
Seat Sleeve Bearing	Oil-Embedded Bronze Sleeve Bearing	for 1" Shaft Diameter	for 1-1/8" Housing ID	3
Support Shaft	Low-Carbon Steel Round Tube	0.188" Wall Thickness	1-1/2" OD	6 feet

The following guide outlines the steps necessary to integrate the subsystems within a tricycle, which can be modified to account for discrepancies between our original tricycle and similar tricycles to be modified.

Step 1: Prepare existing tricycle design

Initial tricycle designs can vary greatly, so any components which could potentially interfere with the adapted design must be removed or altered. This includes, but is not limited to:

- Removing any paint from the tricycle for cleaner welding
- Determining frame material to ensure that welded material is metallurgically compatible
- Modifying the front steering column such that there are no components above the stem of the steering column. Bevel gears will be added to the pre-existing column, so do not remove the entire column
- Removing any chain systems currently on tricycle
- Disengaging or removing the braking system
- Removing the seat from the frame
- Removing any frame components that are directly attached to the seat
- Modifying or replacing original sprockets to match with new sprockets to be added

Step 2: Prepare custom components

Our design consists of many new components for integration with the existing design, but minimal modifications to these components are necessary. For instance, most of the stock tubing modifications for various components are only to cur them to a specified length, with a few holes drilled into some components for fastening with bolts. However, some materials required further machining for proper fit and fastening. These components may differ for those attempting to modify a different tricycle, based on the necessary sizes and fits of the components they are working with. Our group machined the crank arms to include slots on each end for the power bar and crank sprockets to slide into and be bolted together, as shown in Figure 4. We also planned to make angled cuts into new frame components to improve their fit when they were welded to the existing frame, since the frame cross section is round.

Figure 4. Setup on mill to cut slots into crank arms.

Step 3: Size steering shaft

The steering shaft can vary in size, depending on tricycle configuration and material selection, but should not exceed an outer diameter of 1.5” for it to properly fit within the rest of the steering system. To determine the length of the shaft necessary, measure the direct distance between the steering column stem and the lowest point on the rear of the tricycle frame. The steering shaft thickness is dependent on material choice and its desired outer diameter. The steering shaft must also be smooth on each end, which can be accomplished by facing the material, to allow for proper fit with the bevel gears and bearings to be installed later.

Step 4: Prepare frame components for attachment

Tricycle frames will vary, so it is important that the subsystems will be easily integrated into the pre-existing frame. Both the support shaft and crank shaft function as connection points between the frame and the subsystems since they both house bearings which allow for rotational motion relative to the tricycle frame. The support shaft should be approximately 4” long such that it can house two bearings which connect the steering shaft to it. Crank shafts on each side of the tricycle frame house bearings to allow for rotation from the crank arms, which are used to turn the sprockets which power the tricycle and should be sized such that their lengths do not exceed the length of the rear axle in either direction once attached to the original frame. The inner diameter of the support shaft and crank shafts must be identical to the outer diameter of their associated bearings since they will be press-fit to each other. Press-fit bearings to the outside of the steering shaft and then inside the support shaft as well as to the outside of the crank shaft and inside the sprockets which will be used to transfer power to the tricycle.

The third major frame component which must be considered is located at the bottom of the rear of the tricycle and is meant to support the steering shaft with any axial loading. Dimensions and location of this frame member can be adjusted based on tricycle design and the steering shaft length measured, but must be designed such that it will connect to the frame rigidly and be able to house a top hat bearing with axial support, which is sized based on the inner diameter of the steering shaft.

Step 5: Attach new frame components

Figure 5 depicts the modified frame components from our design, including components which we planned on welding to the original frame, since they were all low carbon steel. However, other fastening methods, such as bolting the frame components together or clamping to the original frame could also work, although proper stress testing must be done separately to ensure that fastening components will not deform or break under typical driving loads.

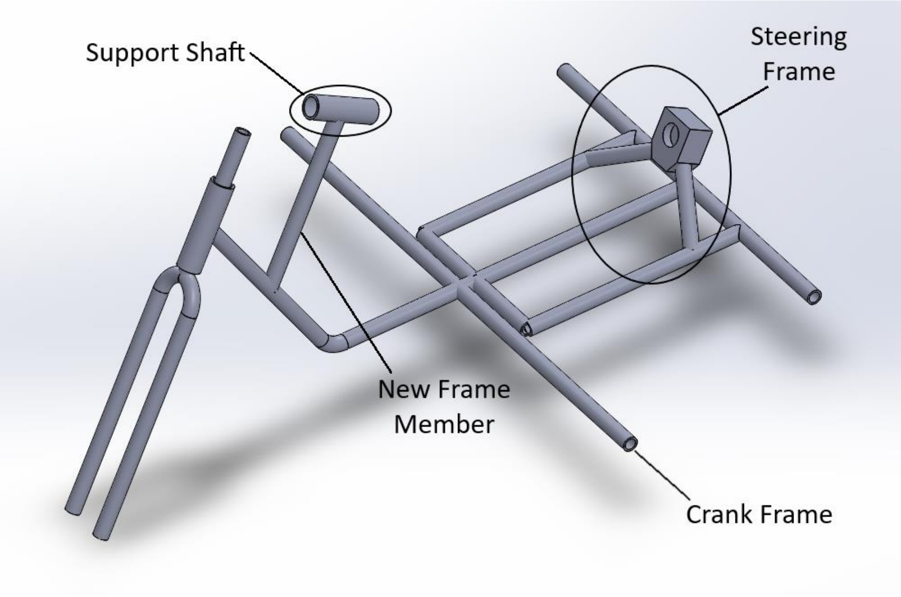

Figure 5. Modified frame components on tricycle assembly.

The support shaft should be attached such that it is perpendicular with the steering column because the bevel gears which will be attached to it and the steering column mesh at a 90° angle. The crank arms must be attached such that the tops of their sprockets are aligned with the top of the existing rear wheel sprockets when the chain connecting them is added. If new rear wheel sprockets are necessary based on a desired gear ratio or inability to find a crank sprocket that meshes with the original rear sprockets, then the alignment can be done once the new rear sprockets are installed. Finally, the rear frame member must be attached such that it transfers any axial forces from the steering shaft, including rider weight, to the frame, so attachment must be done once the support shaft, with steering shaft and bearings already attached, is properly fastened.

Step 6: Attach seat to steering shaft

Once the frame components are properly fastened, seat attachment can be performed, since attaching the seat makes it much easier to locate other components to be attached relative to it. We decided that C-clamps would be the best form off attachment for the seat to the steering shaft based on the original seat design. Our original seat, as shown in Figure 6, had a plate attached to its bottom end for support and to enable us to bolt the C-clamps to the plate once they were attached to the steering shaft. Seat designs can vary greatly between tricycles, so the most important consideration when deciding how to attach the seat to the steering shaft is its rigidity relative to it. If the seat does not directly rotate the shaft, or there is slippage between the two components, then the steering subsystem will not operate effectively. Add any components necessary to either the seat or shaft to ensure secure attachment without greatly increasing the overall weight of the tricycle or interfering with frame members.

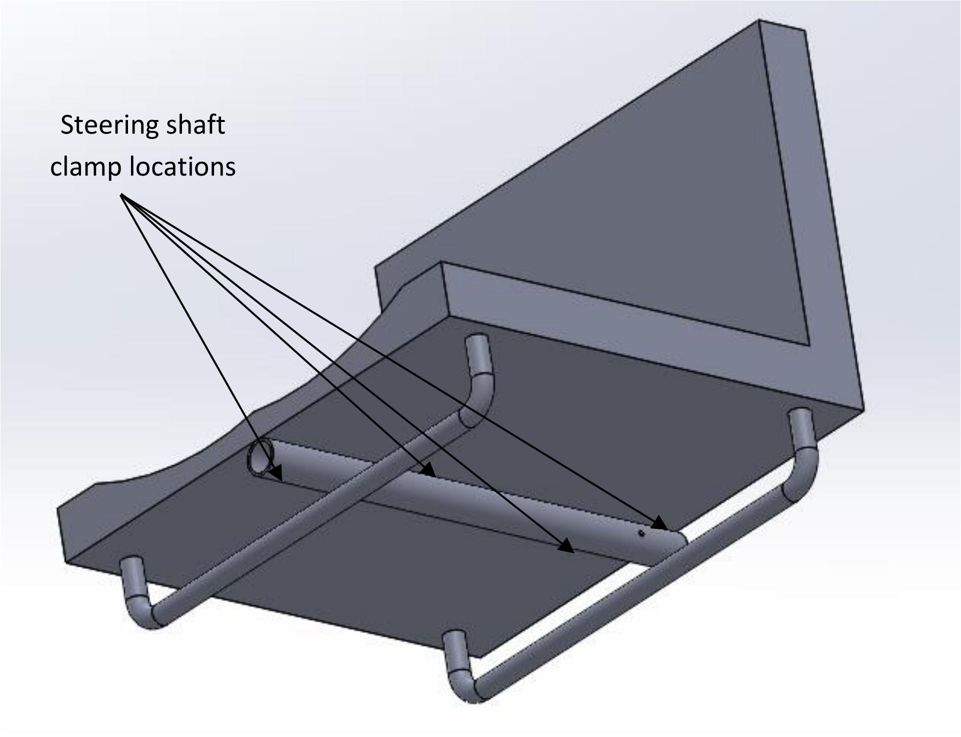

Figure 6. CAD model of original seat design to illustrate clamp locations.

Step 6: Attach bevel gears to tricycle

Once the seat is secure, the bevel gears must be attached to the steering shaft and the steering column. We decided to attach the bevel gears to the steering shaft once the shaft was already on the tricycle to facilitate proper gear meshing more easily, since the steering column has not been altered completely by this step. This may make press-fitting difficult to do, so other attachment methods, such as creating a keyway or threaded insert which can then be attached to the steering shaft and the gears can be bolted to the shaft.

Step 7: Install chains and crank arms

The steering system is now fully assembled, so the power system components, which include the crank arms, chains, and power bar connecting the crank arms. The chains should be installed first, since tensioning them without the rest of the power system attached is significantly easier. Before tensioning the chains, it is helpful to check that all four sprockets match in pitch and that they are all properly oriented for the chain to be added. This orientation can be referenced in Figure 2, which depicts the entire powering system. After the chains are tensioned properly to the both the crank and free sprockets on each side, attach the crank arms to their respective crank sprockets. We decided to bolt them together in our design to simplify the attachment design. Crank arms should be left in the same position, ideally vertically upright as shown in Figure 7, to aid in the attachment of the power bar in the next step.

Figure 7. Crank arm and sprocket orientation once installed.

Step 8: Attach power bar

Power bar installation is the final component of the powering system to install. Simply attaching the power bar to a flat edge on the crank arms with two fasteners on each side was the method we chose for attachment. It is critical that all power system components are tightly fastened, since the loads placed on the powering system are larger than any other subsystem.

Step 9: Install braking mechanism

If the original tricycle braking system was attached to any original components which were removed at any point in the assembly of the tricycle, then a new braking system must be installed to ensure safe and effective tricycle operation. Our tricycle design utilized a newly installed caliper brake on the front wheel, which we recommend as the primary braking wheel to optimize braking performance. The tricycle is designed to be driven at relatively low speeds, so front wheel braking will not suffer from potential tip-over upon engagement.

Attaching a common brake line will connect the caliper brake directly to the power bar to minimize braking reaction time. This line should be tensioned such that in the power bar's neutral position relative to the rider, the brake will engage if the power bar is pulled back. The brake travel must not exceed the distance between the power bar neutral position and the farthest possible distance that the rider can sit back, such that the brake can be fully engaged within the rider's backward leaning range of motion.

Step 10: Attach strap to power bar

The final and most important component to install on the tricycle is the rider strap. The strap allows the rider to pull backwards on the power bar, which is necessary both for continuous tricycle powering and for brake engagement. While we do not have a specific strap recommendation, the strap must have features which allow it to be fit its intended purpose of connecting the subsystems to the rider. The strap must be capable of:

- Fitting securely around the rider and staying on the rider for the ride duration
- Attaching to the powering system tightly and symmetrically relative to each side of the tricycle
- Supporting push and pull loads from the rider, which may include tension forces of up to 200 lbs
- Being flexible enough to handle leaning in multiple directions while operating

Straps should be comfortable while pushing and pulling on the power bar and since the strap will experience cyclical loads from powering and braking, it is recommended that the strap material is capable of experiencing tension and torsional loads at least twice as large as the rider's pulling strength capabilities.

Recommendations

Following the completion of this project, we felt it was necessary to note any recommendations for an individual or group seeking to pursue projects of this scale. First and foremost, it is important to always keep the user at the forefront of the design. As seen throughout this guide, many design decisions were based around the specifications of a person that we believe would use our product. This supports the fact that it is also crucial to test out any ideas or calculations with physical prototypes. These prototypes could be rudimentary as long as they accurately model the mechanism being tested. Once the subsystems have been verified individually, it is then important to test out how the subsystems of any design are able to integrate with each other. Further prototyping and well-organized models can guarantee the integration of these components. However, spontaneously coming up with ideas and prototypes is not an effective strategy as it has no structure and often does not take all necessary considerations into account. Rather, a strong focus on planning and scheduling provides the foundation of a quality project. This plan also needs to be very flexible and ready for any setbacks, as, from our experience, we found are likely to occur. Ultimately, it is essential that the individual or group undertaking this project keeps themselves organized, flexible, and goal-oriented.