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Northern Arizona University

NASA Human Exploration Vehicle Competition

Final Report

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1 Introduction

The objective of this project is to design and build a vehicle that can navigate a multitude of terrains through a half-mile course to participate in the NASA Human Exploration Rover competition. The sponsors that are interested in this project are NASA along with the Society of Automotive Engineers advisor (SAE), Dr. John Tester. Their interest comes from the want to be able to cross the predicted terrains of planet Mars, and to aid with their design for the actual prototype. The completion of this project will provide a working prototype of a design that will suit their needs, as well as become a possible design for future NASA missions

1.1 Project Description

Following is the original project description provided by the sponsor:

> "NASA Human Exploration Rover Challenge revolves around NASA's plans to explore planets, moons and asteroids across the solar system. The project is to design, construct, test and race mobility devices–lightweight, human-powered rovers–capable of performing in the varied, demanding environments to be explored. The challenge will focus on designing, constructing and testing technologies for mobility devices to perform in these different environments." [1]

1.2 Original System

This design project is not a revision build, because of this, we used other designs, products, and projects to help us better understand the design challenges. With no previous or original system to reference, we used projects such as the Human Powered Vehicle (HPV), along with consumer products such as a recumbent bicycle, a quad-cycle, and a tandem bike. The comparison and usefulness of each system will be discussed later in the report.

2 Requirements

This section begins with a description of the requirements outlined by the customer, engineers, how we are going to test our rover, and the design links. The customer requirements are weighted numerically, with higher numbers signifying a more important requirement. Engineering requirements are measureable parameters set by the to help evaluate and design certain aspects of the rover. The engineering and customer requirements are related, and compliment each other's criteria and desired outcomes. Also included are target objectives, which are not substantial requirements that necessitate a weighting; which indicates goals that the team aims to meet. Customer requirements and target objectives are compiled into a House of Quality along with corresponding weight ratings. Testing procedures are the process in which the team will test and verify that our design has met standards and is of quality to compete. The final section, Design Links, is the validation that all of the customer requirements, engineering requirements, and testing procedures have been met and successfully carried out. This section may refer to the design objective as a vehicle or a rover, which are synonymous terms for the design objective.

2.1 Customer Requirements

The customer requires that the team build a vehicle that is solely human powered and propelled around the test course by two students – one female and one male. Tires on the vehicle cannot be inflatable or pneumatic. The vehicle must be sturdy enough with wheel technology able to traverse large obstacles, it must also provide traction and support on soft, hard, rough and smooth surfaces; and be able to cross cracks, crevasses and ruts. The vehicle must be able to do this on flat or inclined surfaces from a moving or static start. All wheels must be covered with dust abatement devices, or fenders, sufficient to mitigate the hazard of flying debris.

To verify ship-ability, the vehicle must be easily deconstructed to fit within a cubical container of sides measuring five feet. The vehicle must be lightweight and portable, such that collapsed shipping configuration can be lifted by the two drivers and carried 20 feet without contacting the ground.

Assembled, the vehicle is constrained to a width no greater than five feet, with no restrictions on length or height. The ground clearance of the vehicle at its lowest surface must be no less than 15 inches. The turning radius of the vehicle can be no greater than 15 feet. The vehicle is required to have a specific set of accessories, which may be real or simulated during testing. They include a high-gain antenna, a national or institution flag, two batteries, a video camera and an electronic control panel. To address safety concerns, the vehicle seats must have adequate restraints to secure the driver. Furthermore, all sharp edges and geometries must be guarded or eliminated. The customer requirements a can be referenced in the House of Quality in the appendix c.

2.2 Engineering Requirements

The engineering requirements create a relationship between the customer requirements, and a measureable approach to each of the design aspects of the rover. These requirements allow the team to measure and evaluate the performance of the vehicle, and if the vehicle design is up to competition standards. The engineering requirements and customer requirements have a strong relationship, and can be seen as complimentary components of our design due to the fact that the engineering requirements were created from the customer requirements. The engineering requirements can be referenced in the House of Quality in Appendix C.

2.3 Testing Procedures

This section reviews the testing procedures implemented on the final design to verify that all the customer requirements are met via meeting the targets for the engineering requirements specified in Section 2.2. The following subsection numbers and descriptions correspond to the numbers that appear in the Testing Procedure row of the House of Quality in Section 2.5.

2.3.1 Measure Air pressure with tire pressure gauge

This testing procedure consists of using a standard tire pressure gauge to measure internal air pressure in the wheel system. The pressure can be taken with the gauge at the air filler valve located on the inner side of the outside of the rim.

2.3.2 Measure with length scale using imperial units

This testing procedure consists of using a length scale to measure the distance between two points. These two points can be the extrema on a component of the design, and the resulting measurement identifies a critical dimension constrained by a target value. The two points can also be the ground and a point on the rover, and this measurement itself, or in combination with others and trigonometric math, will identify a value to compare to the target value.

2.3.3 Weigh with shipping/pallet scale

This testing procedure consists of taking the rover as a whole, or any component or subsystem, and placing it on an appropriate sized shipping scale to find the weight of the item.

2.3.4 Time trial using stopwatch

This testing procedure consists of timing a predetermined activity or test of the rover with a stopwatch. To obtain an accurate measurement, multiple stopwatches will be used and acquired time measurements averaged.

2.3.5 Inspect number of seats and sets of pedals

This testing procedure consists of evaluating the capacity of the rover with respect to the amount of riders that can be transported. The number of seats will identify the amount of people that can ride the rover at any given time. The number of sets of pedals will identify the number of drivers required to power or maneuver the rover.

2.3.6 Measure number of revolutions input to rotate final gear 360 degrees

This testing procedure consists of counting the revolutions of two gears that rotate simultaneously. A radial line or marking on each gear is required to conduct this test. The testing engineer must count the number of full rotations and approximate angle of incomplete rotation the input gear makes while the final gear rotates one revolution, or 360 degrees. Dividing these two angle values will result in a gear ratio that can be compared to the specified target(s).

2.3.7 Inspect log books for build activities and time spent in NAU machine shop

Frame and all parts able to be manufactured must be made in the NAU machine shops or campus. This will include all welding and frame tubing to be finished in house. The team will create steering, suspension, seating, and other non-purchasable parts. Parts not created are wheels, safety restraints, and bearings.

2.3.8 Inspect seat harness material, slack in strap, number of points of harness and load testing

This testing procedure consists of inspecting the material in the harnesses to make sure there are no defects that may cause failures. Adjustments to the harnesses will be made to make sure the drivers are secured tightly in the rover. The number of points on the harness correlates to the comfort and distribution of loads applied to the driver. By utilizing a higher number point harness, we can ensure more safety. After material inspection, adjustments, and correctly chosen harnesses have been completely, simulation of loads the harnesses may experience during various stages of the competition and testing will be applied to make sure there are no failures.

2.3.9 Test drive for control of vehicle

This testing procedure consists of simulating the environments the rover will encounter during the competition. By testing each environment, the driver may suggest modifications to the rover that will allow for greater control and safety of the rover. Testing each environment will apply stresses to the rover, which if a certain part fails, can be redesigned and fixed.

2.3.10 Inspect for sharp edges

This testing procedure consists of visually inspecting the rover for any protruding objects, sharp materials, or any possibility for the drivers to get injured. A physical test will be conducted using a cotton glove, feeling each sub system of the rover to see if any part snags the glove. If the gloves do not snag on any certain part, the rover is safe of sharp edges.

2.3.11 Inspection by representative from NAU marketing department

This testing procedure consists of asking for an evaluation of the rover by a representative from the NAU marketing department. The evaluation will have a form with multiple criteria and a quality scheme for the inspector to grade the design on. The use of multiple evaluators will be used to get an average grade of the overall vehicle presentation.

2.4 Design Links

This section of verifies that each of the engineering requirements specified in section 2.2 are met by our design. The following subsection numbers and descriptions correspond to the numbers that appear in the Design Link rows of the House of Quality in Section 2.5.

2.4.1 Material Selection

This section of the design link establishes the materials chosen for each subsystem. When choosing materials, the main properties considered are how heavy it is, does it allow for a lightweight design, and is the material is cost effective. The material also has to be durable, due to the various environments the rover will encounter.

2.4.2 Component sizing

This section of the design link verifies that the total design meets the size requirements. The main size restriction is that the total design fits within a 5x5x5ft box.

2.4.3 Subsystem placement

This section of the design link supports that each subsystem is placed in the most ideal location. Each subsystem of the design performs a specific function that contributes to the total success of the rover, and has a relationship to the performance of the rover.

2.4.4 Assembly simplicity

This section of the design link focuses on how easily each sub system can be assembled into the whole system. The competition time restriction for assembly is 2 minutes or less.

2.4.5 Fabrication method

This section of the design link focuses on how easily each part of each subsystem can be fabricated or acquired. Fabrication time should be kept to a minimum if possible. Rover testing is set to take place in February of next year, so all parts should be fabricated, acquired, and assembled by this time.

2.4.6 Paint color matches NAU color swatches

This section of the design link focuses on how the rover is to be painted. The initial plan is to have the vehicle powder coated by a school down in Phoenix. If the initial plan doesn't work, the team will look into a cover of plasti-dip. Plasti-dip is a plastic coating of color over the material of the rover that is durable and can peel off whenever it is desired.

2.5 House of Quality

This section briefly discusses the HoQ that is included in the Appendix. The HoQ consists of 17 customer requirements (CRs) each weighted by the importance of its inclusion in the final design. The two most important characteristics of the design are that the vehicle is human powered, and can be easily transported. Cargo space is limited during space travel, so having a light compact design will be more desirable for NASA. To view the rest of the CRs, reference the HoQ in Appendix C.

3 Existing Designs

The following section lays out the preliminary research for the Mars Human Powered Vehicle project. Research was conducted to ensure preventable mistakes are avoided. Below, the research is divided into sub-categories in order to establish the alternative areas to learn about human powered vehicles. The system level and subsystem level sections divide the key areas of focus in order to better understand what the research was focused at studying.

3.1 Design Research

The research for the Mars human powered vehicles comes from the following areas: personal experience, internet research, the Northern Arizona University SAE club (Students of Automotive Engineer), NASA Curiosity engineers and prior internship bike research. The areas of research are broken up into categories to show the various forms of research. The key focus when collecting the data was to evaluate systems and subsystems that the team will encounter in the design and construction of the vehicle.

3.1.1 Personal Experience

This section includes the relevant collective experience of all the team members. This knowledge comes from our own personal interactions with vehicles, whether human powered or motorized, throughout our engineering experience. This experience ranges from repairing and restoring bicycles to fixing cars. The team experience is important in the design and construction of the Mars Rover vehicles. This experience is important for understanding proper materials and the manufacturing of parts and subsystems.

3.1.2 Internet Research

The internet research includes processes and information from various industries including bike shops, motorcycles manufactures, automotive industries, and engineering companies. A large influence in changing the paradigm of the problem came from the competing teams that have pictures on the NASA website [1]. It is important when viewing the competitor's designs to not copy them, but to approach it with the mindset of learning from their success and failures. Additional internet research was done with the SAE and is explained in the following section.

3.1.3 Northern Arizona University SAE

The Northern Arizona University chapter of SAE is one of the project's most valuable resources. All members of the Mars Exploration Rover team are new associates of the organization and are learning about the vast resources of the SAE organization. Such resources include fellow peers within the program, senior engineering professors, machine shop capabilities, and a library with automotive resources of such as the SAE magazines. The importance of SAE is that the chapter heads have decades of experience in automotive vehicles, design, and testing.

3.1.4 NASA Curiosity Engineer

The lead engineer of the Mars Curiosity rover will be in contact with the team leader to help explain challenges and issues that NASA Curiosity group had when designing their multi-million dollar rover. This resource will be used for educational purposes with a small possibility of design help.

3.2 System Level

This section outlines the results of the research mentioned earlier in this document.
There were many different types of designs the team had looked at, ranging from tandem bicycles to quad-cycles. The designs were diverse and not directly related to the actual project in order to understand the different subsystems and how they function together. Each design had the individual subsystems analyzed to determine how each design functioned as a whole. The pros and cons were then weighted against each other to determine which system is best.

3.2.1 Existing Design #1: Quad-Cycle

The quad-cycle can be a one or two person bike with four wheels. Pros of this design are that it is stable, can easily carry two passengers, has plenty of storage space, and is all-terrain capable. Cons are that the frame has a small profile, it appears that the weight is off center and wheel axels appear to be fragile. The quad-cycle cannot navigate large obstacles and currently has no dust abatement fenders. It is unknown if this design has a 15 foot turn radius or if the undercarriage height is at least 15 inches. This design satisfies the requirements of transporting two people, store accessories, less than five feet in width, and can be easily collapsed down into a 5-by-5-by-5 container. A standard quad cycle design can be seen in **Figure *1***.

Figure 1: Quad Cycle

3.2.2 Existing Design #2: NAU Human Powered Vehicle

Northern Arizona University's Human Powered Vehicle (HPV) performed well at last year's competition. Pros of the HPV are that it is lightweight, aerodynamic, and fast. However, it cannot go over large obstacles, cannot accommodate two riders, has no storage space, extremely poor turn radius, cannot be collapsed down, and it is too low to the ground. Two riders can carry this design. The HPV can be seen in **Figure *2***.

Figure 2: NAU HPV

3.2.3 Existing Design #3: Recumbent Bike

A recumbent bike is similar to NAU's Human Powered Vehicle. Recumbent bikes excel at stability, turning radius, are lightweight, and have the potential for storage space. However, a recumbent bike is too low to the ground, it cannot hold two people, cannot collapse into a 5x5x5 box, cannot traverse over large obstacles, and it has inflatable tires.

A recumbent bike design can be seen in Figure 3.

Figure 3: Recumbent Bike

3.2.4 Existing Design #4: Tandem Bike

The tandem bike is built so two people can ride single file while pedaling on the same gear train. They are typically lightweight, fast, have a minimized turning radius, and can navigate over large obstacles. Tandem bikes do not have storage space, cannot collapse, and cannot carry required accessories. A standard tandem bike design is shown in Figure 4.

Figure 4: Tandem Bike

3.3 Subsystem Level

This section breaks the rover design down into six subsystems. Each subsystem will be listed, and will be followed by several prospective designs.

3.3.1 Subsystem #1: Wheels

The effectiveness of the wheels will be a factor in how much force is needed to overcome various terrains in the competition. Durable wheels with good traction that do not require air are necessary if the team wants to do well at the competition.

3.3.1.1 Existing Design #1: Rubber Wheels

The common wheels are standard rubber, inflated wheels. They are good for traversing rough terrain, are easy to transport, and light enough to have spares on board the vehicle. These wheels can traverse large obstacles with the proper propulsion; they have decent traction, and provide some support over soft, hard, and rough surfaces. The cons of these wheels are that they need to be inflated, there are no dust abatement devices, and they can wear down quickly.

3.3.1.2 Existing Design #2: Solid Rubber Wheels

Solid rubber wheels are the same as the previous design, except that they need no inflation. These wheels have a long useful life, and require minimal maintenance. The main disadvantages of these wheels are that they are heavy and difficult to purchase.

3.3.1.3 Existing Design #3: 3D Printed Wheels

3D printed wheels of a new design by Dr. Tester have the potential to be very effective. The problem with this wheel choice is that he has not yet explained their exact specifications, and it is likely that they will not be as durable as off the shelf alternatives.

3.3.1.4 Existing Design #4: Solid Aluminum Wheels

Solid aluminum wheels are another option. These are currently what the Mars Curiosity Rover uses. These wheels are long lasting and greatly exceed the amount of payload they can support when compared to similar designs. The problem with this choice is the added weight, the high cost of material/machining, and the low amount of grip on solid surfaces (no dirt).

3.3.2 Subsystem #2: Braking

As important as propulsion is, braking is equally important. The vehicle needs to brake well to be able to maneuver the terrain and obstacles present at the competition. A good braking system will increase handling around turns as well as protect the drivers and the vehicle if there is a need to come to an abrupt stop.

3.3.2.1 Existing Design #1: Disc Brakes

Disc brakes are very common on bicycles. Pros of disc brakes are the durability, no rim wear/tear, long lasting, resistant to mud/water, and stronger than rim brakes. Cons of disc brakes are the added stress to the spokes, they heat up quickly, require readjustment, and cause torsional stress on the wheels. Disc brakes are relatively standard and provide good control over the vehicle.

3.3.2.2 Existing Design #2: Pad Brakes

Pad brakes are simple, but effective brakes. These brakes allow for easy assembly and low design times. They can be found on most low quality brakes due to their low cost. The problems with them are that they have a long stopping distance and wear quickly. Replacing these brakes requires an entirely new assembly, which is not feasible for NASA applications.

3.3.2.3 Existing Design #3: Reverse Gearing Brakes

Reverse gearing breaks are common on cruiser bicycles. This is the quickest build system as it is simply making it so that any backwards pedaling slows the tires and ultimately the vehicle. Some problems include possibly tire damage, unstable stopping, can hurt the drivers if pedaling fast enough, and low stopping time.

3.3.2.4 Existing Design #4: Drum Brakes

Drum brakes are very common. These can be found on most vehicles today and all older vehicles. The design of the mechanism allows for long life cycles with dependent results. A major problem is that a scaled version of these brakes has not been found, which eliminates it as a potential design selection.

3.3.3 Subsystem #3: Steering

Having good wheels and great brakes will not mean anything if the drivers cannot steer the vehicle. Steering is essential in any vehicle, especially any space-faring vehicles. The operators of this bike need to be able to precisely dictate where the bike goes while in motion. Steering in combination with propulsion and brakes are what make the vehicle useful. However, if the steering is lacking, no amount of propulsion will help the drivers reach their destination if the vehicle cannot be controlled.

3.3.3.1 Existing Design #1: Stem-Wheel

The Quad-Cycle uses a stem-wheel steering apparatus. A steering wheel connected to the stem turns the wheels to steer the vehicle. The exact turning radius is unknown. A stem-wheel design is more familiar to most riders. It provides optimal control of the vehicle without sacrificing functionality.

3.3.3.2 Existing Design #2: Pulley Mechanism

Pulley systems succeed in small designs and can allow for high torque in the vehicle control. The problem with this is that drivers require a long time to learn how to steer in order to grasp how to control the vehicle without damaging it.

3.3.3.3 Existing Design #3: Pull Bars

The NAU Human Powered Vehicle team integrated pull bar steering into their design. This design highlighted many advantages including easy control of the system, it was compact, and light weight. The problem is that the turning was sensitive and had a very small turning radius, but this was not a design concern for their completion.

3.3.4 Subsystem #4: Frame

The frame is the key structure within the vehicle. All of the subsystems need to be compatible with the frame design. The material choice for the frame could change the weight from being 20lbs. to 40lbs. or more. The main three materials to choose from are 6061 aluminum, 6031 steel, and chromoly.

3.3.4.1 6061 Aluminum

Aluminum is a practical, light weight material used in most modern bike frames. This material allows for an inexpensive frame and low weight to strength ratio. The problem with aluminum is that it is difficult to weld, which is going to be the most prominent way to make a frame. Another problem is that it can get damaged quickly in testing applications.

3.3.4.2 6031 Steel

6031 steel is one of the most readily available steels to find today. It is one of the strongest steels that can be purchased from any steel vender. This grade of steel is suitable for all forms of welding. The key issue is that this is a heavy material. The finished frame will also need to be heat treated if using this steel to cure and remove strength reductions caused by welding.

3.3.4.3 Chromoly

Chromoly is a four thousand series of steel. This steel is prominent in the automotive industry. This steel works well with welding and can be purchased from every steel vender. This is the most common steel used in industry due to its variety of uses in machining, bending, and structural fabrication. The weight is less than 6031 steel and greater than the aluminum.

3.3.5 Subsystem #5: Propulsion

A good propulsion system is essential in any vehicle. Any vehicle can have the best tires, frame, brakes and steering, but without propulsion, it will go nowhere. To complete the competition, the bike needs a good propulsion system the drivers can utilize to get the vehicle from start to finish.

3.3.5.1 Existing Design #1: Bicycle Drive-train System

The first design is a bicycle drivetrain. This design is a working and well tested method of transforming human foot power into movement. The benefit of going with a system such as this is that any bicycle system can be taken apart and manipulated for the rover's mechanism. The problem comes with a chain length and stability. The machine being designed needs to be able to withstand high torques to move heavy loads and typical bicycle chains are not the best in high torque situations.

3.3.5.2 Existing Design #2: Belt System

The second design is the belt system. This system is great with high torque scenarios and allows for error in the pedaling that is associated with quick jerks and turns on a tram. The problem with a belt system is the lengths and thicknesses of the belts as they are most commonly a set length and width and can be over-engineered for the design itself.

4 Designs Considered

This section discusses the specific designs considered in the rover project. Each subsystem will be represented by several potential designs, and the pros and cons will be examined.

4.1 Brakes

This section will discuss three different brake subsystem designs considered, with pros and cons, for the team's final design. Also considered for each design is how well it addresses the customer requirement of safety.

4.1.1 Stagecoach Brakes

The first braking system considered is the stagecoach brake design. In this design, a large lever is used to actuate the brakes that apply pressure and create friction between the surface of the tire and the brake shoe. This design is simple, in mechanics and operation, and would be easily implemented in the final design. However, this style of brakes has the least stopping power of the three designs discussed in this section. If too much pressure is applied to the brake shoe through lever actuation, there is potential of chipping the tire material and creating an uneven braking surface leading to even less stopping power. Minimal stopping power warrants these brakes to be less safe than the other brake designs considered. An example of a stagecoach can be seen in Figure 5.

Figure 5: Stagecoach Brake

4.1.2 Rim Pad Brakes

The second braking system considered is the rim pad brake design. This design consists of two brake shoes that rest on the inside and outside of the rim of the wheel, each connected to a rigid metal cantilever. Brake compression is achieved by pulling a wire connecting the free ends of the two rigid metal cantilevers, shortening the distance between them and subsequently the distance between the brake shoes. The driver achieves the wire pull by pulling the brake handle attached to the steering handles. There is more braking power in this design than in the stagecoach brake design, along with a longer expected lifetime. However, this design has an exceptionally high potential to warp the rims of the wheel when too much pressure is applied to the system leading to some loss of stopping power. Some rim pad brakes can be seen in Figure 6.

Figure 6: Rim Pad Brakes

4.1.3 Disc Brakes

The third braking system considered is the disc brake design. This system consists of two brake shoes resting on either side of a disc that is rigidly attached to the wheel. The brake shoes are contained in a caliper that has pistons that expand when filled with oil, creating pressure between the brake shoes and the disc. Oil is fed to the pistons in the caliper through brake lines connected to a brake booster with inputs controlled by the driver. This design is complex and, consequently, expensive to implement. Disc brakes provide the most stopping power of the three designs discussed in this section, and have the longest expected design life. Maximum stopping power warrants these brakes as the safest design of the three brake designs considered. A disc brake system can be seen in Figure 7.

Figure 7: Disc Brake

4.2 Wheels

Three main designs were considered for the Human Powered Mars Rover vehicle once the CR's and ER's were finalized. The three designs are tread over wheels, tread in wheels and clamped tread wheels. All designs considered were for wheels that met the customer requirements. The customer requirements for wheels are that they are not inflated; they need to be able to traverse obstacles, maintain traction, and have dust abatement devices and a minimum diameter of 20".

4.2.1 Tread Over Wheels

Tread over wheels are two separate components, the tread and wheel. The tread is mounted on the wheel by forming it to the wheel for a tight fit. This type of wheel is very common on bicycles and cars. These wheels satisfy the no air requirement. However, while a tread over design is easy to impendent it is not always reliable. This is because the friction holding the wheel stationary in the rim can be lessened as the wheels wear down allowing the rim to spin freely. A tread over wheel design is shown in Figure 8.

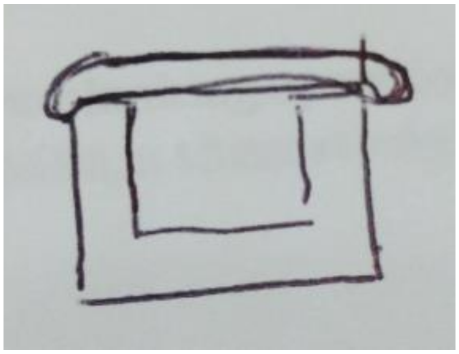


Figure 8: Tread Over Wheel

4.2.2 Tread In Wheels

A tread in design connects the tread to the wheel using pins to secure it in place. This design allows the team to use any material desired for the tread because the final product can be pinned in whereas with a tread over design, a more elastic tread is needed. While the pins hold the tread and wheel together, they also act as stress concentrators that could potentially tear the tread. A tread in wheel is shown below in Figure 9.

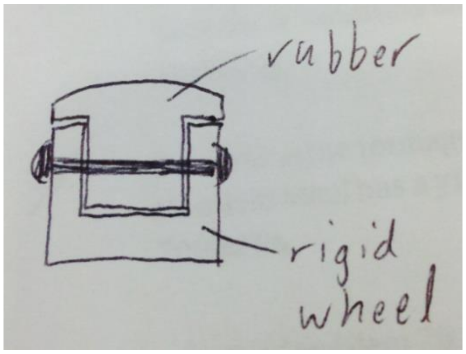


Figure 9: Tread In Wheel

4.2.3 Clamped Tread Wheels

The final design is a clamped tread wheel. Similar to a wheel chair wheel, a solid tread is clamped into the wheel housing without any pins. This is the best design as it guarantees that tread will be secured in the wheel housing whereas a tread over can come off and a tread in can be torn. However, a clamped tread in only works with certain materials such as solid rubber. These wheels are easily obtainable and serve the rover well as there is no air in the tires and they are very durable. An example of a clamped tread wheel is shown in Figure 10.

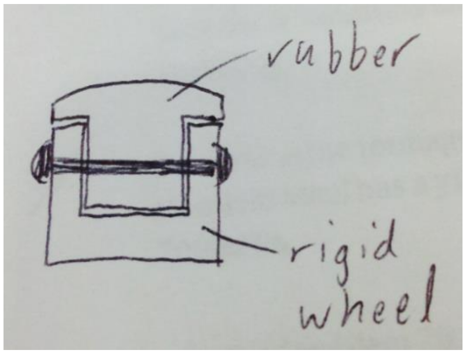


Figure 10: Clamped Tread Wheel

4.3 Suspension

This subsection contained seven different types of suspensions: hydraulic, spring, leaf spring, long arm, and coil over, hoop wheels and rigid body. A basic description, the pros/cons, and a picture of each type of suspension will be provided below.

4.3.1 Hydraulic

Hydraulic shocks, also known as Shock Absorbers, use an incompressible fluid to oscillate the shock arms. The pros of shock absorbers are that they come in many sizes, are cost effective, and durable. The cons are that they are not well controlled and mostly have a rigid feel for the driver. An example is shown in Figure 11.

Figure 11: Hydraulic Suspension

4.3.2 Spring

Spring suspension is a helical shaped metal that is used to absorb an impact, or uses tension to hold an item at a certain length. The pros of the springs are that they are extremely durable, great for constant absorption, and have wide variety of properties and sizes. The cons for springs are that they do not hold shape from shear forces, and mounting is not straightforward. A spring suspension can be seen in Figure 12.

Figure 12: Spring Suspension

4.3.3 Leaf Spring

A leaf spring is a set of pieces of metal curved upwards to create a tension that holds the vehicle up. The pros are that they can be made and attached to the frame quickly and with little fabrication. The cons are they are commonly rigid, and the damping cannot be controlled. An example of a leaf spring suspension system can be seen in Figure 13.

Figure 13: Leaf Spring Suspension

4.3.4 Long Arm

Long Arm uses a combination of springs and control arms to attach a solid axil to the frame. Long arm suspension has great flexion, can be controlled well with different sized springs and arms, and is a well-known type of suspension. The cons are the number of components, the weight of all the components, and are not an easily maintained system. A long arm suspension can be seen in Figure 14.

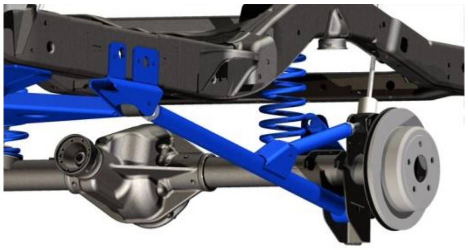


Figure 14: Long Arm Suspension

4.3.5 Coil over

A coil over is a manufactured combination of a spring and shock absorber to create a relationship between absorption and tension. It uses a spring to create a desired length, and is used for oscillation. The shock is used to take extreme impacts and allow for controlled travel. The pros of coil overs are that they create the best ride quality for all speeds and terrains, made in various sizes, and the damping can be controlled. The main con is that the coil overs are expensive. An example of a coil over suspension can be seen in Figure 15.

Figure 15: Coil over Suspension

4.3.6 Hoop Wheels

Hoop Wheels are an innovative type of suspension system where the use of tensioned plastics is used to create the rim of the wheel. The pros of the hoops wheels are that they technically have no components, make the overall design simplistic, and can be maintained. The cons are that they have not been proven to be durable, they are expensive, and cannot be obtained. A hoop wheel example can be seen in Figure 16.

Figure 16: Hoop Wheel Suspension

4.3.7 Rigid Body

This suspension is the simplest design. Instead of suspension components, the wheels are rigidly attached to the frame. Rigid body uses no type of compression or tension component to absorb shock or help with flexion, but relies solely on the strength of multiple components attached together. The pros of this system are it is inexpensive, has no components, and can be maintained. The cons are there is no flexion, and the ride quality is poor. A rigid body system is shown in Figure 17.

Figure 17: Rigid Body Suspension

4.3.8 Engineering Criteria

Each of these systems was graded with the criteria that would help our team identify the most suitable suspension system for our competition. The criteria was chosen with our engineering and customer requirements in mind, as well as thinking toward the build stage, and how to build and incorporate the suspension into the final design. None of the criteria is listed in any specific order.

- Travel: The distance that the system can stretch and compress under a load.
- Flexion: A strong relationship to travel, is the ability for the whole design to have the tires and suspension follow an inclined terrain while keeping the drivers/frame from rolling over.
- Size: Length, width, and height of the system, and all of the incorporating components.
- Cost: Expenses of the components along with the amount it would take to fabricate it to the final design.
- Maintenance: Involves the difficulty of fixing a problem, the cost if a part breaks, and how quickly the problem can be resolved.
- Weight: How heavy all of the suspensions components weigh in pounds.
- Obtainability: How readily available the suspension components are, as a whole system and individual parts for maintenance.
- Damping: The ability to control the amplitude of the oscillations and vibrations.
- Number of Components: The amount of mechanical parts used.
- Ride Quality: The comfort for the drivers while traversing different environments.
- Transferred Force: The amount of shock/impact the whole design absorbs.

4.4 Drivetrain/Seating

In this section, three main designs for the drivetrain and seating arrangements will be considered. The three designs are having the drivers face opposite directions, having the drivers oriented in a way that resembles a tandem bicycle, and where the two drivers are laying side by side. Each design is considered with its pros and cons to decide how well each design fits the customer needs.

4.4.1 Back to back

The first drivetrain/seating arrangement considered is where the drivers sit facing back-to-back. In this design each driver will be pedaling, but they will be applying their power to different axels. This divides the supplied power to the rover allowing it to be more efficient for by allowing for four wheel drive. The center of gravity is also more central in this design making it much more capable of traversing tougher environments while keeping it more stable. With drivers facing the opposite direction, this means that one of the drivers will not know what is coming up next in the course and will have to rely on the judgment of the one driver who can see the course. An example of a back-to-back seating arrangement is shown in Figure 18.

Figure 18: Back to Back Seating

4.4.2 Tandem

The next drivetrain/seating arrangement considered is the tandem style method. This method has both riders facing forward and in line with each other as would those riding a tandem bicycle. This design is a much easier to construct than the other considered designs. Both drivers also face the same direction allowing for both of them to communicate how they believe they should traverse the upcoming obstacles. This design also puts both drivers on the same drivetrain system meaning that all the power given by the drivers is on one axel. While this gives more power to that one axel, it leaves the other set of wheels to just roll and have no power at all. A tandem bike example can be seen in Figure 19.

Figure 19: Tandem Bike

4.4.3 Side by Side

The final drivetrain/seating arrangement considered is the side-by-side method. This method has both drivers facing the same direction, but instead of them sitting in a line, they would sit next to each other. This orientation would be similar to the tandem bike style where both drivers would be on the same drivetrain system. This design also has a much higher storage capacity which is required by NASA. The center of gravity on this vehicle design is set much further back than the other considered designs which makes this more unstable when traversing difficult obstacles. A side-by-side seating system can be seen in Figure 20.

Figure 20: Side-by-Side Seating

4.5 Frame

In this section the selected frame design, material, and tubing will be explained. The designs were created to meet the following engineering and customer requirements:

1. The center of gravity is greater than 30 inches above the ground.
2. The design must be suitable for one cubic foot of storage
3. The width of the vehicle can be no greater than five feet wide.
4. The vehicle must be collapsible to fit into a 5ft. by 5ft. by 5ft. box before the competition.
5. It must be able to seat two drivers, one of each gender.
6. The finished design, without drivers, weighs less than 100 pounds and able to be carried by the drivers.
7. The vehicle must be able to be taken apart in order to lower shipping costs.

The frame will be broken up into two subsections, geometry and tubing to closely analyze how the frame design was chosen.

4.5.1 Geometry

The frame geometry had many variations in appearance and application. Weight, cost, and simplicity weighed heavily when designing each of the following frames.

4.5.1.1 Compact Car

The first frame design considered was the car which can be seen below in Figure 21.

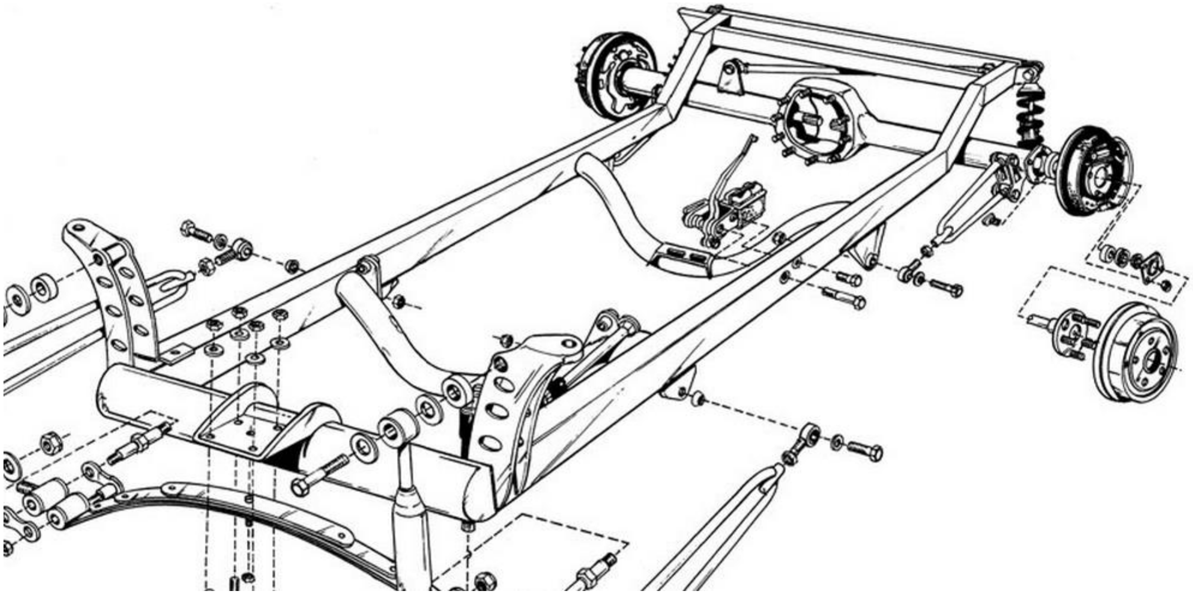


Figure 21: The basic frame of a T-Bucket to show the concept of car frames using c-rail and box steel members

The frame is made into a rectangular shape using both c-rails and box shape members. Typical frames allow for maximum top loads and adjustability. The diversity in the frame would allow for seating, steering, and other key systems to be easily attached. The disadvantage with this design is the fabrication and material costs. This frame would need to be a custom build and is difficult to establish since any errors in fabrication would likely result in a rebuild of the entire frame which is costly and timely. Weight is another concern as the drivers are required to carry the vehicle. This heavy design is typical due to car frames needing to accommodate for long life expectancies.

4.5.1.2 Go Kart

The go kart design is made of tube members and is designed to allow for a large storage space inside the vehicle. This design is a hybrid between the following frames and the previous car designs. The go-kart frame can be seen below in Figure 22.

Figure 22: The go-kart frame that utilizes a wide spacing to allow for storage and low ride

This design uses a wide base to allow for the engineering team to build storage around the drivers as well as keep the drivers inside the vehicle (as opposed to on top of the frame). The simply design allows for ease of fabrication. The frame also allows for a low center of gravity which is contrary to one of the engineering requirements. The greatest disadvantage to this design is the inability for the vehicle to collapse.

4.5.1.3 Trapezoidal Tube Design

The next movement of design was to go for a narrow build to accommodate for the five feet width requirement. This caused the team to design a long two piece system with a trapezoidal cross section. This shape and design can be seen below in Figure 23.

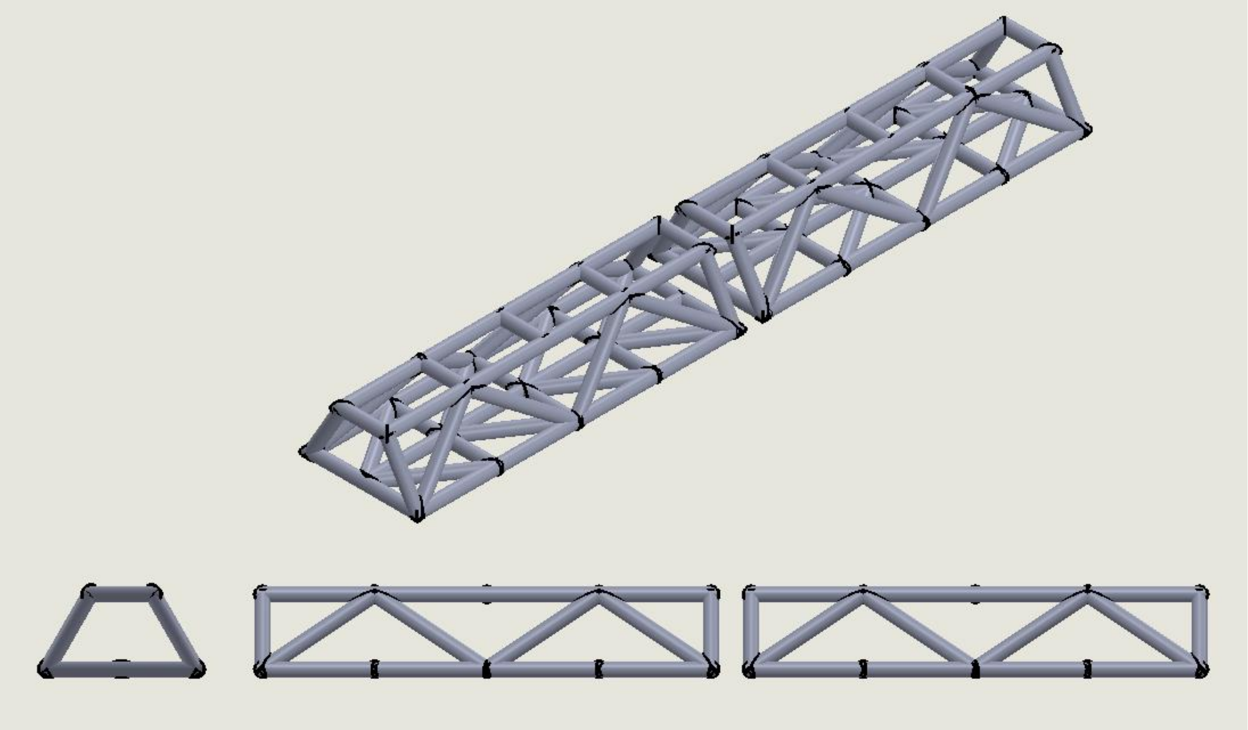


Figure 23: Two piece trapezoidal frame with the front, side, and isometric view

The trapezoid geometry of the frame allows for high loads in all directions. The two piece system allows for the frame to collapse in the middle into half of the original length. The narrow design and tube frame allows for ease to carry. The flat top allows for simple attachment of seating. The hollow inner section would be used for the gearing and chains as well as over two cubic feet of storage. The disadvantage comes from the weight. This design requires a high amount of tubing in comparison with the triangular frame that will be explained next.

4.5.1.4 Triangular Tube Design

The triangular tube design is a close comparison with the trapezoidal design. The difference between the two is the cross sectional shape being triangular. This design can be seen below in Figure 24.

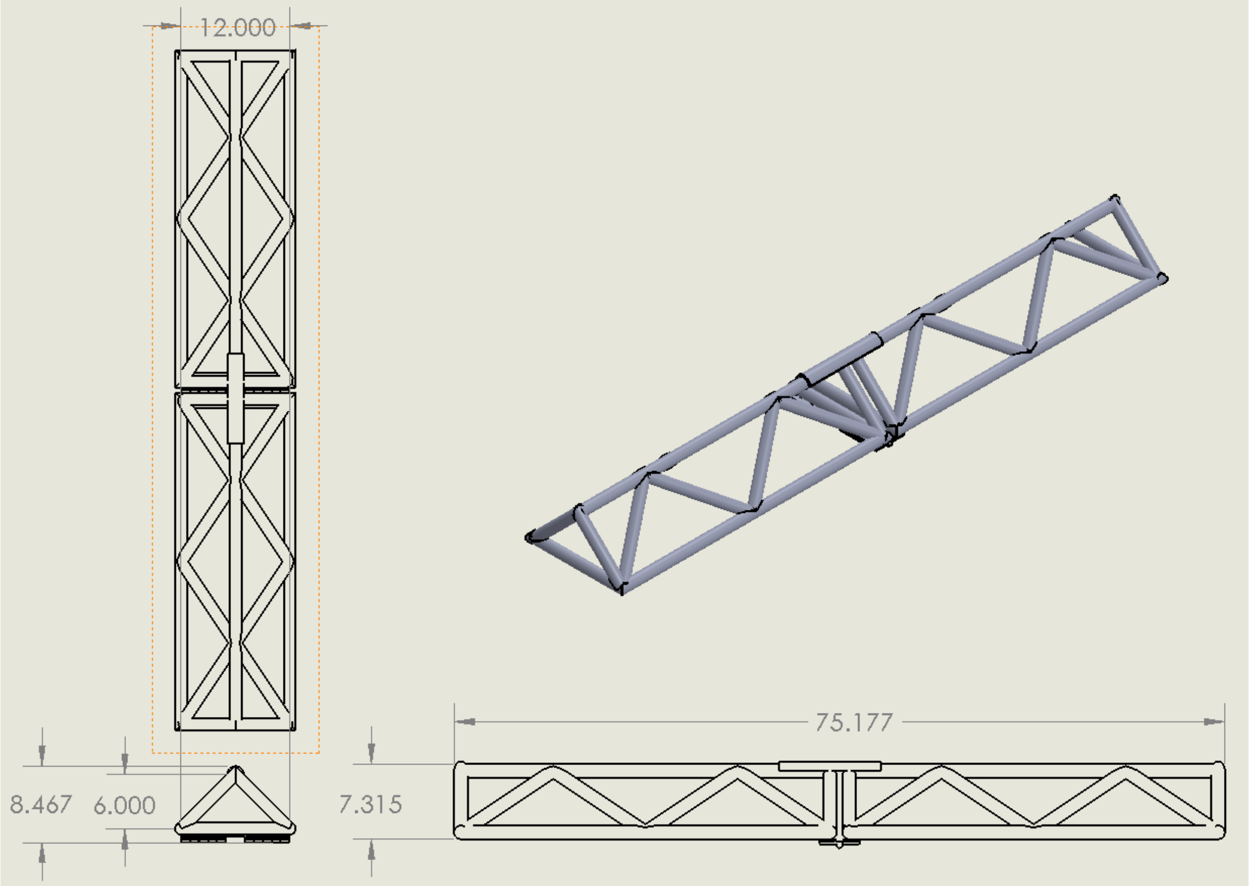


Figure 24: Two piece triangular frame with the front, side, and isometric view

The triangular design allows for high strength. The structure of this design allows for a decrease in required tubing with a slightly less storage volume. The seat attachment is increasingly difficult initially, but suspension and axel attachment is simplified. The collapsibility is increase in this design by relieving the system of weight when transporting in the collapsed stage. The fabrication of this design is cost effective and easily modified.

4.5.2 Tubing Shape

The tubing of the frame is being evaluated due to the requirement that this project is fabricated by the Northern Arizona University team. The focal points of each tubing design are the ability of fabrication, strength, and weight. The three considered designs are square, hexagonal, and circular tubing. The three designs with dimensions can be seen below in Figure 25.

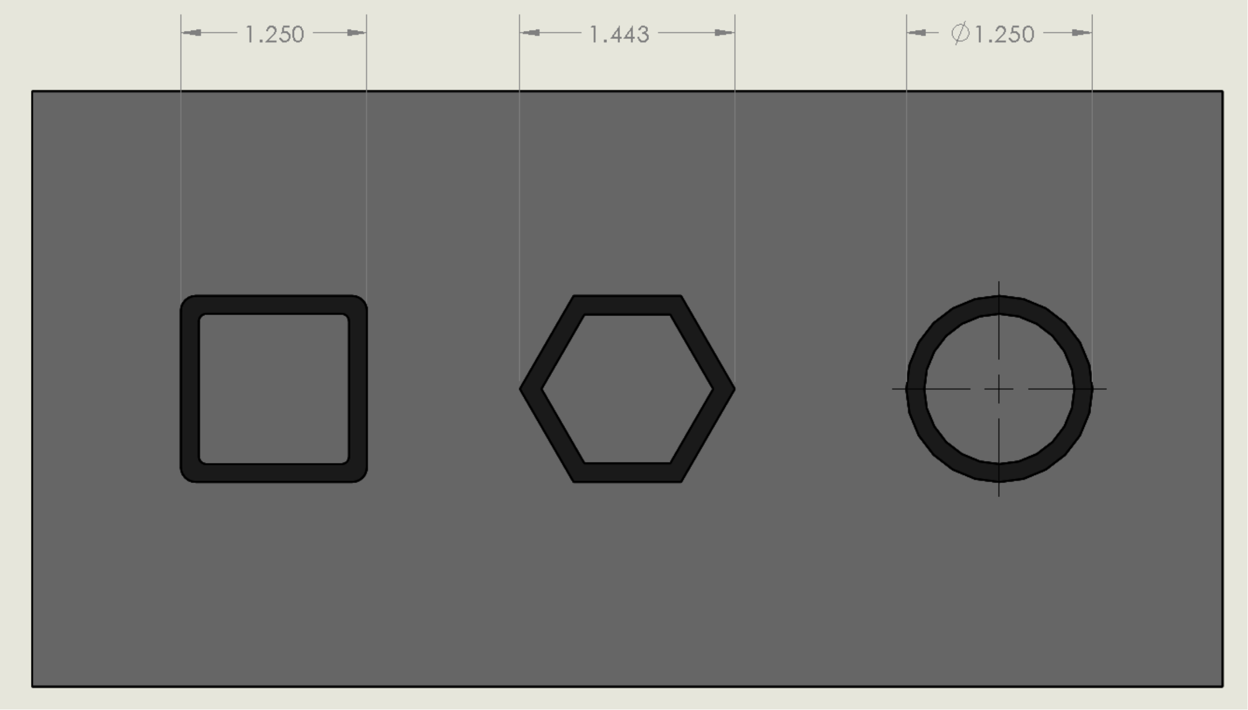


Figure 25: All three tubing designs considered for the frame.

All three tube cross sections have a 0.120” wall thickness. The cross sectional area for all three tubes is: 0.536” for the square, 0.487” for the hexagon, and 0.426” for the circular. The shape with the smallest cross sectional area will have the least amount of material, resulting in a lighter frame. The fabrication of a square or hexagon frame is difficult in comparison with the circular. Circular frames require a single saw blade to cut, which introduces error into the cuts, while the other two shapes require a band saw with multiple measurements and cuts. This project will involve over 100 cuts, and having to switch blades would increase the amount of time required to complete the cutting.

4.5.2.1 Material

The materials selected to be evaluated for the frame are 6061 aluminum, 1030 steel and chromoly. 6061 aluminum is the lightest material selected and is standard for many modern bicycle, aero, and vehicle frames. Aluminum is a difficult material to weld onto and requires a specific weld and set up in order to create strong welds.

1030 steel is the heaviest material selected, and comes at the highest cost from online suppliers. 1030 steel is not the most readily available tubing and comes in most circular dimensions, but not all. This steel offers the highest strength. 1030 is also easy to fabricate since almost all welders work with this steel on a regular basis and provide solid welds.

Chromoly offers a middle ground between the aluminum and 1030 steel with the cost. The strength is less than that of the 1030 steel and higher than the aluminum. The cost of this material is also the middle ground. The ability to weld with chromoly is almost the same as the 1030 steel.

The comparison of strength, density and cost can be seen in Table 1.

Table 1- material properties of 6061 aluminum, 1030 steel, and chromoly [7].

Material	Density ($10^3 \frac{kg}{m^3}$)	Yield Strength (MPa)	Cost per foot
6061 Aluminum	2.70	270	11.09
1030 Steel	7.86	800	15.20
Chromoly	7.85	435	12.46

4.6 Steering

This section discusses the three steering subsystem designs considered. Each steering mechanisms will be presented with its pros and cons, in relation to the other considered designs. The three designs are bicycle steering, rack and pinion, and under seat steering. All designs considered were for steering and seating configurations that met the customer requirements. The customer requirement for steering is that the rover must have a 15' or less turning radius. The customer requirements for seating are that the passengers are secured in their seat, and they do not touch any surfaces that are 15" or less from the ground. At the end of the section, the team's final design will be discussed.

4.6.1 Bicycle Steering

Bicycle type steering uses a handlebar design historically used in consumer bicycles. This design is simple, easily implemented, and a comfortable choice for nearly all possible drivers of the rover. However, this design does not allow for a high turning ratio, or for the driver to plant themselves in their seat in order to have maximum leverage while delivering power to the drivetrain. This design also has the highest turning resistance due to the direct input of driver to turning the wheels, without any mechanical aids. An example of bicycle steering can be seen in Figure 26**Error! Reference source not found.**.

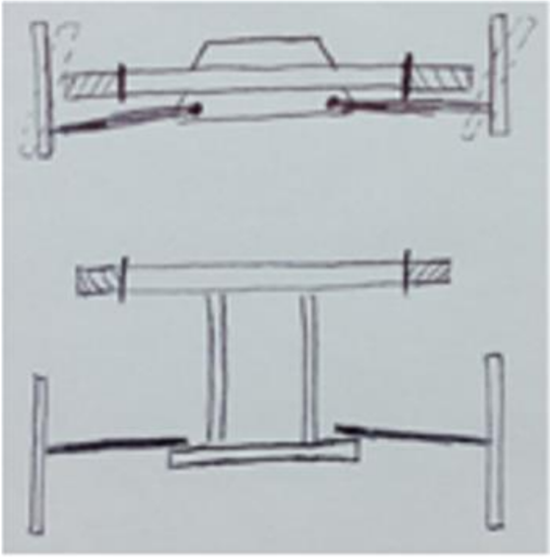


Figure 26: Bicycle Steering

4.6.2 Rack and Pinion

Rack and pinion steering uses a pinion gear mounted to a straight input shaft, to drive a rack gear. Input from the driver rotates the pinion gear and causes linear motion to the rack which is connected to tie-rods to turn the wheels.

This design has the highest turning ratio of all the designs considered. This design also has the lowest turning resistance because the use of gears reduces the power input needed to get the same result. However, this design constrains the geometry of our vehicle due to the need for a straight steering shaft, or a series of input shafts. With the geometry constrained, the driver would need a steering wheel type input mechanism, which like the bicycle steering system, does not allow the driver to put all of their energy into the drivetrain. A rack and pinion example can be seen in Figure 27**Error! Reference source not found.**.

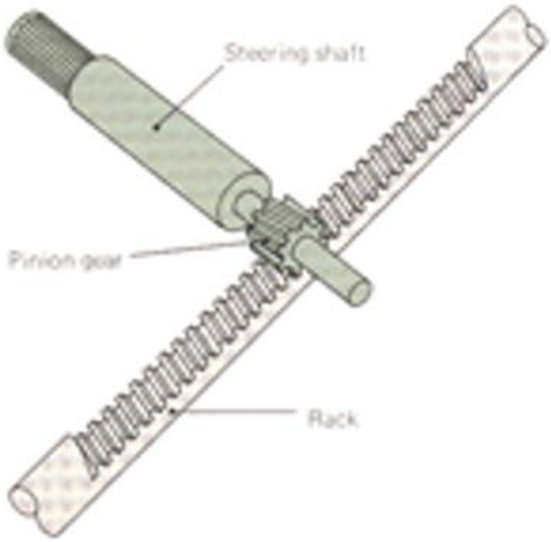


Figure 27: Rack and Pinion

4.6.3 Under Seat

Under seat steering utilizes a set of levers at the sides of the driver that are positioned such that the driver can use them to hold them in their seat while pedaling over difficult terrain. This design articulates the wheels through input links that run parallel to the frame. If the right lever is pushed, and the left lever is pulled, the rover will turn left. This design has more turning resistance than the rack and pinion design, but less than the bicycle steering. This design also has a lesser turning ratio than rack and pinion, but larger than the bicycle steering design. Because this design was a compromise between the comfortable bicycle steering, and the efficient rack and pinion steering, it was chosen as the final design for the rover. An example of under seat steering can be seen in Figure 28.

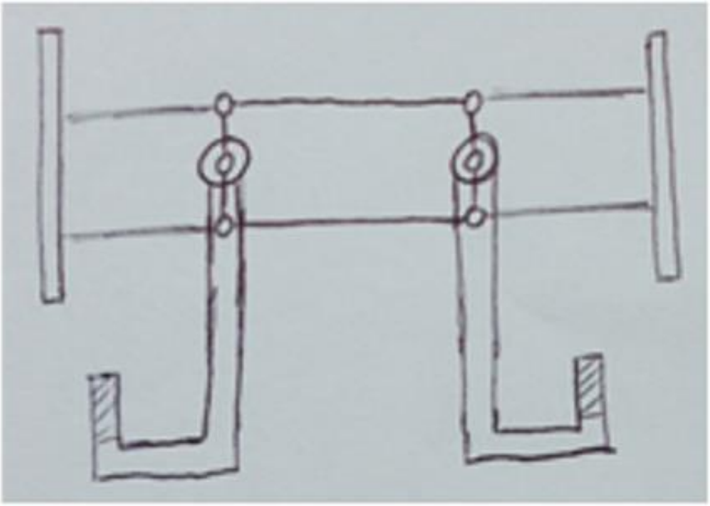


Figure 28: Under Seat Steering

5 Design Selected

This section discusses the final design selection for each subsystem. Each subsystems function will be described, and will be followed by the final selected design. The selected design will then be represented by a SolidWorks model, and be explained in detail.

5.1 Rationale for Design Selection

5.1.1 Design Chosen: Disc Brakes

The brake design chosen for the final system is the disc brakes as it scored highest in the weighted Pugh Chart. This design addresses most of the customer requirements of having a human propelled rover. Power to move the rover must be counteracted by a safe braking system to allow the driver to have full control of the mechanical system. Furthermore, the disc brake design scores high in the braking distance, maintenance, and longevity factors of the weighted Pugh chart. A short braking distance is synonymous with the stopping power discussed in the previous brakes subsystem section, and is why the disc brakes score high in this category. High longevity and maintenance scores correspond to the long expected design life and low maintenance expectancy over that life, that are desirable for a rover being sent into space where performing maintenance is difficult.

5.1.2 Design Chosen: Clamped Tread Wheels

After considering multiple designs and narrowing the choices down to these three, the final design selected was Clamped Tread wheels. Clamped tread wheels are readily available, have great traction with their solid rubber, are not inflated, and can have a minimum diameter of 20" easily. With a clamped in tread, it is highly unlikely that the tread would come off or tear during competition unlike a tread over or tread in design. With enough power from the drive train, they could also navigate obstacles easily. An example of a clamped tread wheel can be seen in Figure 29.

Figure 29: Clamped Tread Wheel

5.1.3 Design Chosen: Coil over

Coil overs were chosen as the final design. When graded with each criterion, the coil over suspension design scored the highest overall. The most successful criterion of the coil over is the flexion it allows in the vehicle, the amount of travel that is capable with different designed coil overs, and increased ride quality they create. These were not the only criterion they excelled in; they are great for absorbing the force on the vehicle and reducing the amount of transferred force, the dampening is adjustable for different types of terrain, and has only a few components. Even though the costs of the coil overs are the most expensive of all the possible designs, they are easily obtainable, low weight, and have a wide variety of sizes. For our design, as long as our budget allows, coil overs are the best available choice.

5.1.4 Design Chosen: Back-to-Back

Overall, the design with the drivers seated back to back was the best option. This design was best suited to traverse the many different types of obstacles that will be tested on the course. With the central center of gravity, the stability is increased making it much easier to traverse slopes as well as rocky terrains fairly easily. Having each driver in control of a different axel will allow for a lot more power to be given to the rover overall making it easier to cross other obstacles such as the sand pit. This design is also relatively simple to build as it is symmetric. Once one side of the rover is built, the other should be relatively the same. This also allows for the rover to be broken down or folded in half much easier. This design is also flexible to be able to meet other requirements such as storage capacity. Although one driver will not be able to see the course, the team decided that this design had more positive aspects that outweighed the negative.

5.1.5 Design Chosen: Triangular Frame with circular tubing made of 1030 Steel

5.1.5.1 Geometry

The geometric shape chosen for the final design is the triangular shape. The frames were all compared using the engineering and customer requirement in Section 3 of the report. In addition to the requirements, the team chose additional design considerations and compared each frame in a weighted Pugh chart. The additional design considerations are:

a. Versatility / Adaptability – the ability of the frame to be altered or added upon
b. Amount of Tubing Required – the physical footage of tubing required for the final design
c. Approximate Width – how wide the final frame is from left to right

d. Approximate Length – how long the final frame is in driving position (non-collapsed)
e. Maintenance – the amount of work needed to keep the vehicle working
f. Fabrication Difficulty – the level of skill and time required to build the frame
g. Maximum Load Capacity – the maximum amount of weight that can be applied to the frame without damage or failure occurring
h. The Flexion – the ability of the frame to deform without damage or failure to the system

The triangular frame is easily adaptable due to the tube framing and geometry of the vehicle. It was not better than the trapezoidal shape, but the next best option. Axles, chains, and suspension can be built either outside or inside the hollow center space of the frame without interference of the drivers and cargo.

The amount of tubing for the triangular frame was the least. The triangular frame required 51.2% of the amount of tubing needed for the trapezoidal frame. The reduction in tubing is a direct relationship to the weight. In other words, the triangular frame would weigh approximately half the weight of the trapezoidal frame.

The approximate width of the frame would allow for a width much less than the 5ft. requirement. The length will be approximately 9 ft. long. This length would allow for a small turning radius and agility needed for obstacles.

Maintenance of the vehicle would be minimal and simple. The reduction in tubing needed allows for quick repairs throughout the system without high amounts of restriction. Fabrication difficulty is low due to the geometry of the frame. No angle would restrict a welder or circular cutter from getting inside the frame.

Due to the triangular shape, the load capacity is maximized in all axial directions. Twisting would be restricted, consequently removing stress on axles and directing the load toward the suspension. The flexion in the system is small. This lack of give in the system forces the suspension to take most of the impact in abrupt points of acceleration.

The final design factor when creating the frame is the collapsibility. If the vehicle cannot fit inside the 125 cubic foot box then the team will be immediately disqualified. Both the extended and collapsed pictures can be seen below in Figure 30 and Figure 31.

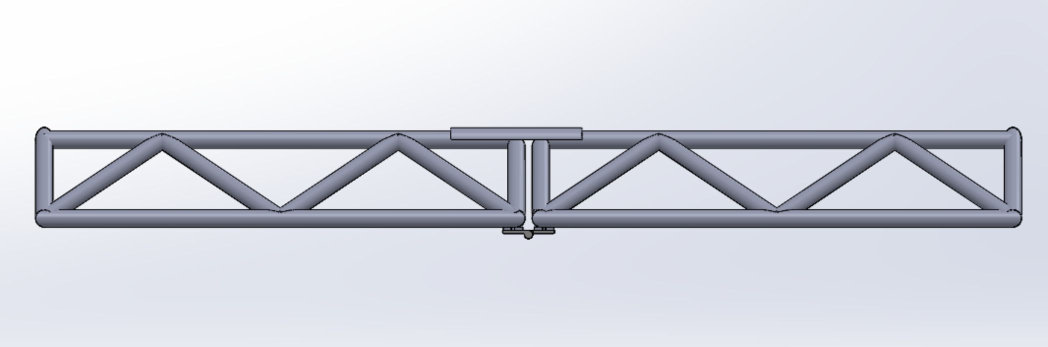


Figure 30: The triangular frame is extended in the driving position.

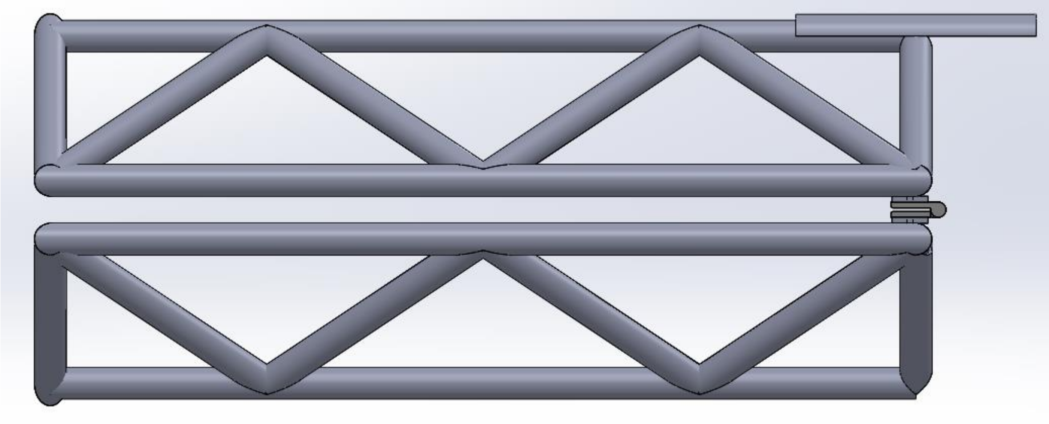


Figure 31: The triangular frame is collapsed in the closed position.

The brace location and pivot hinges allow for the length to be cut in half and detached if desired. This fits the shipping and storage requirements established above.

5.1.5.2 Tubing Shape

The tubing shape selected is the circular cross section. The circular cross section is the least difficult to fabricate due to need for one drill bit and a high amount of error allowable. Both the hexagonal and square shapes would require a many measurements and cuts for one weld. The tolerance of the tube being cut at an improper angle is small due to the colliding geometries. The circular tubing is the cheapest and most attainable tubing.

5.1.5.3 Material

The material selected was the 1030 steel. The main reason for this is the cost. The SAE machine shop has this available for free. The decrease in strength between this and the chromoly will most likely be unnoticeable in competition. The 6061 aluminum was chosen to not be used due to the difficulty in welding and the decrease in strength.

5.1.6 Design Chosen: Under Seat Steering

The steering design chosen for the final design is the under seat steering. The steering systems were all compared using the engineering and customer requirement in Section 2 of the report. In addition to the requirements, the team chose additional design considerations and compared each steering system in a weighted Pugh chart. The Pugh chart resulted with the under seat steering design being the highest scored. This design was favorable because it allows the passengers to deliver more power to the drivetrain by leveraging the steering controls.

Upon finalizing the CR's and ER’s for the Human Powered Exploration Rover (Chapter 2 above), the three main steering designs from Chapter 4, were put into a weighted Pugh chart. The criteria below denoted with their weightings, were used to evaluate the designs.

a) Turning Resistance (15)
b) Turning Ratio (20)
c) Fabrication Difficulty (25)
d) Adjustability (10)
e) Number of Parts (10)
f) Durability (20)

5.6.1 Turning Resistance

The turning resistance for each design was evaluated by the number of moving parts it contains, and the amount of friction surfaces. Steering systems with fewer potential energy losses were given a better ranking in the Pugh chart than those with more.

5.1.7 Turning Ratio

The turning ratio for each design was evaluated through research conducted on each design. Steering mechanisms are a highly debated topic, which made the information on turning rations readily available.

5.6.3 Fabrication Difficulty

The fabrication difficulty for each design was evaluated by the number of parts that need to be machined. The time it would take to machine each part, or send it out to be machined, was also included in the ranking of each system in the Pugh chart.

5.1.8 Adjustability

The adjustability of each system was evaluated by the ability of the steering linkages to be adjusted to fine tune the motion of the rover. The under seat steering design has fully adjustable linkages, which allow for toe adjustments to be made on the rover.

5.1.9 Number of Parts

The number of parts required for each design is a major factor that dictates the final cost of the design. This was evaluated by sketching each system and determining the parts of the system that would need to be purchases or fabricated.

5.1.10 Durability

The durability of the steering systems was evaluated by the predicted strength of the joints in the system (heim joint vs weld), and the material/cross sectional shape of the shafts between joints.

5.2 Design Description

5.2.1 Frame

5.2.1.1 Geometry

The geometric shape chosen for the final design is the triangular shape. The frames were all compared using the engineering and customer requirement in Section 3 of the report. In addition to the requirements, the team chose additional design considerations and compared each frame in a weighted Pugh chart. The additional design considerations are:

a. Versatility / Adaptability – the ability of the frame to be altered or added upon
b. Amount of Tubing Required – the physical footage of tubing required for the final design
c. Approximate Width – how wide the final frame is from left to right
d. Approximate Length – how long the final frame is in driving position (non-collapsed)
e. Maintenance – the amount of foretold work needed to keep the vehicle working
f. Fabrication Difficulty – the level of skill and time required to build the frame

g. Maximum Load Capacity – the maximum amount of weight that can be applied to the frame without damage or failure occurring
h. The Flexion – the ability of the frame to deform without damage or failure to the system

The triangular frame is easily adaptable due to the tube framing and geometry of the vehicle. It was not better than the trapezoidal shape, but the next best option. Axles, chains, and suspension can be built either outside or inside the hollow center space of the frame without interference of the drivers and cargo.

The amount of tubing for the triangular frame was the least. The triangular frame required 51.2% of the amount of tubing needed for the trapezoidal frame. The reduction in tubing is a direct relationship to the weight. In other words, the triangular frame would weigh approximately half the weight of the trapezoidal frame.

The approximate width of the frame would allow for a width much less than the 5ft. requirement. The length would be anywhere between 6ft. and 8 ft. long. This length would allow for a small turning radius and agility needed for obstacles.

Maintenance of the vehicle would be minimal and simple. The reduction in tubing needed allows for quick repairs throughout the system without high amounts of restriction. Fabrication difficulty is low due to the geometry of the frame. No angle would restrict a welder or circular cutter from getting inside the frame.

Due to the triangular shape, the load capacity is maximized in all axial directions. Twisting would be restricted, consequently, removing stress on axles and directing the load toward the suspension. The flexion in the system is small. This lack of give in the system forces the suspension to take most of the impact in abrupt points of acceleration.

The final design factor when creating the frame is the collapsibility. If the vehicle cannot fit inside the 125 cubic foot box then the team will be immediately disqualified. Both the extended and collapsed pictures can be seen below in **Error! Reference source not found.** and **Error! Reference source not found.**

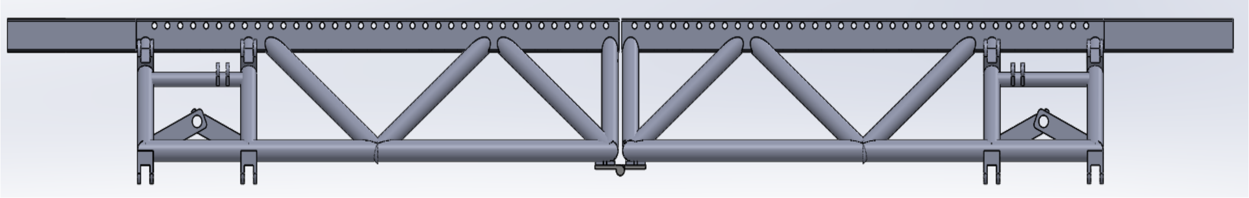


Figure 32: The triangular frame is extended in the driving position

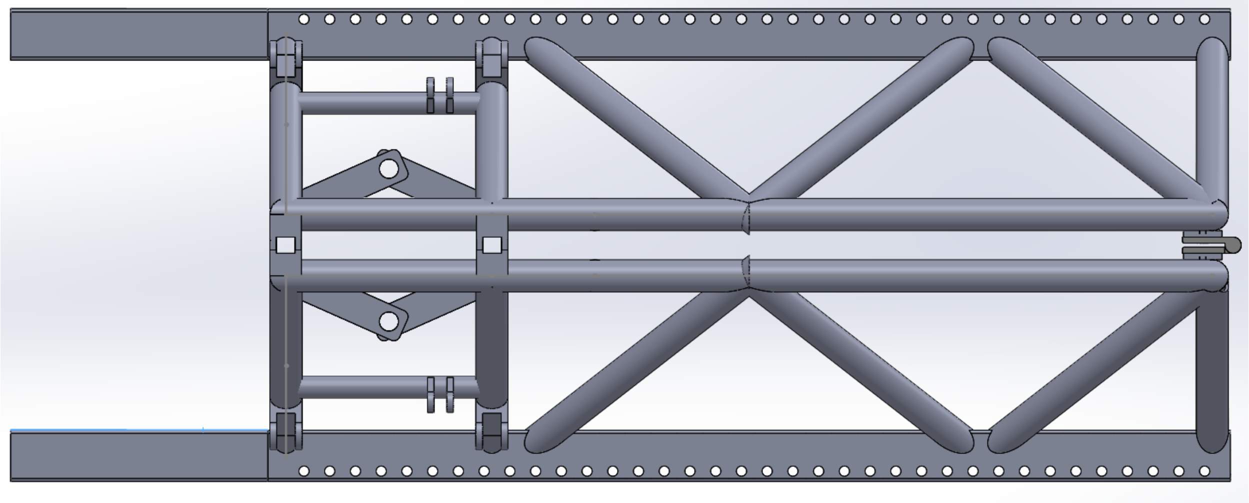


Figure 33: The traingular frame is collapsed in the closed position

The brace location and pivot hinges alloy for the length to be cut in half and detached if desired. This fits the shipping and storage requirements established above.

5.2.1.2 *Tubing Shape*

The tubing shape selected is the circular cross section. The circular cross section is the least difficult to fabricate due to need for one drill bit and a high amount of error allowable. Both the hexagonal and square shapes would require a many measurements and cuts for one weld. The tolerance of the tube being cut at an improper angle is small due to the colliding geometries. The circular tubing is the cheapest and most attainable tubing.

5.2.1.3 *Material*

The material selected was the 1030 steel. The main reason for this is the cost. The SAE machine shop has this available for free. The decrease in strength between this and the chromoly will most likely be unnoticeable in competition. The 6061 aluminum was chosen to not be used due to the difficulty in welding and the decrease in strength.

5.2.2 Brakes

The brake subsystem the team chose to use is a set of four disc brakes, one for each wheel on the rover. A mechanical caliper system was chosen, instead of hydraulic, because of ease of installation and performing maintenance. We will purchase the “Black MTB Mechanical Bike Disc Brake Set” from VkTech through Amazon. Figure 34 is a picture of all the included parts in the kit. This kit includes all components needed for an installation on the front and rear wheel of a mountain bike. Therefore, we will buy two kits in which we will have four calipers, four rotors, four brake lines, four handles, and all hardware needed for install. The two extra brake handles can be used in the event that there is failure in either of the two installed on the rover. Each kit costs $38, and we estimate a total of $83 for two kits including tax and shipping.

Figure 34: VkTech “Black MTB Mechanical Bike Disc Brake Set” [8]

5.2.3 Clamped Tread Wheels

The specific wheel chosen is a 26" by 2.125" solid rubber wheel with a compatible solid steel rim. The 26" diameter wheels/rims are large enough to support the heavy loads that will occur during the competition and provide the minimum clearance required by NASA. The 2.125" width of the tires provides more surface contact for the tires which leads to better traction and lower rolling resistance propelling the tires and vehicle forward. The selected tire and rim can be seen in Figure 35 and Figure ***36***.

Figure 35: Solid Rubber Tire

Figure 36: Solid Steel Rim

The steel rim has a tensile strength and compressive strength of 370 MPa making it an ideal material for a rim that will traverse harsh terrain as it is resistance to deformation in the longitudinal and lateral directions [9].

Solid rubber tires are puncture proof and never go flat. However, they are difficult to install onto a rim correctly due to their resistance to deformation. These tires also have a longer life span than standard pneumatic tires due to their resistance to abrasion and lower operating temperatures. The rolling resistance of solid rubber is also much lower than standard tires meaning, less force is needed to propel the tires forward [10].

Traction is not as good for solid rubber tires when compared to pneumatic tires. In a pneumatic tire, the tire conforms to the road or surface providing more traction as the wheel digs into the ground. A solid rubber tire does not conform as much providing less traction. However, the NASA requirements state no air is allowed in the tires, so solid rubber tires are the ideal choice.

The tire pictured above costs $33.95 per tire. The rim pictured above costs $54.99 per rim. With an expected purchase of 4 tires and rims (plus one spare each) the total costs to use this combination is $444.70

5.2.4 Suspension

The final suspension type that the team has chosen to use is a coilover, which is complimented with the use of control arms and a spindle. This section will include a description of the suspension system, how it met engineering and customer requirements, basic load analysis of the shock, and a 3D drawing of the suspension as a whole. Coilovers are the combination of a shock absorber and spring, as described in the above section. A coilover is only one of the three components needed to have a complete suspension system. Below in Figure 37, shows the three components needed: Coilover, control arms, and spindle.

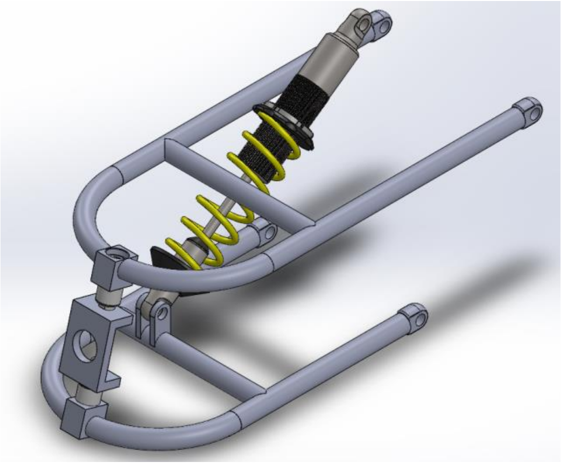


Figure 37: Complete Suspension with Coilover, Control Arms, and Spindle

Control arms are a hinged suspension link that connects the frame to the spindle, which attaches to the wheels, drivetrain, and steering. The control arms are attached to the frame using bushing to allow for almost frictionless movement in a desired axial direction. The arms are also attached to the spindle with ball bearings, which allow axial and radial motion. Spindles are a component that connects both of the control arms to the wheel, brake, drive train, and steering systems. The spindles are meant to keep the brakes, steering rods, tie rods, and wheels rigidly connected while the rest of the suspension travels with the changing environment. The arms are also connected to a coilover, and the coilover connects to the frame. This relationship between the coilover, frame, and control arms is to absorb any impact and will allow our rover to traverse various environments without tipping over, as well as with comfort. The shock will meet the engineering requirement of not having any pneumatic components, due to the strut being filled with oil. The suspension system will meet the requirements that there be at least 15” of clearance between the lowest part of the rover touching a driver and the ground, and that the rover will be able to traverse various environments.

Our team will manufacture the spindles and control arms, which will be considered in the purchasing of materials, and the coilover will be purchased from MotoPartsMax. The coilover chosen is the 13.8” Rear Shock Absorber Suspension for GY6 150cc Scooters as seen in Figure 38.

Figure 38: 13.8” Rear Shock Absorber

The weight of the fully loaded rover including riders will roughly weigh 380 pounds, split between four shocks, is 95 pounds of load each. With the implementation of a factor of safety of 2 to allow for stresses applied during operation, each coilover needs to have a working load of 190 pounds. The shocks chosen have a working load of 200lbs, with an adjustable spring to allow for a more rigid or soft ride. As stated, four shocks will be needed, with a cost of $41.90 each and a total of $167.60.

5.2.5 Drive Train

The final drive train design came down to repurposing the drive train system seen in a typical bicycle. This section will include a description of the drive train system and how it's attached as well as how this will meet our requirements and the force analysis applied by the drivers. The drive train system is two sets of gears that are linked together with a chain. There will be a single gear where the riders' feet will be and then an 8 speed gear system attached to the drive shaft. An 8 speed gear system was chosen because they are commonly found on bikes and customizing the amount of speeds the drive train can have would be complex and could ultimately cost more. There will also be a derailleur just below the 8 speed gear system that will allow the chain to switch gears. To switch the gears, controls will be attached to the handlebars and controlled by the drivers how they see fit. The derailleur essentially pushes the chain onto other gears by guiding it over the other gears. The drivers will need to know what to expect for different speeds. If the vehicle needs to go faster, the drivers need to recognize that they should have the chain on a smaller gear. If the terrain is tough or hard to pedal, the chain should be moved to a bigger gear to make pedaling easier. The gear system will be attached to drive shaft. It was decided that the drive shaft would be made of the same material as the rest of the frame. The drive shaft placement is higher that the base for the wheel and needs to be able to spin. It was found that universal joints (u-joints) are able to transmit torques in different directions provided they can handle the torque applied by the driver. With the u-joints, the torque can then be transmitted to the wheels on a lower shaft. The drive train system and shaft can be seen in Figure 39 and Figure 40

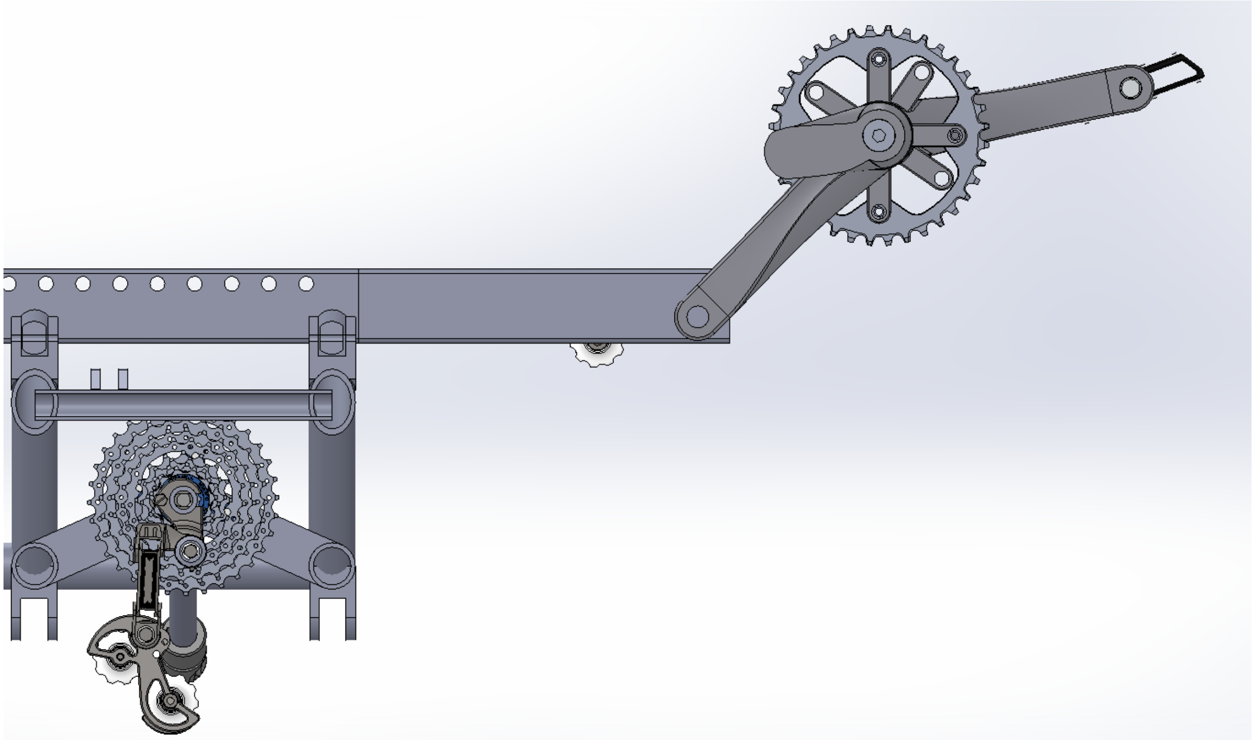


Figure 39: Side view of Drive Train System

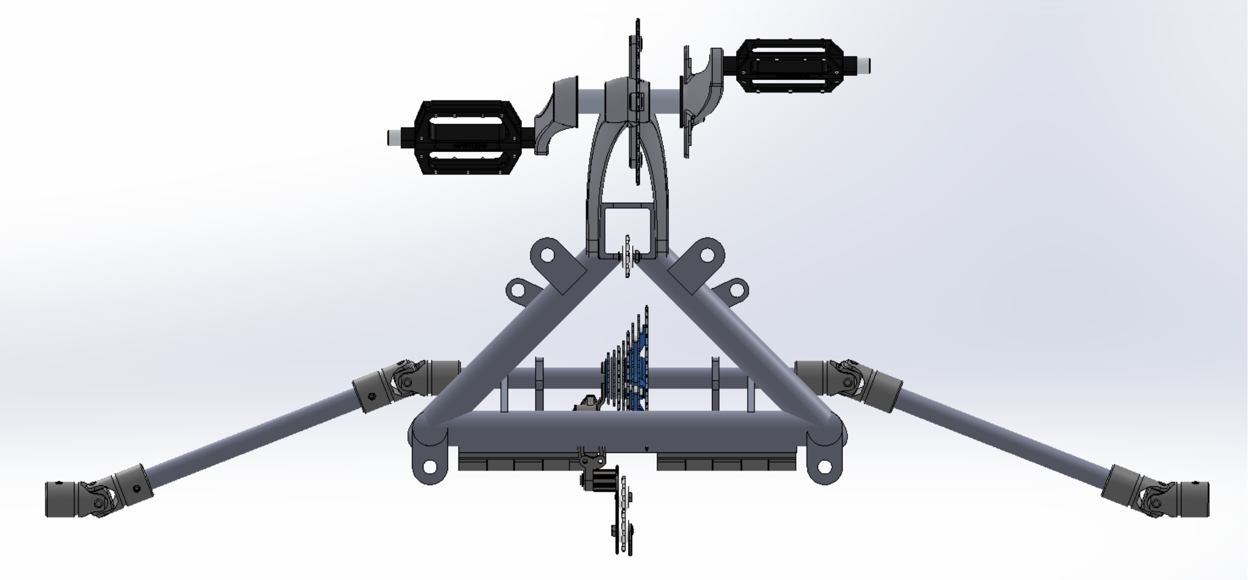


Figure 40: Front view of Drive Train System

Now that the final design had been selected, the team needed to calculate the appropriate forces that the drivers would put on the system to see if it could appropriately handle it. These tests were mainly conducted to see if the drive shaft would succumb to torsion and possibly shear under the forcers applied by the drivers. We had looked up the average force that a typical person can apply with their legs and it was found that, with both legs, a human can push around 1.8-2.2 times their body weight. [13] It could then be assumed that each leg would be able to push half of that value. We assumed that each leg could push 1.1 times their body weight. This force is applied 7 inches away from the center producing a torque on the first gear of 2772lb-in. The force that the gear pulls the chain with can be determined from this torque and the radius of the gear being 3.25in. From this information it was determined that the force through the chain is 426.5lb. This force is transmitted to the secondary gear system where it will apply a torque on the drive shaft. The max torque would come from the chain being on the biggest gear in the system. With the force applied on that gear, it was shown that the maximum torque was 115.5lb-ft which was well within the limits of what the steel can handle with a factor of safety of 2.14.

The main components of this drive train system are the pedals, gears, chain ring, chain, and derailleur. The costs of each part come from REI. The pedals would be made of plastic and was found to be $19.50 and would require toe clips which would be an extra $7.00. The chain ring that would be attached to the pedal system would cost around $8.00. A chain is what combines the chain ring and the gear system and was found to be around $45.00. The gear system itself was shown to be around $28.00 with the derailleur being $47.00. The total cost of this system would be around $154.50. The shaft should be supplied along with the tubing supplied with the frame and the only thing to buy would be the u-joints. There are many different prices depending on the material of the u-joints but an average cost can range from $60-$80 for steel u-joints. There would be a total of 8 u-joints necessary in the total scheme of the rover. This could cost anywhere between $400 and $800. There may need to be a way to machine and/or find a much cheaper method of obtaining u-joints as the budget would not allow for such a huge expense.

5.2.6 Under Seat Steering

The under seat steering design uses push-rods that the driver controls with handles. The push-rods are connected to a center link that runs perpendicular to the frame. The center link transfers push pull motions from the driver into a swivel motion that is used to turn the wheels. The tie-rods transfer the rotary motion from the center link to the spindle at the end of each drive shaft. The heim joint that connects the tie-rod to the spindle will be located at the front of the spindle axis to ensure enough torque will be produced to overcome the frictional turning resistance in the system, and between the wheels and the ground. The under seat steering is pictured below in Figure 42.

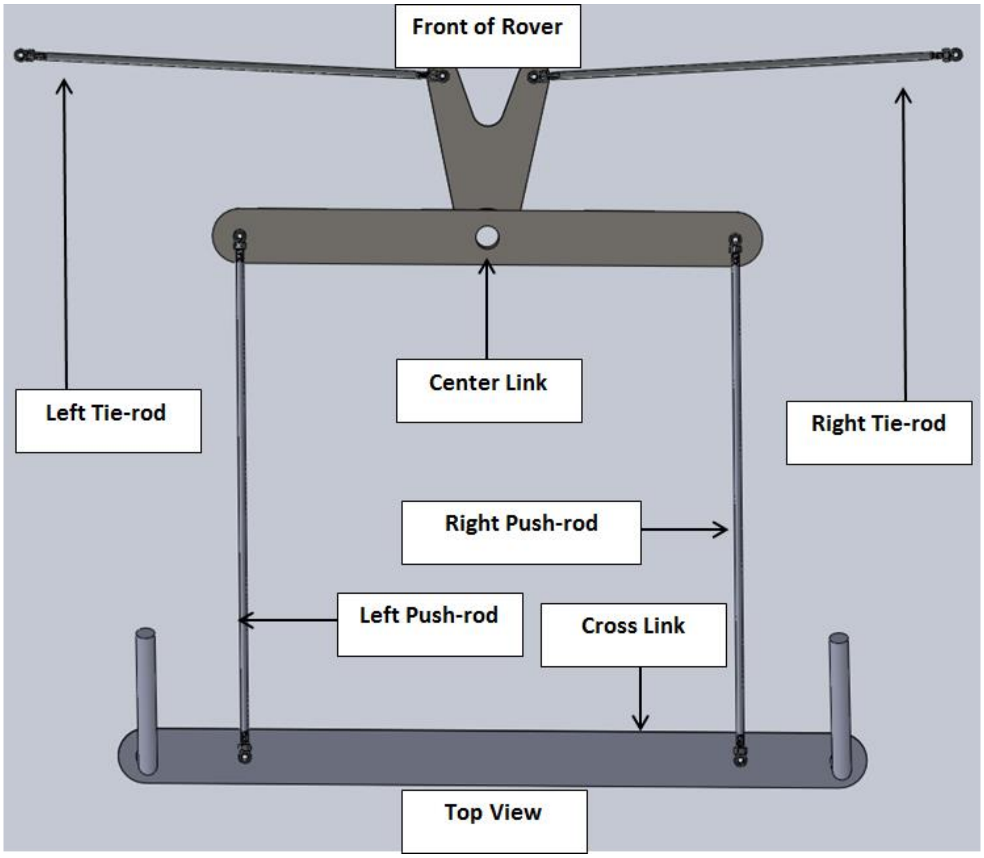


Figure 41: Under seat steering

The under seat design consists of a four link system that is connected primarily through off the shelf heim joints that allow pivoting. These joints are historically used in automobiles and off highway vehicle steering and suspension, and are well suited to this application. Collars are needed to join steering members between heim joints and will be fabricated from steel tubing with a thicker wall than the frame to account for thread tapping.

The driver steers by pushing one handle forward and pulling the other backward. For example, pushing the right handle forward, and pulling the left handle backward will cause the wheels to turn to the left, doing the opposite will turn the wheels to the right.

6 Implementation

This section of the report describes the method used to implement our design, a breakdown of the needed resources, and a bill of materials. It will also include a comparison and justification of the implementation we have chosen, and a schedule for the any activities corresponding to our design.

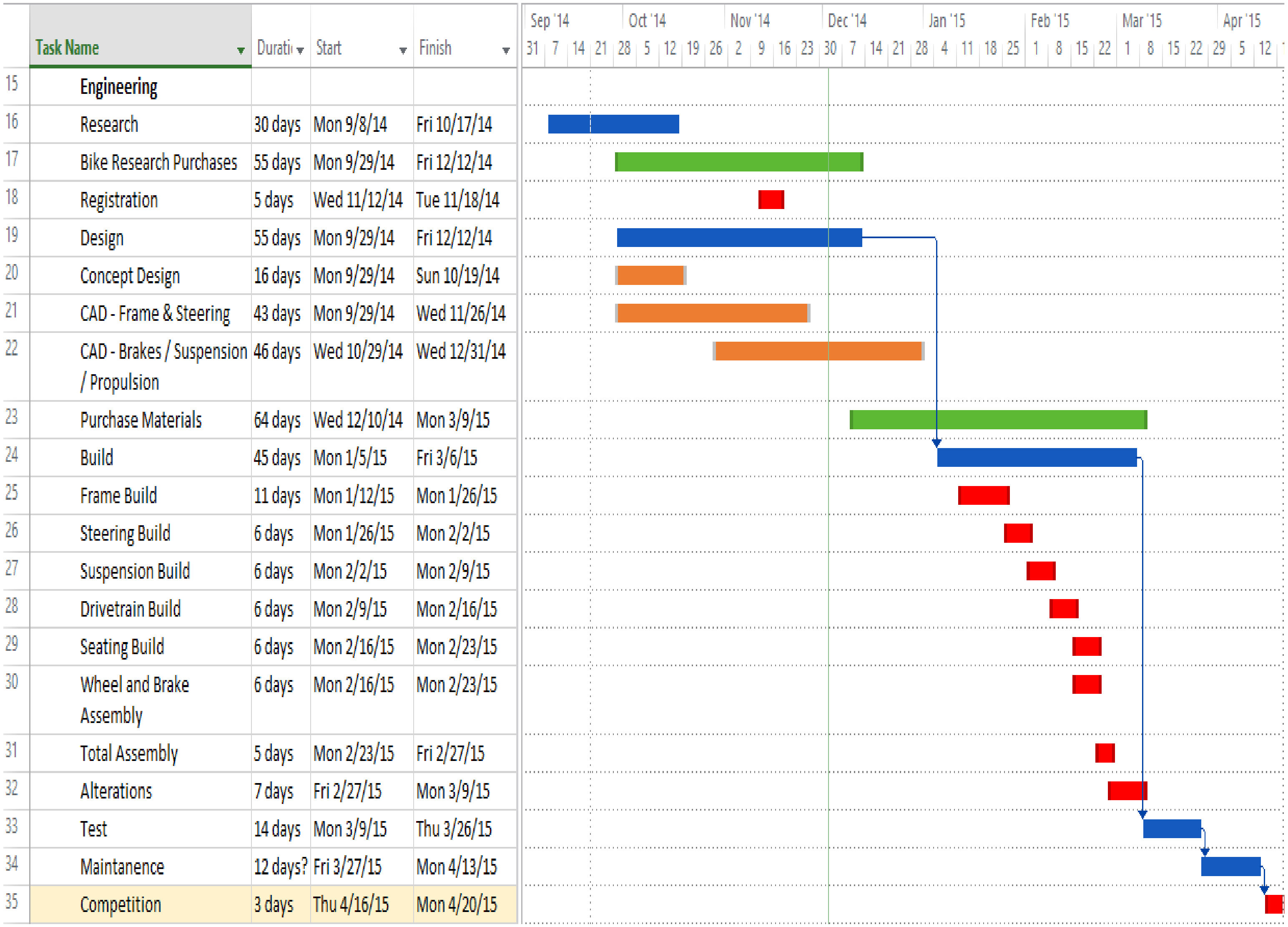
Our team is using the 3D CAD software SolidWorks to completely model and perform force analysis of the created design. The reason for using SolidWorks instead of prototyping or making physical and operational changes is due to the lack of funding. Creating a prototype to test and redesign would significantly increase the needed funding, and require more time than we have to have a completed design. Using the information taken from SolidWorks, our team was able to create a bill of materials, and use engineering drawings to help manufacture parts in the Northern Arizona University Machine Shop. Appendix A contains a complete Bill of Materials for the final rover design described in the design description section. The total of all components in the Bill of Materials is about 2800 dollars, as compared to the allotted SAE budget of 1300 dollars. The difference of these two costs are 1500 dollars, which can be mitigated by receiving raw materials and bike parts from various sponsors. The final balance needed to complete the design will be roughly 300 dollars, which the team will acquire through fundraising. A plan including a detailed schedule for next semester will be included in Appendix B.

Appendix A

Bill of Materials

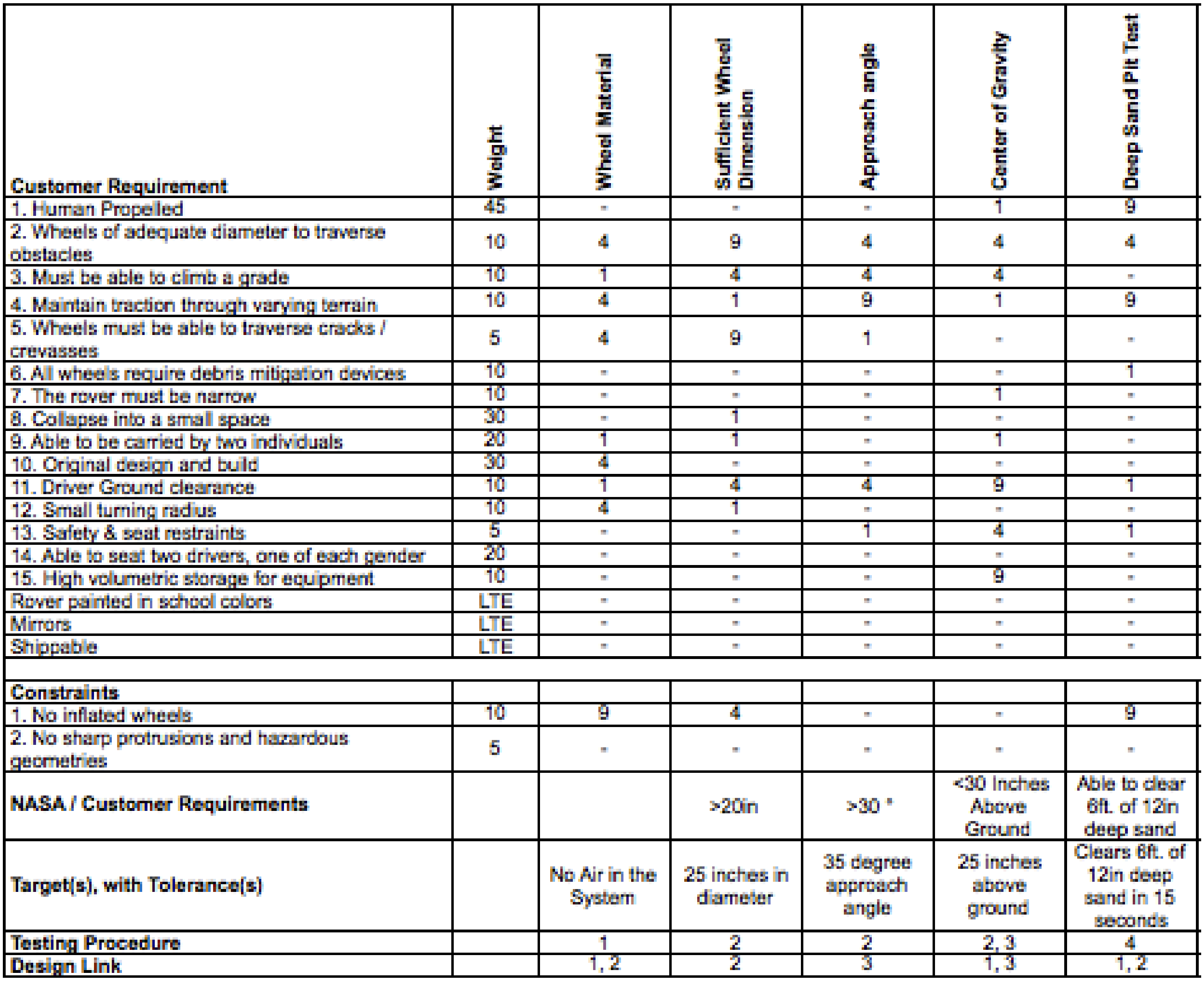
Description	Distributor	P/N	Price	QTY	Subtotal
VkTech Disc Brake Set	Amazon	B00J2O4HY0	$ 37.99	2	**$ 75.98**
13.8" Rear Shock for GY6 150cc Scooters	Moto Parts Max	375-999008	$ 31.95	4	**$ 127.80**
Husky Airless 26 X 2.125 Tire	Bike Mania	-	$ 33.95	4	**$ 135.80**
STA-TRU 26 X 2.125 Steel Wheel	Bike Somewhere	RW2625CB	$ 58.99	4	**$ 235.96**
1-1/4 OD x .120 Wall x 96" Round Steel Tube A513	Metals Depot	T2114120	$ 62.64	4	**$ 250.56**
1/8" Thick, 1/2 Holes on 11/16 Centers, Al Sheet	Metals Depot	PA12512	$ 96.00	2	**$ 192.00**
.840 OD X .147 Wall x 96" Round Steel Tube	Metals Depot	T51280	$ 35.28	4	**$ 141.12**
1/2 X .065 Wall X 120" Round Steel Tube	Metals Depot	T212065	$ 20.30	1	**$ 20.30**
10 Gauge Steel Sheet 1 X 4 ft	Metals Depot	S110	$ 38.76	1	**$ 38.76**
10 Gauge Steel Sheet 2 X 2 ft	Metals Depot	S110	$ 38.76	1	**$ 38.76**
2 X .188 Wall X 60" Square Steel Tubing	Speedy Metals	ts2x.188-60	$ 33.18	3	**$ 99.54**
2.5 X .188 Wall X 36" Square Steel Tubing	Speedy Metals	ts2.5x.188-36	$ 26.14	1	**$ 26.14**
3 X .356 Thick Steel C-Channel	Speedy Metals	hc3x6-24	$ 20.31	1	**$ 20.31**
Novara ATB Bike Pedals	REI	872094	$ 19.50	2	**$ 39.00**
Novara Toe Clips with Straps	REI	874007	$ 7.00	2	**$ 14.00**
Shimano Deore M532 Chainring 64mm-22 Teeth	REI	778825	$ 8.00	2	**$ 16.00**
Shimano SLX CN-HG75 10-Spped Chain	REI	872867	$ 45.00	2	**$ 90.00**
Shimano Alivio RM410 Rear Derailleur	REI	753543	$ 47.00	2	**$ 94.00**
SPRAM PG 850 8-Speed Cassette	REI	698250	$ 28.00	2	**$ 56.00**
71 X 24 X 1/2" thick Yoga Mat	Amazon	B00IIQUBY8	$ 17.50	1	**$ 17.50**
Heavy Load Hinge	Misumi	HHSZ125	$ 39.42	2	**$ 78.84**
U-Joint	McMaster-Carr	8285K150	$ 86.58	8	**$ 692.64**
Axle Shaft 6 ft	McMaster-Carr	9220K511	$ 23.95	1	**$ 23.95**
Ball Joint	McMaster-Carr	8412K461	$ 13.79	8	**$ 110.32**
Hinge Pin	McMaster-Carr	59895K130	$ 10.57	16	**$ 169.12**
3/8"-24 Nylon Ball Joint End	McMaster-Carr	1064K541	$ 6.12	8	**$ 48.96**

Appendix B



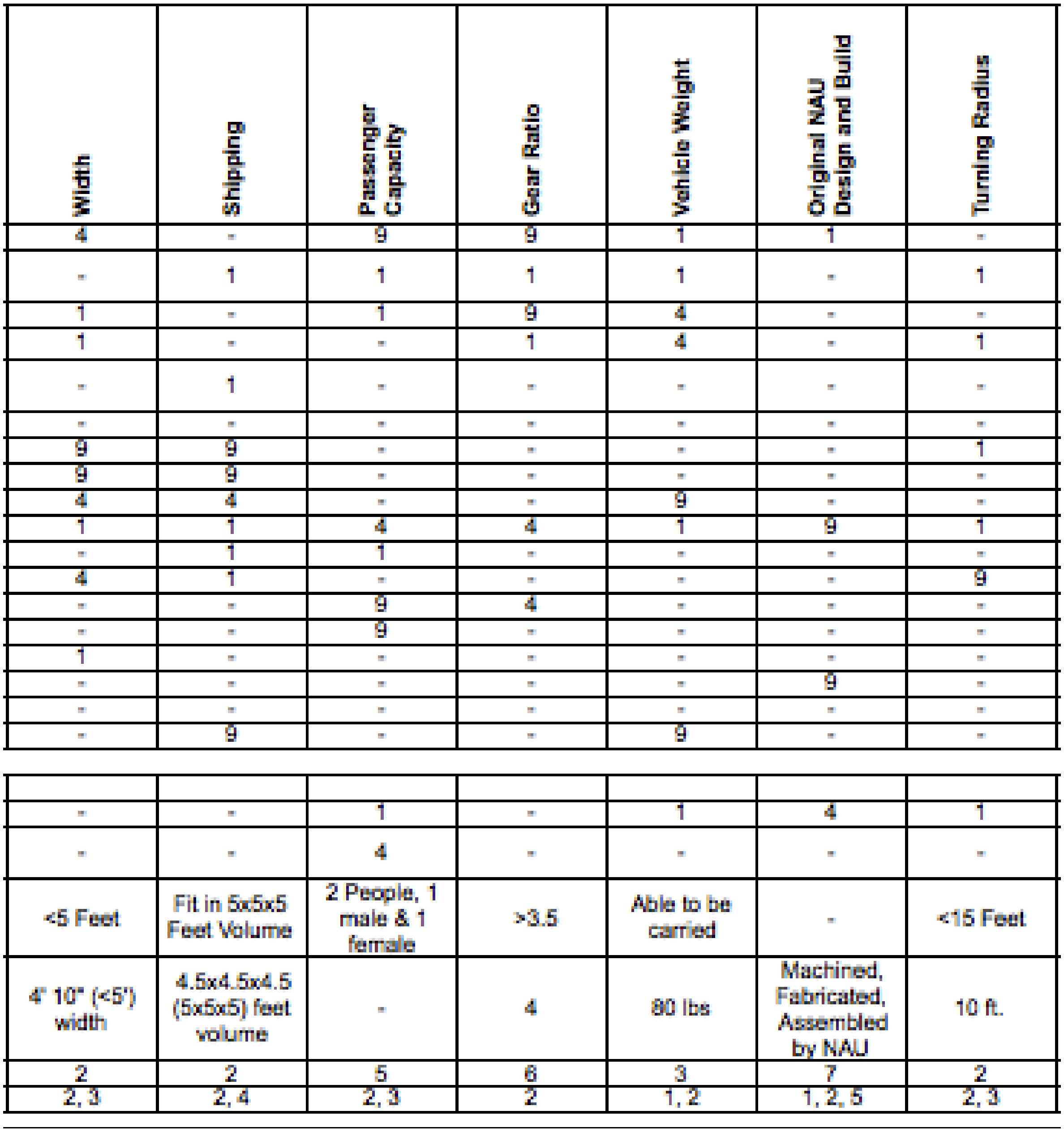
	Task Name	Duration	Start	Finish
15	**Engineering**			
16	Research	30 days	Mon 9/8/14	Fri 10/17/14
17	Bike Research Purchases	55 days	Mon 9/29/14	Fri 12/12/14
18	Registration	5 days	Wed 11/12/14	Tue 11/18/14
19	Design	55 days	Mon 9/29/14	Fri 12/12/14
20	Concept Design	16 days	Mon 9/29/14	Sun 10/19/14
21	CAD - Frame & Steering	43 days	Mon 9/29/14	Wed 11/26/14
22	CAD - Brakes / Suspension / Propulsion	46 days	Wed 10/29/14	Wed 12/31/14
23	Purchase Materials	64 days	Wed 12/10/14	Mon 3/9/15
24	Build	45 days	Mon 1/5/15	Fri 3/6/15
25	Frame Build	11 days	Mon 1/12/15	Mon 1/26/15
26	Steering Build	6 days	Mon 1/26/15	Mon 2/2/15
27	Suspension Build	6 days	Mon 2/2/15	Mon 2/9/15
28	Drivetrain Build	6 days	Mon 2/9/15	Mon 2/16/15
29	Seating Build	6 days	Mon 2/16/15	Mon 2/23/15
30	Wheel and Brake Assembly	6 days	Mon 2/16/15	Mon 2/23/15
31	Total Assembly	5 days	Mon 2/23/15	Fri 2/27/15
32	Alterations	7 days	Fri 2/27/15	Mon 3/9/15
33	Test	14 days	Mon 3/9/15	Thu 3/26/15
34	Maintanence	12 days?	Fri 3/27/15	Mon 4/13/15
35	Competition	3 days	Thu 4/16/15	Mon 4/20/15

Appendix C



Customer Requirement	Weight	Wheel Material	Sufficient Wheel Dimension	Approach angle	Center of Gravity	Deep Sand Pit Test
1. Human Propelled	45	-	-	-	1	9
2. Wheels of adequate diameter to traverse obstacles	10	4	9	4	4	4
3. Must be able to climb a grade	10	1	4	4	4	-
4. Maintain traction through varying terrain	10	4	1	9	1	9
5. Wheels must be able to traverse cracks / crevasses	5	4	9	1	-	-
6. All wheels require debris mitigation devices	10	-	-	-	-	1
7. The rover must be narrow	10	-	-	-	1	-
8. Collapse into a small space	30	-	1	-	-	-
9. Able to be carried by two individuals	20	1	1	-	1	-
10. Original design and build	30	4	-	-	-	-
11. Driver Ground clearance	10	1	4	4	9	1
12. Small turning radius	10	4	1	-	-	-
13. Safety & seat restraints	5	-	-	1	4	1
14. Able to seat two drivers, one of each gender	20	-	-	-	-	-
15. High volumetric storage for equipment	10	-	-	-	9	-
Rover painted in school colors	LTE	-	-	-	-	-
Mirrors	LTE	-	-	-	-	-
Shippable	LTE	-	-	-	-	-
Constraints						
1. No inflated wheels	10	9	4	-	-	9
2. No sharp protrusions and hazardous geometries	5	-	-	-	-	-
NASA / Customer Requirements			>20in	>30 °	<30 Inches Above Ground	Able to clear 6ft. of 12in deep sand
Target(s), with Tolerance(s)		No Air in the System	25 inches in diameter	35 degree approach angle	25 inches above ground	Clears 6ft. of 12in deep sand in 15 seconds
Testing Procedure		1	2	2	2, 3	4
Design Link		1, 2	2	3	1, 3	1, 2

Appendix C Cont.



Width	Shipping	Passenger Capacity	Gear Ratio	Vehicle Weight	Original NAU Design and Build	Turning Radius
4	-	9	9	1	1	-
-	1	1	1	1	-	1
1	-	1	9	4	-	-
1	-	-	1	4	-	1
-	1	-	-	-	-	-
-	-	-	-	-	-	-
9	9	-	-	-	-	1
9	9	-	-	-	-	-
4	4	-	-	9	-	-
1	1	4	4	1	9	1
-	1	1	-	-	-	-
4	1	-	-	-	-	9
-	-	9	4	-	-	-
-	-	9	-	-	-	-
1	-	-	-	-	-	-
-	-	-	-	-	9	-
-	-	-	-	-	-	-
-	9	-	-	9	-	-
-	-	1	-	1	4	1
-	-	4	-	-	-	-
<5 Feet	Fit in 5x5x5 Feet Volume	2 People, 1 male & 1 female	>3.5	Able to be carried	-	<15 Feet
4' 10" (<5') width	4.5x4.5x4.5 (5x5x5) feet volume	-	4	80 lbs	Machined, Fabricated, Assembled by NAU	10 ft.
2	2	5	6	3	7	2
2, 3	2, 4	2, 3	2	1, 2	1, 2, 5	2, 3

Appendix C Cont.

Turning Radius	Critical Driver Components	Seat Safety Harness	No Sharp Protrusions	Storage Volume	Vehicle Presentation	Rear Vision Test
-	4	4	4	-	-	-
1	4	-	-	-	-	-
-	-	4	-	1	-	1
1	-	1	4	-	-	-
-	4	-	-	-	-	-
-	-	-	1	-	-	-
1	-	-	-	4	-	1
-	-	-	-	4	-	-
-	-	-	4	1	-	-
1	4	1	1	4	9	1
-	9	-	-	-	-	-
9	-	1	-	-	-	-
-	-	9	-	-	-	4
-	1	4	1	-	-	1
-	4	-	-	9	-	-
-	-	-	-	-	9	-
-	-	-	1	-	-	9
-	-	-	1	-	-	-
1	1	-	-	-	-	-
-	1	-	9	-	-	4
<15 Feet	>15 Inches above ground	Drivers are Unhurt	Safe to Operate	>1 Cubic Foot	Painted In School Colors	Able to View Behind
10 ft.	17 (>15) inches	>= 3 point harness	Passes Penetration Test	3 cubic feet	Painted Blue and Gold	Rear View Mirrors
2	2	8, 9	10	2	11	4, 9
2, 3	2, 3	1, 2	5	2, 3	6	2, 3

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