Vehicle Wheelchair Storage Final Design Report

June 8, 2020

Exhibit D

Sponsor: Quality of Life Enhanced (QL+)

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Executive Summary

The scope of this project is to design a wheelchair storage mechanism for Peter Way, a retired army veteran. The goal is to design and build a solution that will allow Peter to quickly store his wheelchair into the cab of his truck securely without causing damage to the chair and the truck.

Our team has gone through several design iterations before coming up with our finalized universal storage solution. The final design offers Peter a reliable, safe, and efficient way to store his wheelchair and wheels through a two-part storage system. The first rack system is used to hold his wheelchair safely in the backseat taking up one seat's space leaving enough room for his service dog. The second rack system stores the wheels of his wheelchair along the backside of the driver's seat.

Before leaving school due to the COVID-19 situation, our team was able to complete an initial prototype which was then sent to Peter so he could put it to use and provide us with any feedback. He has ensured our team that our storage system has met his expectations and successfully meets all his needs. However, there are still a few minor issues that could be addressed. Our final design includes effective solutions to those issues. He will continue to use our product and when we have the chance, we will provide him with updated parts of our storage system. Our team has provided a thorough detailed manufacturing and assembly instructions on how to execute the changes we have made to our design in the future.

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1. Introduction

The team consists of four mechanical engineers: Alexander Cherry, Mikio Habu, Alex Morcate, and Chloe Ng. Vanessa Salas is the Project Manager for QL+ at Cal Poly and is the sponsor and main point of contact throughout the project. Our QL+ challenger, Peter Way, is a retired army veteran whose right leg was amputated above the knee. Previously, he used a wheelchair crane lift installed on his Toyota Tacoma for transport. Because that method is too slow for his active lifestyle, he has resorted to throwing the chair into the bed of his truck which has slowly been damaging his wheelchair. He is looking for a better solution that makes it easier on himself and protects his wheelchair from the environment. This document contains all information regarding our finalized design: background research, prototypes, how we decided on specific design decisions, all manufacturing directions, and assembly instructions.

Before leaving school due to COVID-19, the team was able to complete our first prototype, and had it shipped out to Peter so he could put it to use. With the feedback he provided to us, we implemented some new design changes to our storage system. Due to the COVID-19 situation, we were not be able to build a new rendition of our storage system with the changes. However, we have provided detailed instructions so that these changes can be implemented in the future or by another party.

2. Background

Extensive research was conducted in order to a gain concrete understanding of the problem's details as well as solutions that currently exist. Research included examining existing patents, products, and conducting interviews with sponsors and stakeholders. This acts as the starting point for ideation and the beginning of the design process.

2.1 Interview with Sponsor

The interview with Peter gave a clear idea of what requirements were needed by the client. The biggest problem Peter had with the wheelchair crane lift that he used in the past was the aesthetic qualities and the speed. The bulkiness of the lift destroyed the look of his truck and the process of storing his wheelchair took too long. Currently, Peter manually stores his wheelchair in the truck bed leaving it exposed to the outside environment and weather. Sometimes he stores it as seen in Figure 1. Below is a complete list of Peter's wants and needs taken from our initial meeting with him.

Needs:

- Fast
- Fits in backseat of truck cab
- Doesn't damage interior of truck
- Protect wheelchair from outside elements
- Safe for use with service dog

Wants:

- Portable, can be moved to other vehicles
- Requires little permanent modifications to his truck

2.2 Existing Product Research

As a part of background research, several existing products were examined. From these products, concepts and attributes were collected. Most of the products already on the market lack many of the requirements that our client requested, however many had features that could be useful and implemented into the design. Descriptions of these existing products can be found in Table 1 and pictures are found in Appendix A.

In addition to looking at existing products, patents of similar products and designs were collected using Google Patent Search. (Appendix B). Similar to the existing products, the lifts found through the patent search had features that can be implemented in the design, but many of them lacked a majority of the requirements of the client. A table of these findings is in Appendix B. While there was not a product that had most of the requirements that Peter requested, key features from each product can be implement into the design. The team's process working towards designing a solution that meets all the requirements desired by the client through extensive brainstorming and prototyping is detailed in the next sections.

Figure 1. Peter Loading His Wheelchair into the Passenger Seat from the Driver Side

Table 1. Existing Products and Description

Product Name	Description	Figure Number
Harmar AL825 Pickup 225 Speed	• External lift attached outside in truck bed • Ability to load any mobility device • Unloads to driver/passenger side doors • Controlled wirelessly with remote control	18A
Bruno Out-Rider	• Specifically designed for pick-up trucks • Can be easily removed and installed into other vehicles • Operates quickly and uses a hand-held remote • Installed in truck bed	18B
Access Unlimited: Easy Stow PIT Pickup Truck Wheelchair Lift	• Protected wheelchair storage inside truck cab • Compact design • Controlled with hand-held remote control • Wheelchair needs to be collapsible but wheels do not need to be removed	18C
All Terrain Conversions (ATC) 45 Degree Platform Wheelchair Lift	• Utilizes a 45-degree angled pan allowing for 50% faster load/unload time • Fewer chances of damaging interior/exterior of the vehicle • Power unit fits under the hood of truck freeing up back seating • Extensive modifications	18D
Commander 200 Truck Mount	• Interior mount allow for quick loading/unloading • Compact and delivers maximum maneuverability • Assembly and disassembly can be done in 30 seconds	18E

2.3 Relevant Literature

More research was conducted to gain a better understanding of the client's needs and what kind of features they are looking for in products that enhance mobility. Our research was initially focused on lifting mechanisms before the scope of our project shifted to storage. Based on a study conducted by the Department of Rehabilitation Science and Technology, University of Pittsburgh on robotic assisted transfer devices, 83% of participants agreed that it was important to develop this kind of technology to increase the ability of people with mobility impairments and allow them to participate in more daily activities [1]. Research has shown that products that increase mobility for people with disabilities and improves their quality of life also improves their mental health by reducing depression [2]. Understanding the experience of travelling for people with disabilities is extremely important when designing products to ease transportation [3]. In addition, safety is a main concern for mobility enhancement devices. According to the Federal Motor Vehicle Safety Standards, approximately 40% of injuries to wheelchair users interacting with a motor vehicle occurred when entering or exiting the vehicle and 26% were a result of lift malfunction [4]. Durability and reliability are also concerning when designing a wheelchair lift due to their complexity. The lifetime of lifts designed for transit-buses are short and inspecting them is difficult [5]. With this information in mind, we have worked towards creating a product that allows our customer to access his truck on his own terms.

2.4 Relevant Mechanisms

This section focuses more on the mechanisms used than the product as a whole. These mechanisms offer inspiration for possible concepts that we can develop upon to produce a full product.

The Multi-Lift Disability Handicap Lift offers a small footprint lift that could easily be modified for a lifting a wheelchair. This concept design also has a profile that could allow for the dog to pass through. Because our focus has shifted towards just a storage solution, the hooking device used here can help us design a wheelchair holding hook.

Figure 2. Multi-Lift Disability Handicap Lift

The design shown in Figure 3 below offers a good way of connecting the wheelchair to whichever lifting mechanism is decided as the best solution. This configuration works when the wheels are on when the chair is stored. This is not the case however for Peter so further research must be conducted.

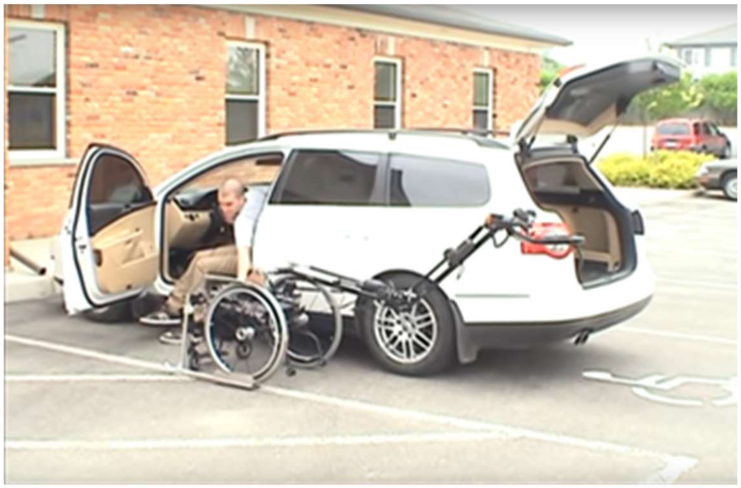

Figure 3. Arm Placing Wheelchair into Passat

2.5 New Research for Storage System

This section highlights the new research we conducted due to the scope change of our project. Instead of focusing on a lifting device, we have shifted our focus to developing a secure storage system. Bike storage systems were used for inspiration. The arms on the bike wall mount shown in Figure 4 below provide two points of contact and are strong enough to hold Peter's wheelchair as well as work with the geometry of the chair.

Figure 4. Bike Wall Mount

A method of attaching the device to the back seat of the truck was needed. The car seat attachment straps shown in Figure 5 below are a good option to consider for strapping down the structure to the car seat hooks of the truck.

Figure 5. Child Car Seat Connector

3. Objectives

Further preliminary analysis was performed during the formation of the problem statement and project objectives. Once the project boundary conditions were defined, needs and wants were translated into system specifications. These are necessary in forming a path toward a solution that meets all of the necessary criteria. Further risk analysis was conducted to ensure solutions developed are deliverable.

3.1 Problem Statement

Initially, Ret. Major Peter Way needed an efficient lifting and storing mechanism that takes up a minimal amount of space in the cab of his truck and protects his wheelchair from the outside elements and environment. Now, we are focused on designing Peter a universal, easy to use, storage system for his wheelchair.

3.2 Boundary Diagram

The boundary diagram shown below in Figure 6 gives us an idea of how much space is available to work with. (Note: the pickup pictured is not the same brand or model as Peter's but has a similar structure.) Any solution will have to fit in the cab of his truck and will take up about one third of the backseat space. The remaining space will need to be left unused in order to accommodate Peter's service dog and the Dog Ramp group. Peter would like to avoid making permanent modifications to the car that might make it hard for him to sell his truck in the future.

Figure 6. Boundary Diagram

3.3 List of Client's Wants and Needs

Project information gathered from the Sponsor and Challenger interviews can be seen in Table 2, which outlines the customers' needs and wants.

Table 2. Client Wants and Needs

Needs	Wants
Fast (<2min)	No truck mods
Does not interfere with dog	Design life 6-10 years
Fits behind driver (w/ or w/o backseat in)	Does not negatively affect look of truck
No mods that make truck hard to sell	Ease of use
Protect wheelchair from outside elements	Low maintenance
	Adaptable to different trucks

The list of client needs and wants was derived from interviews with Peter where he discussed requirements for the project. His wants and needs were incorporated into a Quality Function Deployment (QFD).

3.4 Quality Function Deployment (QFD)

The Quality Function Deployment is a process used to determine appropriate specifications for a new design based on client needs. The QFD was also used to compare client needs with the engineering specifications developed to benchmark potential solutions and help arrive at the target design specifications. The QFD can be seen in Appendix C.

3.5 Specification Table

Results from the QFD have been processed into a Specification Table (Table 3) which outlines the Specification number, Description, Customer's Needs, and Risk level.

Table 3. Specification Table

Spec. #	Description	Target Value	Tolerance	Strongly Related Customer Needs	Risk	Compliance
1	Measurements	Fit in Cab		Size, Weight	L	I, A, T
2	Development Cost	$1000	Max	Low Cost	L	S, A
3	Stow Test	2 minutes	Max	Ease of Use, Portability, Weight, Deployability	M	T, I
4	Weight	25	Max	Ease of Use, Portability, Weight, Deployability	M	I, A
5	Number of Custom Parts	50%	Max	Minimal Customization	H	I
6	Hold wheelchair in place	Limited motion	N/A	Safety	H	I, A, S
7	Install	20 min	Max	Safety, Ease of Use, Portability, Deployability	L	I, T
8	Noise	survey	N/A			T

3.6 Specification Description

The specification table indicates the initial target value and the client needs that are most strongly correlated for each specification. Initial values are based on background research and discussions with stakeholders. The related client needs were determined using the QFD (see Appendix C). Each of these specifications will be tested throughout the production of the design. The method used to determine compliance is listed in the Compliance column of the Specification Table. The letters indicate as follows: I is inspection, T is testing, S is similarity to existing products, and A is analysis. Each specification and how it will be verified is described below:

- **Measurement:** Analysis and inspection of dimensions and to determine whether it fits in the cab based on Tacoma specifications; also needs adequate space for dog ramp storage
- **Cost:** Analysis based on part cost and pricing manufacturing similarity to current products
- **Deployment test:** Analysis and prototype testing
- **Weight:** Analysis based on part weight and inspection via a scale
- **Number of Custom Parts:** Visual inspection
- **Limiting Motion:** Installing in a vehicle with a wheelchair or adequate analog and visually inspecting any motion during driving
- **Install:** Inspection of parts to be installed and prototype testing
- **Noise:** Will be surveyed during driving tests

3.7 Risk Assessment

The risk column indicates how achievable each specification target seems at this stage of the project. L indicates low risk, M medium risk, and H high risk. Low risk indicates that there is confidence that this specification will be met or exceeded and high risk indicating there is a significant degree of uncertainty in whether the specification is achievable. High risk specifications are space requirements and the number of custom parts. The space available in the Tacoma is limited and must also be shared with the dog ramp team. The number of custom parts will be very dependent on the nature of the final design which may necessitate a larger than ideal number of custom parts. If these specifications are not fully met, it is still believed that the design will be satisfactory to the primary stakeholders.

4. Concept Design

The concepts and their development are described in this section. Models and prototypes were used to provide proof of concept. All initial analysis and concept models were made before the project scope was changed. They are therefore concerned primarily with lift rather than storage devices.

4.1 Concept Models

From the preliminary analysis, various system functions were modeled using craft supplies. This process is important to help gain a physical understanding of the mechanism and the geometry being discussed.

The intake concept uses either gears and sprockets or a pneumatic cylinder to actuate the intake arm up and down. The geometry in Figure 7 would pivot around a single axis of rotation. It would store retracted in the cab, possibly past center. Gas springs are also being considered. The intake would be wide enough store the chair and for a dog to walkthrough before deployment.

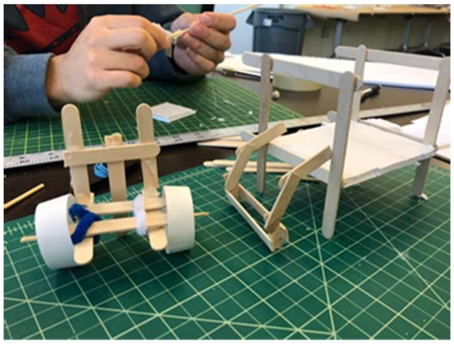

Figure 7. Intake 1 Concept Model

The angle of the intake arm has not been decided and will need further prototyping to determine what angle would be most advantageous. Figure 8 shows the difference in geometry between the two intakes.

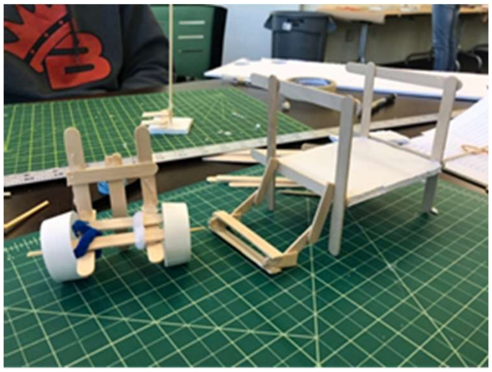

Figure 8. Intake 2 Concept Model

The Indoor Crane shown in Figure 9 below features a fixed angle and height system that would lift the wheelchair using a spool system. This design is similar to the crane that was previously used and abandoned.

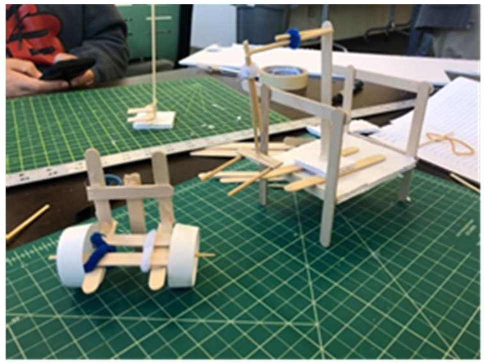

Figure 9. Indoor Crane Concept Model

The elevator concept in Figure 10 uses sprocket and chain elevator for actuation. It could either fold or slide out so that it stores within the cab. This design may be difficult to accommodate the dog's walking lane.

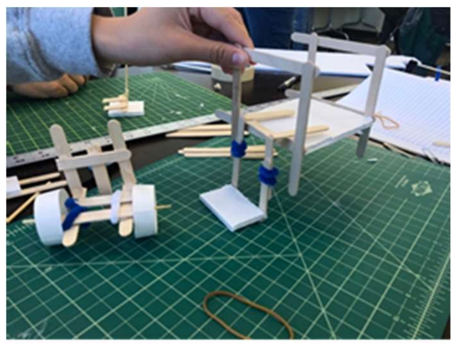

Figure 10. Elevator Concept Model

A pulley system, shown in Figure 11, that slides in and out on a linear slider system would be able to store nicely but would provide an overhead hazard for the dog.

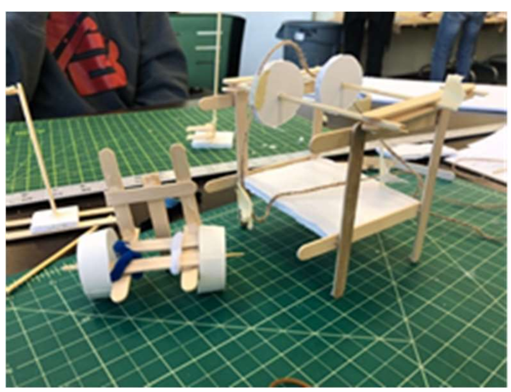

Figure 11. Pulley Rack Concept Model

The folding shop crane in Figure 12 has many degrees of freedom allowing it to lift and store the wheelchair in a variety of configurations. This makes it adaptable for other trucks. This geometry takes inspiration from the Multi-Lift Disability Handicap Lift. This compact design offers a significant amount of space for the chair frame, wheels, and dog path.

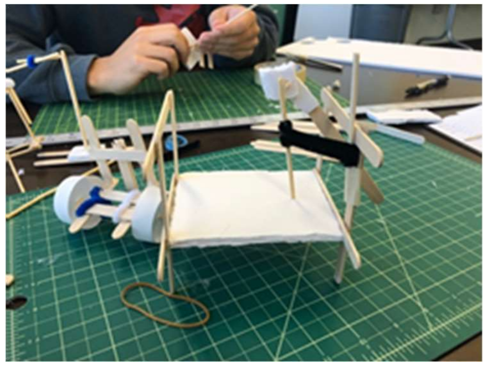

Figure 12. Folding Shop Crane Concept Model

A wristed claw intake on linear sliders (shown in Figure 13) would provide a low-profile solution to lifting the chair in and out of the cab. One potential drawback is that the claw might not be able to minimize ground clearance compared to other models.

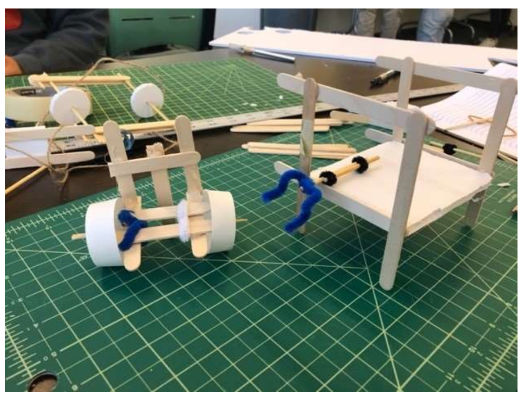

Figure 13. Claw Concept Model

The concepts above were modeled in class on October 29th, 2019. Further analysis of each was done below using Pugh Matrixes detailed in the next section.

4.2 Concept Model Analysis

In order to create a more refined design, Pugh matrices and a weighted decision matrix were used. These matrices were used to evaluate the functions for each of the concepts. This process allowed us to decide which solutions are the most promising.

The weighted decision matrix shown in Table 4 compares all of the concept designs. This matrix compares different design alternatives with respect to a set of design specifications. Each specification was assigned an overall level of importance (1-5). Each alternative was ranked relative to the overall level of importance.

Pugh matrices were created for each critical function of the design. The Pugh matrices can be found in Table 5. The critical functions were motion type, actuation, and the interface with Peter's service dog. Design specifications for each of concept were compared to Peter's current solution which requires him to manually lift his wheelchair into his truck.

The best concepts were chosen to begin prototyping. In Table 4, seen below, the Intake Lifter and Variable Angle Shop Crane score the highest out of all the concepts, with total scores of 106 and 112, respectively. Therefore, these two designs have been prioritized for initial prototyping

Table 4. Weighted Design Matrix of Concepts

Specification	Weight	Concept Prototypes											
		Pulley Rack		Intake Lifter		Linear Rail + Claw		Elevator		Variable Angle Shop Crane		Wrap Around Door Rack	
		Score	Total	Score	Total	Score	Total	Score	Total	Score	Total	Score	Total
Safety	5	2	10	3	15	3	15	3	15	4	20	3	15
Ease of use	5	2	10	4	20	4	20	4	20	4	20	5	25
Durability	3	2	6	4	12	3	9	2	6	4	12	3	9
Size	3	3	9	3	9	2	6	1	3	5	15	4	12
Portability	2	1	2	2	4	4	8	1	2	5	10	3	6
Weight	1	2	2	4	4	3	3	1	1	4	4	3	3
Deployability	2	4	8	5	10	4	8	4	8	4	8	4	8
Low Cost	1	3	3	3	3	2	2	2	2	2	2	3	3
Simplicity	3	4	12	4	12	4	12	2	6	3	9	2	6
Minimal Customization	3	3	9	3	9	3	9	3	9	2	6	2	6
ADA	2	2	4	4	8	3	6	5	10	3	6	2	4
Totals		28	75	39	106	35	98	28	82	40	112	34	97

Table 5. Pugh Matrices

Analysis	Motion Type

Concept	Manual Storage	Pulley Rack	Intake Lifter	Linear Rail + Claw	Elevator	Varible Angle Shop Crane	Wrap Around Door Rack
Characteristic	Lift	Linear	Rotation	Linear and Rotation	Linear	Multiple Rotation	Multiple Rotation
Specification							
Safety	S	+	+	-	+	-	-
Ease of use	S	+	+	+	+	+	+
Deployability	S	-	+	S	-	S	S
Storage	S	+	+	+	+	+	+
Size	S	-	-	-	-	-	-
Reliability	S	-	+	S	+	S	S
Total	0	0	5	0	2	-1	-1

Analysis	Actuation

Concept	Manual Storage	Pulley Rack	Intake Lifter	Linear Rail + Claw	Elevator	Varible Angle Shop Crane	Wrap Around Door Rack
Characteristic	Manual	Piston and Motor	Motor	Piston and Servo	Motor and Piston	Multiple Servo	Multiple Servo
Specification							
Safety	S	+	+	+	+	+	+
Ease of use	S	-	+	-	-	-	-
Deployability	S	+	+	+	+	+	+
Storage	S	+	+	+	+	+	+
Size	S	+	+	+	+	+	+
Reliability	S	+	+	-	+	-	-
Total	0	5	6	2	5	2	2

Analysis	Interface with Dog

Concept	Manual Storage	Pulley Rack	Intake Lifter	Linear Rail + Claw	Elevator	Varible Angle Shop Crane	Wrap Around Door Rack
Characteristic	Lift	Linear	Rotation	Linear and Rotation	Linear	Multiple Rotation	Multiple Rotation
Specification							
Safety	S	-	S	-	-	S	S
Ease of use	S	S	-	-	-	S	S
Deployability	S	+	+	+	+	+	+
Storage	S	+	+	+	+	+	+
Size	S	-	-	-	-	-	-
Reliability	S	+	+	+	+	-	-
Total	0	1	1	0	0	0	0

Key		
S		Same
+		Better
-		Worse

4.3 Cab Scale Model

Because we are working alongside the dog ramp team who will be using the same back cab space as us, we have agreed that a 1-1 scale model of the interior of the truck cab would aid in the design and prototype testing phases of the project. Dimensions from the visit to the Toyota Dealership allowed the team to model the truck in SolidWorks, as seen in Figure 14 below.

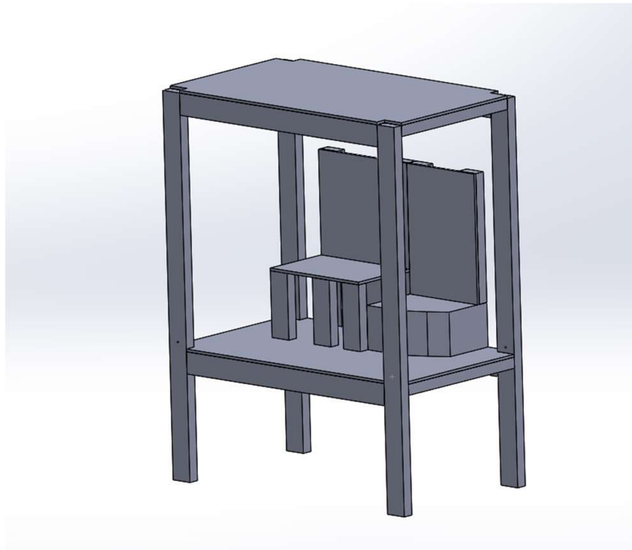

Figure 14. Cab Model CAD

The Cab mock-up represents the back seat with the seat cushion removed from the cab and the backrest remaining upright. It was agreed that this configuration maximized the amount of usable space for both teams.

Figure 15. 1-1 Scale Wooden Cab Mock-Up

The model in Figure 15 was constructed out of wood. It is currently being stored in the QL+ Laboratory. The model will be taken apart for scrap material once in person labs resume.

4.4 Wheelchair

The team got in contact with the company that designed and build the wheelchair, PER4MAX. They provided a drawing of the wheelchair seen in Figure 16. This was used alongside the dimensions of the cab from the local Toyota dealership to help understand the space that is available.

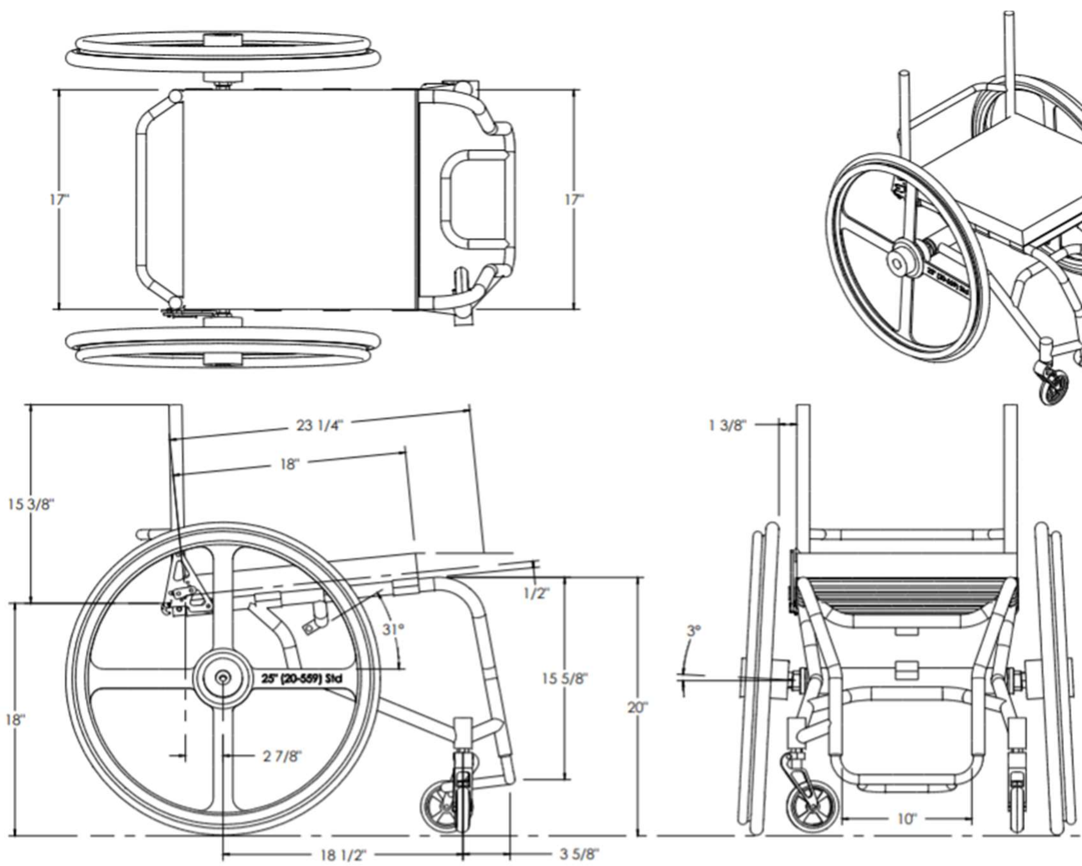

Figure 16. PER4MAX Wheelchair Drawing

4.5 Concept Prototypes

Prior to the scope change, the team determined which concepts to prototype first based on the results from the decision matrixes. These prototypes focused on lifting and storing Peter's wheelchair. Further decisions regarding design direction require additional prototyping and testing. The Intake concept and Shop Crane concepts were the first to be prototyped out of wood and PCV.

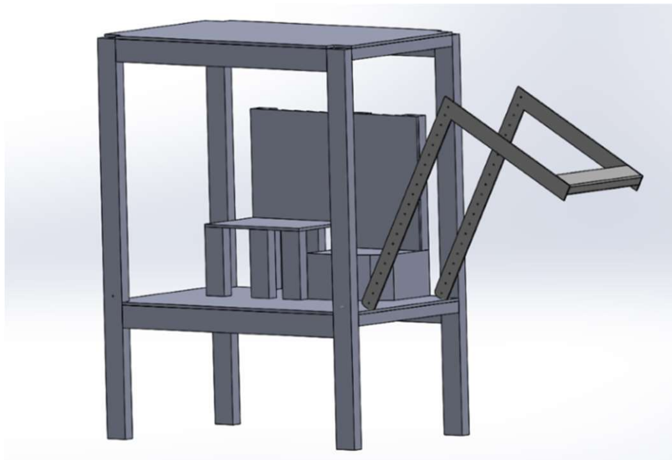

Figure 17. Model of Intake in Cab Mock-Up

The Intake arm deploys and retracts around single pivot point which makes controlling the motion simple. The intake stores past center when retracted in the vehicle. The arms are 20 inches apart with a 2-inch square tubing crossbar that is wide enough for the dog lane. The arms utilize a 0.5-inch plate and would be made of either steel, aluminum, polycarbonate, or a combination. Polycarbonate is appealing for its durability, weight, and flexibility. It would be long lasting and easily replaceable. The weight would reduce moments and needed motor output. Polycarbonate is also more forgiving if the device crashes into any objects. Figure 18 below shows the Intake prototype attached to the cab model. This prototype gave us a good visualization of how it interfaced with the truck while in motion and how much space it took up.

Figure 18. Wooden Intake Prototype Building

The shop crane in Figure 19 attaches to the vehicle at a single point located behind the driver's seat, next to the door frame. It features three different points of rotation that allow for multiple configurations when storing the device with or without the wheelchair. This is important because this design would be adaptable for multiple truck types. The opportunity for pneumatic and motorized lifting mechanisms are both available as well with this design.

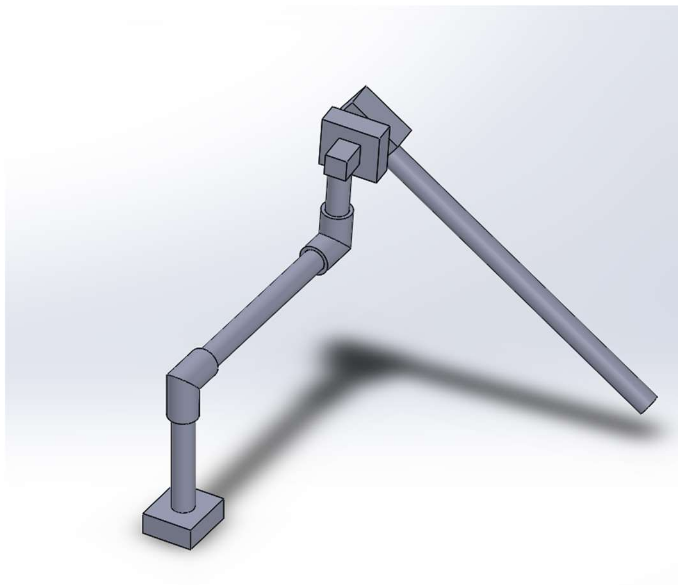

Figure 19. Model of Folding Shop Crane

4.6 Preliminary Analysis

Preliminary engineering analysis was performed on the intake arm concept design to find the total system torque. Modeling the two intake arms with the 25 pound wheelchair attached to the end with a factor of safety of 2, it was found that the total system torque needed to be 1050 in-lb. Hand calculations for this can be found in Appendix E.

4.7 Potential Risks

The most prominent obstacle the team faces is the very limited space available to work with. The Tacoma doorway is roughly 28-inches by 43-inches. The wheelchair is approximately 20-inches by 35-inches by 34-inches without its wheels. Currently, the goal is to have the dog ramp and wheelchair storage device operate out of the same door. This means that there needs to be enough room for both devices to operate without interfering with each other and allow the dog to move past the wheelchair storage device. Collaboration between the two groups yielded that the configuration should be left to Peter. Safety related risks are shown in the hazard checklist in Appendix F.

4.8 Scope Change

After receiving a video of Peter's current solution and talking with him over the phone, it was decided that a lifting mechanism is not the most efficient and beneficial system for Peter because he is physically capable of lifting his wheelchair without any problem. Peter also switched to a smaller Toyota Tacoma which drastically reduced the space we had to work with. Focus was shifted towards creating a wheelchair storage system that will be adaptable to different trucks and wheelchairs. The storage system will give Peter an easy way to store his wheelchair in the back seat of his truck leaving ample space for the Service Dog Ramp team to store their device. The lifter design approach ultimately took up too much space to allow for the dog ramp to be stored inside the cab. The lifter could also not lift the wheelchair into the cab faster than Peter while also maintaining safe operating speeds. The storage rack alternative allows for all of Peter's needs and wants to be met while also better accommodating the Dog Ramp team. The storage device has a slimmer profile, can be operated quickly, and involves no permanent modifications to the truck.

5. Final Design

The following section outlines the final storage system design including how it functions and the design justifications that lead to this solution.

5.1 Final Design Description

The wheelchair storage system, shown below in Figure 20 below, will allow Peter to easily store and secure his wheelchair in the backseat of his truck. A separate storage system for the wheelchair wheels will hang over the back of the driver's seat. All component drawings and specifications can be found in Appendix J. Figures 21 and 22 show the final storage systems installed in a Tacoma.

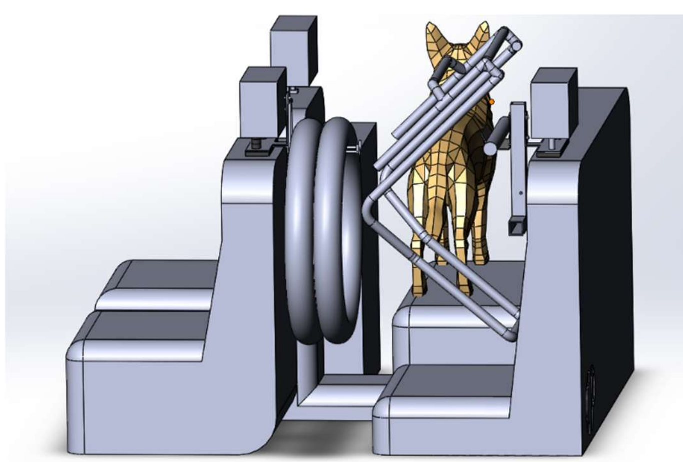

Figure 20. Expected Storage Arrangement for Wheelchair (front right), Wheels (front left), and Dog Ramp (back left)

Figure 21. Wheelchair Rack Installed in Toyota Tacoma

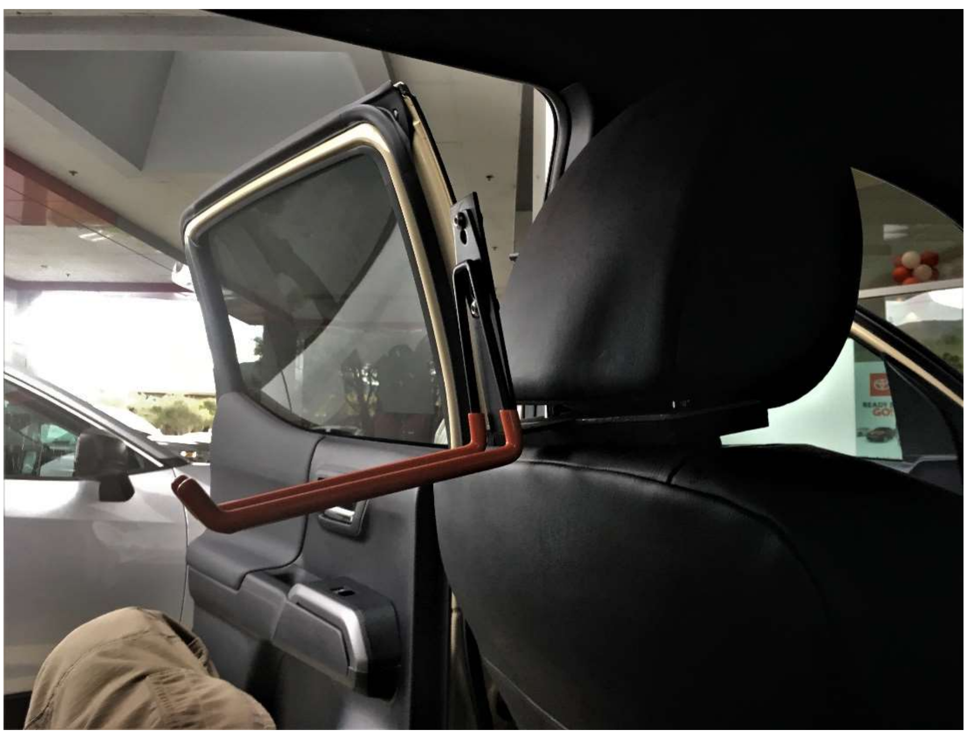

Figure 22. Wheel Rack Installed in Toyota Tacoma

5.2 Functionality Description

The wheelchair storage rack shown below in Figure 23 is designed to hold up to 120 pounds. This exceeds the weight of Peter's wheelchair, which is approximately 22 pounds. The much higher load capacity is designed to accommodate dynamic loading during driving. The wheelchair is to be placed on the steel plate shelf, as shown in Figure 23. The shelf has a minimal footprint which gives Peter's service dog enough space to pass through. Initially the wheelchair was meant to sit on hooks like those used on the wheel rack as shown in Figure 24. While these hooks were able to hold the static loads expected in simulation and real world testing the team found that the hooks could not reliably handle the dynamic loading. This was made clear to the team during a driving test where the racks were installed and loaded with weights. While driving over a large depression in an unpaved road the dynamic load was high enough to permanently deform the hooks meant to hold the wheelchair frame. This was not acceptable, so the hooks were redesigned and retested. The replacement designed by the team was a shelf made of eighth inch plate steel shown in Figure 23. This design has a much higher load capacity as described earlier in this section. Both in simulation and live testing the shelf was fully capable of handling dynamic loads far exceeding the capabilities of the original design. The wheel racks attach to the seats using the headrest posts. The posts slide through two holes in the rack securing it to the seat. Two car seat buckles are also used to secure the structure down. One of these buckles passes through the vertical tube and over the seat to the car seat hook on the back of the seat. The other buckle passes through the horizontal tube and attaches to two hooks on both sides of the back seat. Below are the two storage rack systems.

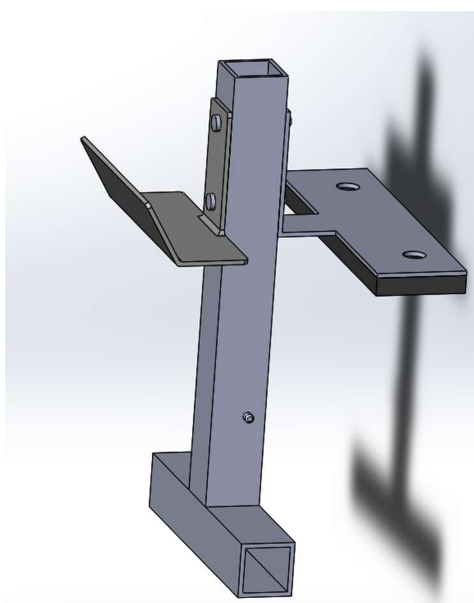

Figure 23. Wheelchair Storage Rack

A separate storage rack, shown in Figure 24 below, is used to hold the wheels of Peter's wheelchair. The same top headrest plate is used and slots through the driver's seat headrest. With this system, the wheels will be stored on the back of the driver's seat.

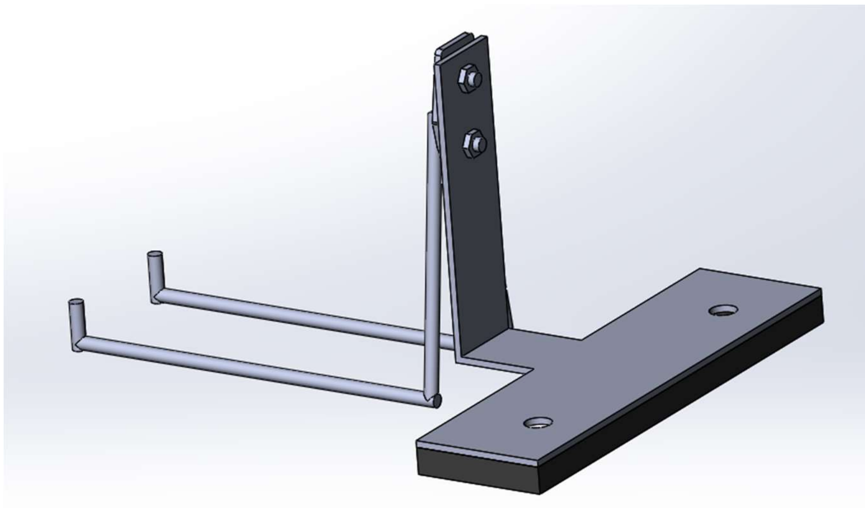

Figure 24. Wheel Storage Rack

Both storage systems utilize the same modular headrest plate design. This modular headrest plate is fabricated out of 1/8-inch steel and can be seen below in Figure 25.

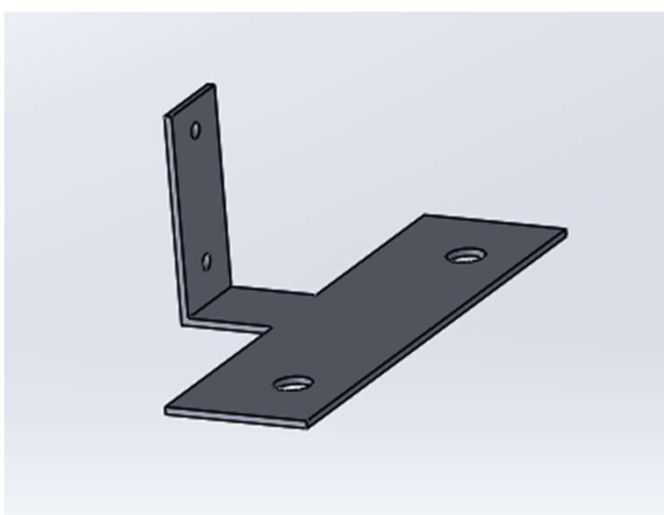

Figure 25. Modular Headrest Plate

5.4 Design Specifications

The two storage systems are designed such that they can be attached to most cars and models. The wheelchair system is designed to hold weights up to 120 pounds giving our product a factor of safety above 2 even during dynamic loading. The system has a low profile and is light weight ensuring that it does not interfere with passengers or Peter's service dog.

These storage systems are also easy to install and uninstall. The modular headrest plate slides easily into the two headrest pegs while car seat buckles also allow for easy attachment. The device can be easily buckled and unbuckled to car seat hooks found in all cars.

The hitch pin that is placed in the vertical steel tube of the wheelchair storage rack is strong enough to support 200 pounds making it more than capable of supporting our structure. The strength of the pin was tested in CAD modelling and loading simulation. The top strap anchors to the device by connecting to the hitch pin.

Most of the parts and all the fasteners are commercial off-the-shelf (COTS). This reduces the number of custom parts needed to be manufactured and thus, reduces overall cost. Additionally, using COTS parts makes replacing parts easy as well. If any of the fasteners or straps were to break over time, their replacements can be ordered on Amazon.

Simple deflection and life cycle fatigue testing for static and cyclic loading demonstrated an appropriate use of steel. The steel T-frame coated with a corrosive resistant paint not only protects it from the elements but also adds to the aesthetics.

5.5 Design Justification

Deflection calculations were performed on the rack shelf and the hitch pin. The shelf saw a maximum deflection of 0.00645 inches when loaded with 120 pounds. This load was meant to simulate dynamic loading combined with a factor of safety of 2. The hitch pin was loaded with 200 pounds and saw a maximum deflection of only 0.00140 inches. The shelf was modeled assuming a maximum load of the wheelchair and fixed on one side. The hitch pin was modeled with the same assumptions except supported on both sides. See Appendix F for more calculation details. Both remained within the elastic region during both static and dynamic testing. The dimensions for the steel T-frame were determined based on the size and shape of the seat on which it is designed to be installed. The 12-inch vertical bar matches with the flat section at the top of the seat and the 8-inch horizontal section fits within the center portion of the seat. 1.5 by 1.5-inch square stock was chosen as this was the smallest cross section that could accommodate the size of the car seat strap. Both steel and aluminum were considered when the team was considering materials. Steel was more cost effective and did not exceed maximum weight requirements. Further, all fasteners and pins selected are steel and it was decided that maintaining the same material throughout was preferred.

The seat safety connectors seen in Figure 5 were selected because of the systems high safety rating and universal design. Compared to other models available on the market, their low profiles allow them fit down a smaller sized tube, which is ideal in reducing the size of the device. The universal LATCH connector is compatible with any car and rated to secure child car seats.

A black automotive rubberized undercoating was applied to the steel parts of the devices. The automotive spray was selected to protect the metal from corrosion. The rubberized coating was selected to protect the vehicle from the pressure imparted by the device. To further protect the seat a seat cover was purchased which would fit over the back seat between the seat and the rack without creating interference.

5.6 Safety, Maintenance, and Repair Considerations

Both the seat safety connectors and the racks are rated to withstand the static and dynamic loads that this device will experience during its lifetime with a minimum safety factor of 2. The storage device is easily disassembled which makes replacing components quick. The connectors have quick release buttons and the rack is fastened with only two bolts. Users will only need two wrenches to make any necessary repairs.

With Peters service dog Rory sitting in the backseat next to our product, his safety is a concern. We have eliminated all major pinch points from our structure as well as any fast-rotating elements. Our structure is designed to be robust enough to securely support the wheelchair while it is in typical transit.

After receiving the storage racks and using them Peter has confirmed that his service dog is comfortable with the device.

5.7 Cost Analysis

The project is currently only billing at 11.4% of our $1000 budget. This design is relatively inexpensive with no single component exceeding $30. The total cost and cost broken down by component can be found below in Table 6. The total cost calculated is the price of a single unit constructed from scratch. If it were to be manufactured on a larger scale, the per unit cost would decrease as multiple parts could be made from a single piece of stock instead of just the one. However, while more parts can be made from the initial stock, labor costs would increase as the work time is now being extended. For example, the Steel Sheet Metal for Headrest Plate can be made into three mounts which is enough for 1.5 storage devices. Refer to Appendix H for the complete iBOM. It takes approximately 4 hours to manufacture one of these devices, but that process can be scaled up to complete about 6 units instead of one. Assuming labor to be $15/hr, the cost of Materials would be $59/unit and the cost of Labor would be $10/unit which would bring the unit cost to $69/unit.

Table 6. Cost List of Each Component

Part	Unit Price
1.5’’ x 1.5’’ Steel Tubing	$15.29
Steel Sheet Metal	$26.25
Spray on Rubber	$10.99
Steel Bolts	$3.70
Hitch Pin	$1.94
Seatbelt Straps	$13.99
Nylon Lock Nuts	$1.18
Wheel Hook	$13.99
TOTAL COST	**$ 87.33**

6. Manufacturing Plan

The manufacturing section explains the necessary steps to create the storage device. These steps outline where to acquire the proper materials, how to fabricate the customer parts, and how to assemble the device before installation. Please refer to Appendix J for the complete drawing package.

6.1 Procurement

All parts needed for the device are easily accessible and available from a variety of places including: Amazon, Home Depot, and QL+ Lab. The parts listed in Table 7 are required to construct the wheelchair storage device. Refer to Appendix I for links to the materials.

Table 7. Material Procurement Schedule

Description	Quantity	Vendor	Date	Cost
1.5” Square Steel Tubing 20” long	1	Online Metals	1/9/2020	$15.29
Car Seat Straps with Safety Connectors	2	Amazon	1/10/2020	$13.99 ea
¼-20 – 2.25” SHCS	2	Home Depot	1/23/2020	$3.70
¼-20 Nylon Lock Nut	2	Home Depot	1/23/2020	$1.18 ea
Hitch Pin ¼” x 1-¾”	1	Home Depot	1/23/2020	$1.94
0.125-inch Steel Plate	1	Online Metals	1/23/2020	$26.25
Spray on Rubber	1	Amazon	1/23/2020	$10.99
Wheel Hook	1	Amazon	1/23/2020	$13.99

6.2 Manufacturing

Instructions on how to manufacture the systems limited custom parts can be found outlined below.

Wheelchair Rack T-frame (Drawing #’s 1102, 1103, 1107 as reference)

1. Use a chop saw with grinder wheel to cut steel tubing into 12-inch and 8-inch sections
    a. Deburr sharp edges until smooth to touch
    b. Set the 8-inch section aside for later
2. Center the shelf (see below) in the middle of the 12-inch tube and justify it along the top so that the edges are flush with each other. Use a center punch and Sharpie to copy the hole pattern onto the steel tube

3. Rotate the tube and mark another hole on the untouched side, 0.5-inch from edge and 2.5-inch from the bottom (see drawing spec)
4. On the drill press, use an F bit to create ¼-20 clearance holes for the wall bike rack hole pattern
5. Use an H bit to create a through hole for the ¼ inch hitch pin
6. After the holes are made on the 12-inch tube, place it vertically at the center of the 8-inch tube so that the two tubes form a T-shape (See Figure 26)
7. MIG weld the two pieces together welding all around the workpiece

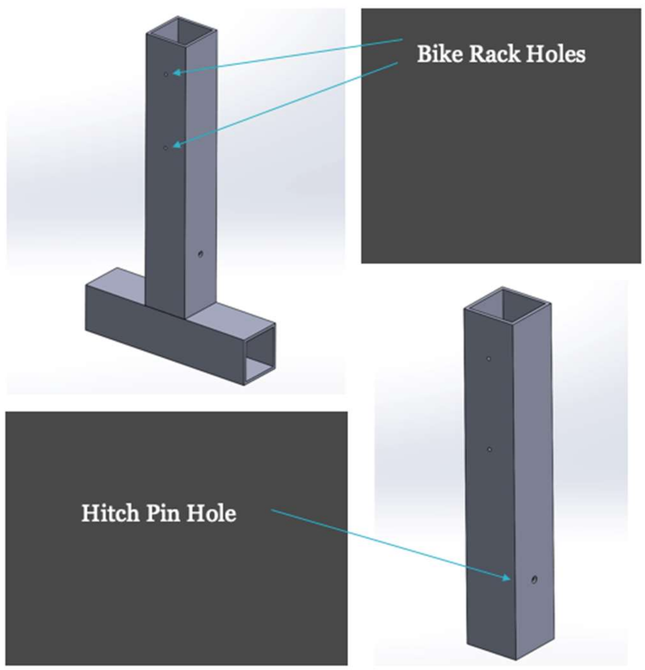

Figure 26. Manufacturing Aid for Wheelchair Rack

Headrest Plate (Drawing #'s 1104, 1204, 1104F, 1204F as reference)

1. Use water jet to cut headrest plate out of 1/8" sheet metal
    a. Use flat drawing (1104F and 1204F) converted to .dxf files
2. Use press brake to create 90-degree bend on center flange (use 1104 and 1204 as reference)

Wheelchair Shelf (Drawing #'s 1101, 1101F as reference)

1. Use water jet to cut shelf out of 1/8" sheet metal as specified in drawing

2. Use finger break to bend the shelf that holds the wheelchair footrest in place about 45-degrees from horizontal
3. Use finger break to bend the attachment point to the T-frame 90-degrees

L bracket

1. Use the water jet to cut the L bracket out of 1/8” sheet metal
2. Use finger break to bend the L bracket 90-degrees
3. Plug weld holes using MIG to attach to mainframe

6.3 Assembly

Once the tubes have the proper holes and are welded into a single work piece, assembly can begin. The following steps are for assembling the wheelchair frame storage device as seen in Figure 27:

1. First, insert the hitch pin into its respective hole
2. Slide one of the car seat connectors down the tube and connect it to the hitch pin
    a. There will be an audible click. Once heard, the buckle should be secured
3. Slide the other car seat connector through the bottom cross bar such that there is a connector exposed on either end of the cross bar
4. Align the wheelchair shelf with its respective holes and attach using the ¼-20 SHCS and nylon lock nuts
5. To install, remove the headrest and place headrest mount over the openings and reinstall the headrest
6. Finally, connect the three connectors to the vehicle anchors located in vehicle and tension straps

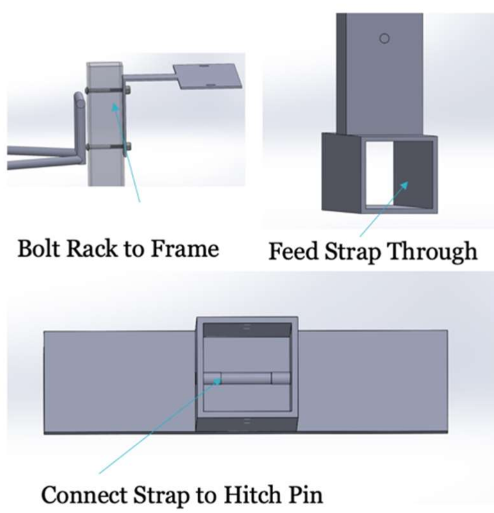

Figure 27. Assembly Aid

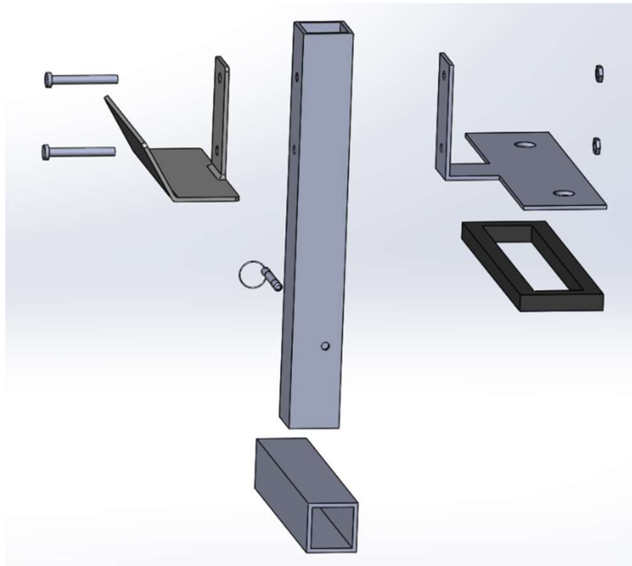

Figure 28. Exploded View of Wheelchair Storage Device

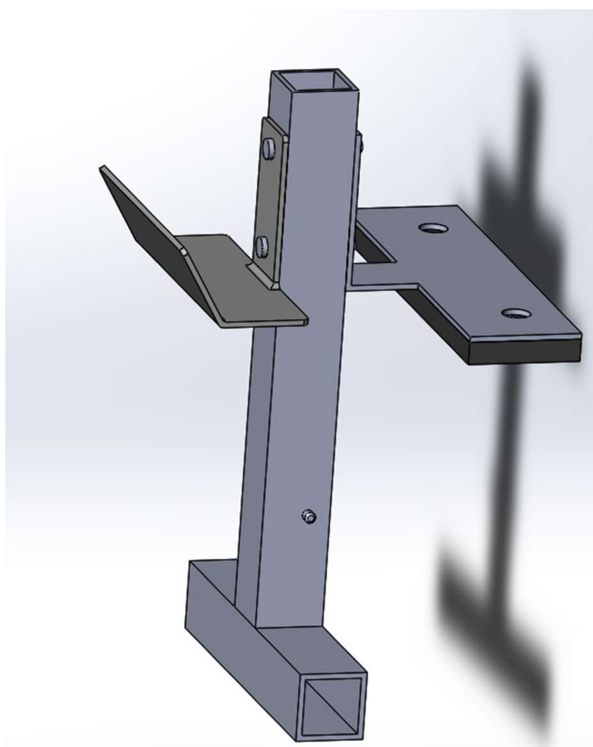

Figure 29. Assembled Wheelchair Storage Device

Assembling the Wheel Storage device is simple. Bolt the wheel rack to the headrest mount using two ¼ -20 x 0.5-inch SHCS and two nylon lock nuts, see Figure 27. Plug weld the holes in the L bracket to the car interface frame. Install the wheel rack by removing the headrest and inserting the headrest mount over the holes before reinstalling the headrest.

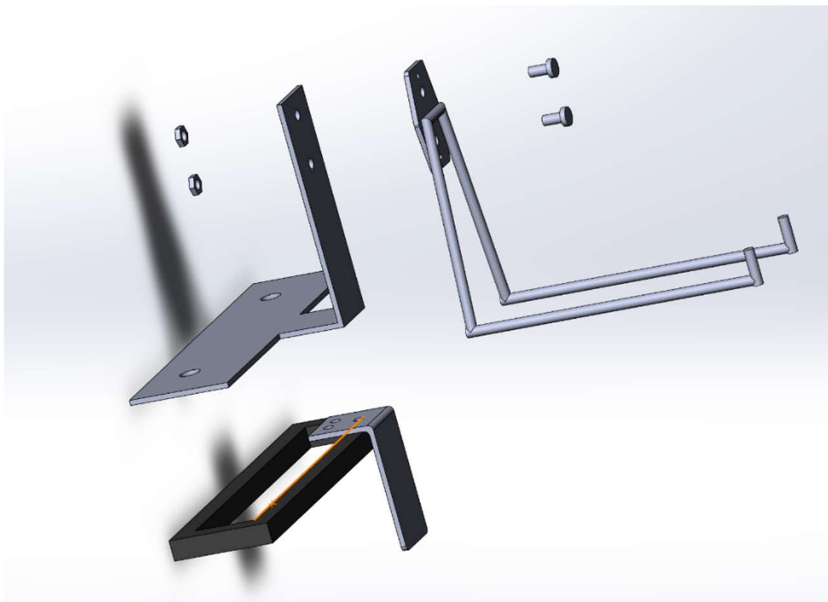

Figure 30. Exploded View of Wheel Storage Device.

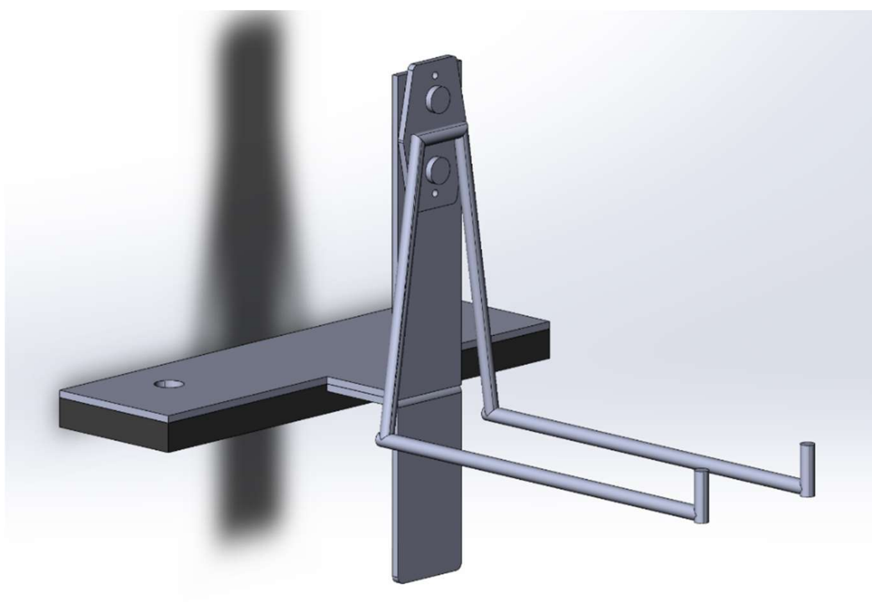

Figure 31. Assembled Wheel Storage Device

6.4 Outsourcing

Both storage systems can be manufactured with the machinery and tools provided by Mustang 60 and the Hanger on campus. This design does not require any outsourcing for manufacturing.

7. Design Verification Plan (DVP)

It is necessary to thoroughly test the device to make sure it performs as designed and to make improvements. Refer to Appendix G for complete DVP.

7.1 Detailed Description for Each Specification

Spec 1: The storage system needs to fit into the 40% side of the back seat of the truck and still allow the dog ramp to be deployed on the same side of the cab, allowing the dog to cross through to the other side.

Spec 2: The storage system must not cost more than $1000 throughout the entirety of the design process. The Total Unit Cost, including materials and labor should not exceed $100

Spec 3: Peter must be able to store his wheelchair in less than 2 minutes. Otherwise it becomes inconvenient to use because it typically takes him about 2 minutes to store his chair without this storage system.

Spec 4: The storage system must not weigh more than 50 pounds to increase Peter's ability to move it to other vehicles.

Spec 5: The storage system should be less than 50% custom parts to make it cheaply to repeatedly manufacture

Spec 6: The storage system must install in less than 20 minutes to make it easier for Peter to move it to other vehicles when he decides to change trucks.

Spec 7: The storage system must not make a lot of noise when Peter is driving to the point where it will annoy him or Rory, even during heavy off-roading.

7.2 Tests and Equipment Needs

The team was able to test all the specifications described above in section 7.1. For details on each verification see the following:

Spec 1: The prototype storage racks were installed by the team in a Toyota Tacoma at a Toyota dealership in San Luis Obispo, CA. The team was able to verify that both racks fit in the vehicle. We then sent our prototype to Peter in order to further confirm this specification had been met. Peter was able to install both racks and store his wheelchair within the 40% side of his back seat. Based on this feedback the team is satisfied that this specification was met.

Spec 2: The whole project ultimately cost far below the target $1000. Recall that the initial $1000 came from a $10,000 QL+ donation that was divided amongst ten QL+ teams working with challengers. It is important to QL+ that challengers receive quality products made from high quality materials. Even though the project was interrupted by COVID-19, all materials had been purchased beforehand for the final product. Had the project been completed fully, the team is confident that this specification would have been met regardless. For more details on the overall budget and spending see Appendix L. In Section 5.7 Cost Analysis, the individual unit cost is $69 which is less than the target $100.

Spec 3: Peter confirmed that he was able to load and unload his wheelchair quickly from the storage devices. Based on this feedback, the team is satisfied that this specification was met.

Spec 4: The overall weight of both storage racks and all other parts such as straps and buckles are less than 20 pounds. This is less than half of the 50 pounds criteria.

Spec 5: The overall percentage of custom parts to stock parts is roughly 35% custom parts. This is below the 50% custom part criteria. Based on this the team is satisfied that this specification was met. For a full list of parts see Appendix H.

Spec 6: Peter described being able to install the system in less than 20 minutes and that he was able to do it faster after he had done it the first time. Based on this feedback, the team is satisfied that this specification was met.

Spec 7: The team tested the noise produced by the racks in our own vehicles and found that little to no noise was produced. After using the racks, Peter confirmed that noise was not an issue while driving with the racks fully loaded in his vehicle. Based on this feedback, the team is satisfied that this specification was met.

Overall, the team believes that all specifications set for the project have been met. Further, Peter has expressed that he is very satisfied with the design. Since his satisfaction is the ultimate goal of the design, the team believes the design and prototype are acceptable.

8. Project Management

A project this complex requires thorough planning. Coordination between the Wheelchair Storage Team and Dog Ramp Team is essential to the project's success. In order to accomplish this the two teams met frequently to ensure we are working in tandem on the two best integrated solutions for Peter.

8.1 Project Milestone Deadlines

For the duration of the project, the team maintained a project Gantt Chart as shown in Appendix D. The Gantt Chart was subject to change due to California's Shelter in Place (SIP) issued in response to the COVID-19 Pandemic. Despite two scope changes the group was able to deliver a useful prototype to the challenger Peter.

Table 8. Project Milestone Deliverables and Deadlines

Deliverable	Deadline
Scope of Work	10/18/19
Preliminary Design Review Submission	11/15/19
Failure Mode and Effects Analysis	11/19/19
Interim Design Review	1/16/20
Critical Design Review	2/7/20
Manufacturing & Assembly	2/25/20
Manufacturing & Test Review	3/12/20
Testing	4/30/20
Final Design Review	5/26/20

Developing a solution that satisfies all stakeholders requires thorough and thoughtful work. At this point in time, this document contains all conducted research, defined design specifications, prototype results, the final proposed design concept, as well as in-depth manufacturing details. Refer to Table 8 for project Milestone deliverables and dates.

8.2 Next Steps

Based on Peter's feedback after he used the prototype storage racks it was determined that the wheel rack needed improvement. Peter's feedback is available in Figure 32.

The team discussed both quick fix solutions Peter may be able to implement on his own and long-term solutions that could be used if a final prototype is ever manufactured. The team came up with several solutions for each then used a comparison matrix to help determine the best path moving forward. The matrices are shown below in Figure 33.

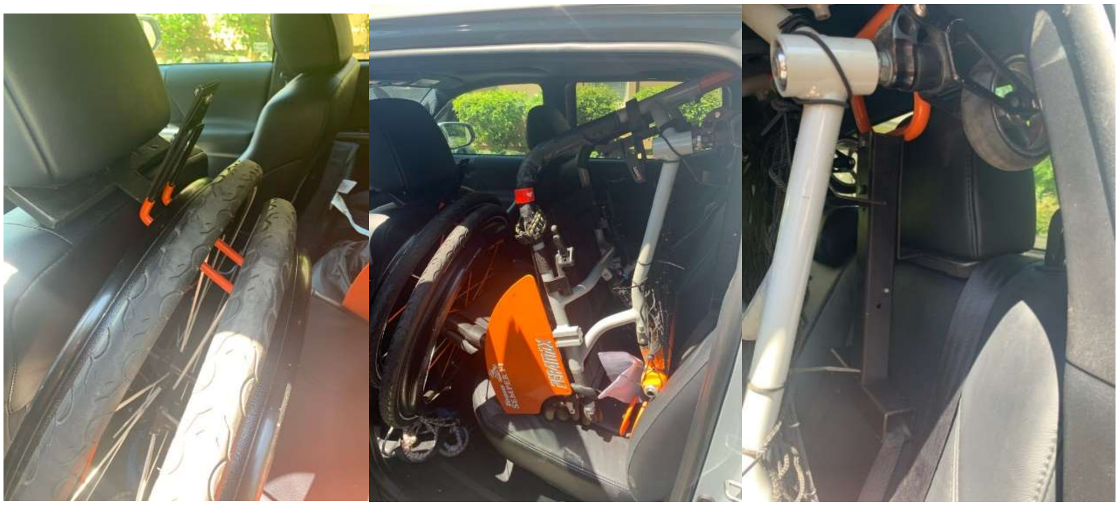

Figure 32. The Shipped Prototype Being Used by Peter (Works Even with Seat Cushion, Which Was Need During COVID-19). The Wheelchair Rack Lifts the Driver's Headrest Up When Loaded

Solutions	Install Difficulty	Cost	Rigidity	Endurance	Fit in Space	Total
Flip	4	5	5	5	1	20
Spacers	5	2	2	5	4	18
Flat strap	4	5	4	4	4	21
Tape	3	5	3	2	3	16
Hardstop	3	3	4	3	4	17
String	4	5	3	3	4	19

Solutions	Redesign Extent	Cost	Rigidity	Manufacturing	Fit in Space	Total
Ipad holder redesign	2	2	4	2	4	14
L bracket	5	5	3	5	5	23
Triangle bracket	4	4	3	4	5	20
Hook redesign (shorten w/ plate flip)	3	3	4	3	4	17

Figure 33. The quick fix solutions are shown at the top and long-term options shown at the bottom

Based on the team's discussion and the comparison matrices it was determined that a strap wrapped around the headrest would be the best short-term solution. Augmenting the wheel rack with an L bracket would be the best long-term solution. Both solutions have since been modeled. That said, the team cannot confirm whether the solutions will be effective without the ability to test. If there is ever an implementation of these solutions in the future, manufacturing and testing would have to take place then.

It is recommended that teams looking to continue the development of this design can explore the alternatives listed in Figure 33. Additionally, the device is made from steel but using aluminum should be examined in order to reduce weight and avoid corrosion. Finally, the location of the hitch pin for connecting the safety strap can also be adjusted.

9. Conclusion

The team agrees to meet its obligations by getting deliverables in on time and with a high quality of work in order to hit milestones and keep the project moving. From aesthetics to functionality, the team strives to provide Peter with the solutions he needs. If no exceptions are taken to the above stated deliverables and specifications, all Parties agree and refer to the terms located in this Final Design Report.

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Appendix A: Current Product Figures

Figure 34. Harmar AL825 Lift

Figure 35. Bruno Out-Rider Lift

Figure 36. Easy-Stow Wheelchair Lift

Figure 37. ATC 45 Degree Platform Lift

Figure 38. Commander 200 Truck Mount Lift

Appendix B: Patent List

Patent Name	**Patent Number**	**Key Characteristics**
Driver Accessible Wheelchair Carrier	US7404505B2	● Enclosed carrier for folded wheelchair ● Mounted adjacent to driver's door ● Easy for user to shift from wheelchair to driver's seat
Device for Loading a Folded Wheelchair Inside a Motor Vehicle	US5096361A	● Doesn't require modifications/attachments to outside of car ● Easy to install and does not interfere with back seat ● Operated from driver seat with remote control
Car Top Carrier For Wheelchair	US4376611A	● Stores wheelchair on roof of car ● Allows user to lift and store wheelchair without aid of others
Wheelchair Lift	US4176999A	● Incorporated into door/entrance of vehicle ● Series of 4 platforms that slide into a ramp ● Compact design
Vehicle Wheelchair Lift	US20110070057A1	● For vehicle with small cabin space such as a pickup with cab space ● Lift is positioned within vehicle cabin but doesn't sacrifice seating capacity

Appendix C: QFD: House of Quality

Correlations	
Positive	+
Negative	–
No Correlation	

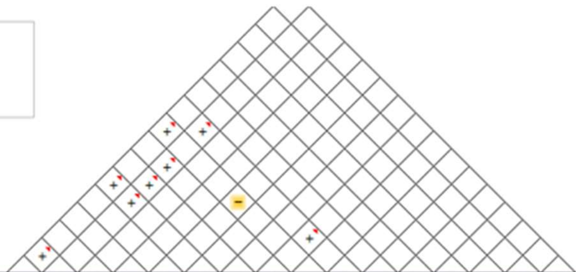
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: Wheelchair Lift and Storage

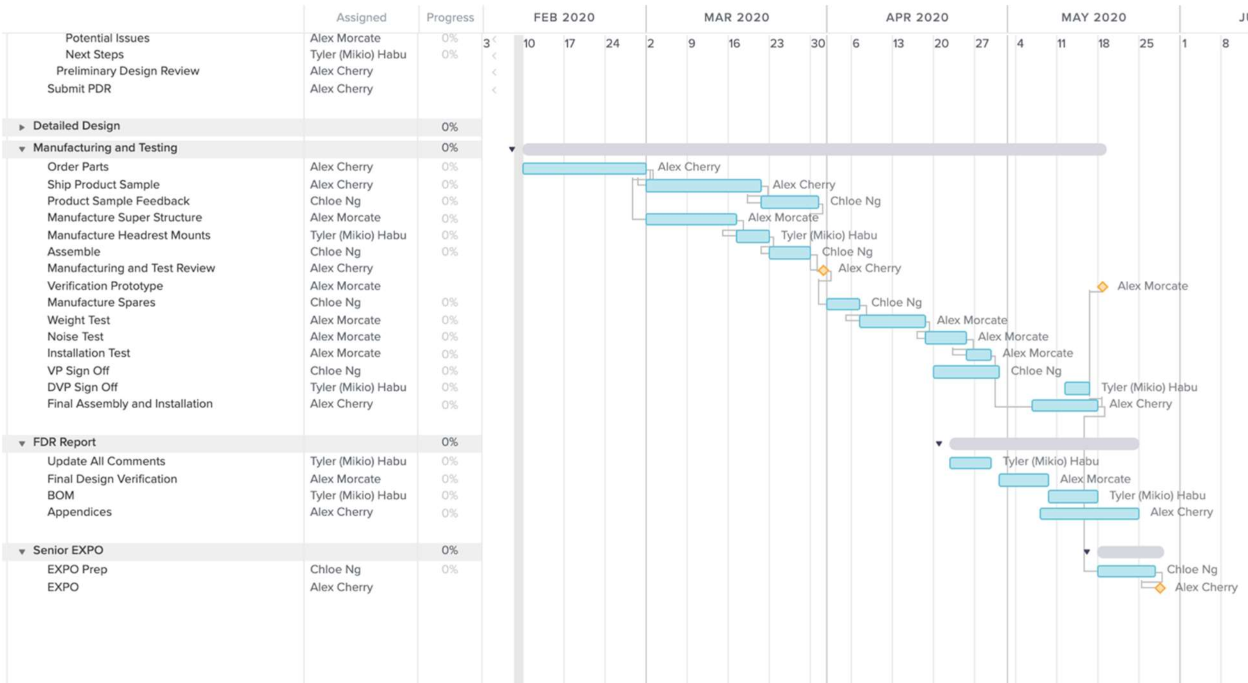
Revision Date: 10/10/19



								Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16						
	WHO: Customers							Direction of Improvement	▼	▼	◇	◇	▼	▼	▼	◇	▼	◇							NOW: Curr. Products					
Row #	Weight Chart	Relative Weight	Peter Way	QL+	Manufacturing Team		Maximum Relationship	WHAT: Customer Requirements (Needs/Wants) / HOW: Engineering Specifications (Tests)	Measurements	Cost	Lift Test	Actuation Speed	Deployment Test	Weight	Number of Custom Parts	ADA Requirements	Install	Cycles							Truck Bed Crane	Manual Storage	Custom Cab	Pulley System	Cab Lift Arm	Row #
1		11%	8	10	3		9	Safety	○	▽	●		○	○		●	●	●							5	2	5	3	5	1
2		###	10	7	3		9	Ease of use				●					●	▽							5	1	5	4	5	2
3		###	8	8	7		3	Durability	▽				○												5	1	4	2	3	3
4		8%	10	5	1		9	Size	●			▽						▽							1	5	3	4	2	4
5		7%	7	5	2		9	Portability					●												1	5	1	3	2	5
6		6%	7	4	1		9	Weight	●			▽	●												1	5	1	4	1	6
7		6%	7	4	1		1	Deployability							▽	▽		▽							1	5	1	4	2	7
8		###	3	9	5		9	Low Cost		●	▽			▽			▽								1	5	1	3	1	8
9		11%	3	3	10		3	Simplicity		▽							○								2	5	1	3	1	9
10		###	7	3	9		9	Minimal Customization							●	▽		▽							4	5	2	2	3	10
11		6%	3	8	1		9	ADA	○	▽	○		○	▽	▽	●	▽	○							5	1	5	3	4	11
12		0%																												12
13		0%																												13
14		0%																												14
15		0%																												15
16		0%																												16

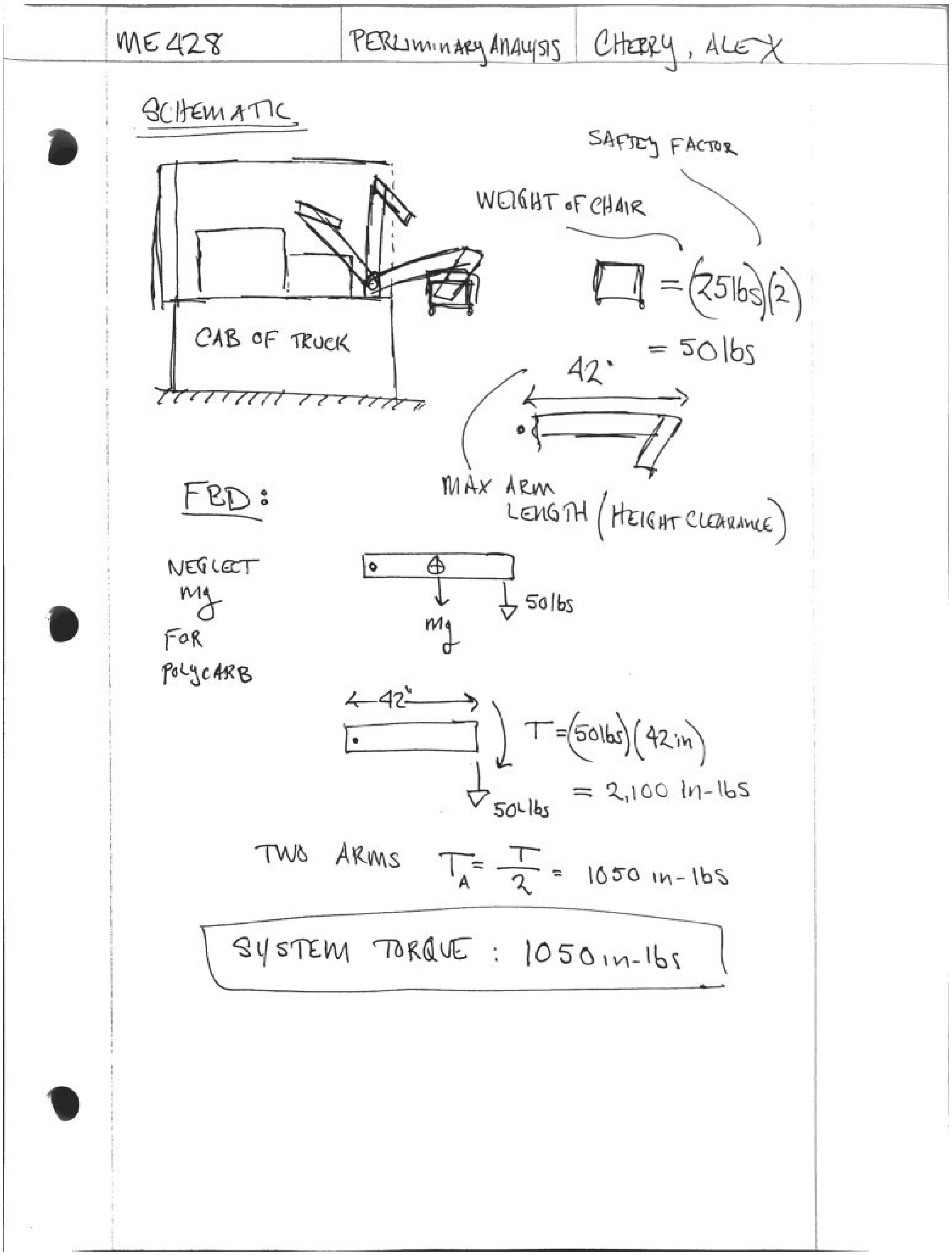
HOW MUCH: Target Values	Fit in Cab	$3,000	350 lb	TBD	2 minutes	125 lb	Less than 10%	See ADA Requirements	1 hour	44,000						
Max Relationship	9	9	9	9	9	3	9	9	9	9						
echnical Importance Rating	189	116	128	108	210	49.1	117	173	241	154	0	0	0	0	0	0
Relative Weight	13%	8%	9%	7%	14%	3%	8%	12%	16%	10%	0%	0%	0%	0%	0%	0%
Truck Bed Crane	0	3	5	0	2	3	2	5	2	5						
Manual Storage	5	5	0	3	2	5	5	0	5	2						
Custom Cab	4	2	5	3	3	5	2	5	2	5						
Pulley System	4	4	2	3	4	3	4	2	3	3						
Cab Lift Arm	4	3	5	4	4	3	2	5	2	5						
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Appendix D: Gantt Chart



Appendix E: Preliminary Analysis

System Torque Calculation



Hook Arm Deflection Calculation

1/16/2020

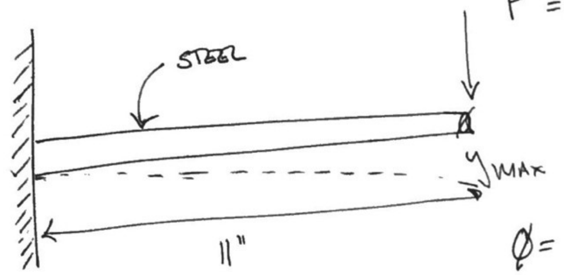
BEND ANALYSIS ON FRAME STORAGE

$\frac{26}{2} = 13$

$P = 13$ lbs + (? TENSION OF HOLD DOWN) ~~23~~

↖ HALF OF FRAME

T



$\emptyset = 0.25"$

$r = 0.125"$

$$y_{max} = -\frac{PL^3}{3EI}$$

$I = \frac{1}{4}\pi r^4$ ~ FOR CIRCULAR NEED TUBING

$= \frac{1}{4}\pi (0.125)^4$

$= 0.00019201$

$E = 30 \times 10^6$ psi

$$y_{max} = -\frac{13(11)^3}{3EI}$$

$$y_{max} = \frac{-17303}{17280.9}$$

$y_{max} = 1.001$ in $r = 0.125"$

IF $r = 0.25"$ ~

~~$y_{max} = 0.060665$~~

$y_{max} = 0.062665$

CONFIRMED

$\emptyset = 0.21175$

$r = \urcorner$

$\therefore y_{max} = 0.121757"$

Fatigue Calculation

FATIGUE CALCS

$S_e = k_a k_b k_c k_d k_e k_f S_e'$ — assume square bar d_e

$S_{ut} = 45000\ psi = 45 kpsi$

$S_e' = 0.5\, S_{ut} = 22.5\ kpsi$

$k_a = a S_{ut}^{b}$ $\quad a = 14.4 \quad b = -0.718$

$= 14.4(45 kpsi)^{-0.718} = .936$

$d_e = 0.808\, h = 1.616\ in$

$k_b = (d/0.3)^{-0.107} = (1.616/0.3)^{-0.107} = .835$

$k_c = 1$

$k_d = 1.000$

$k_e = 1$

$k_f = \phi$

$S_e = (.936)(.835)(22.5 kpsi) = 17.59\ kpsi$

$a = f(S_{ut})^2/S_e \quad f = 0.9$

$b = -\frac{\log(f S_{ut}/S_e)}{3}$

$S_{ut} = 45000 \frac{lbf}{in^2}\left(\frac{1 in}{2.54 cm}\right)^2\left(\frac{100 cm}{1 m}\right)^2 \frac{4.45 N}{1 lbf}$

$310.39\ MPa$

$a = \frac{(0.9)(45 kpsi)^2}{17.59 kpsi} = 103.61\ kpsi$

$b = -\frac{\log((0.9)(45 kpsi)/17.59 kpsi)}{3} = -.1207$

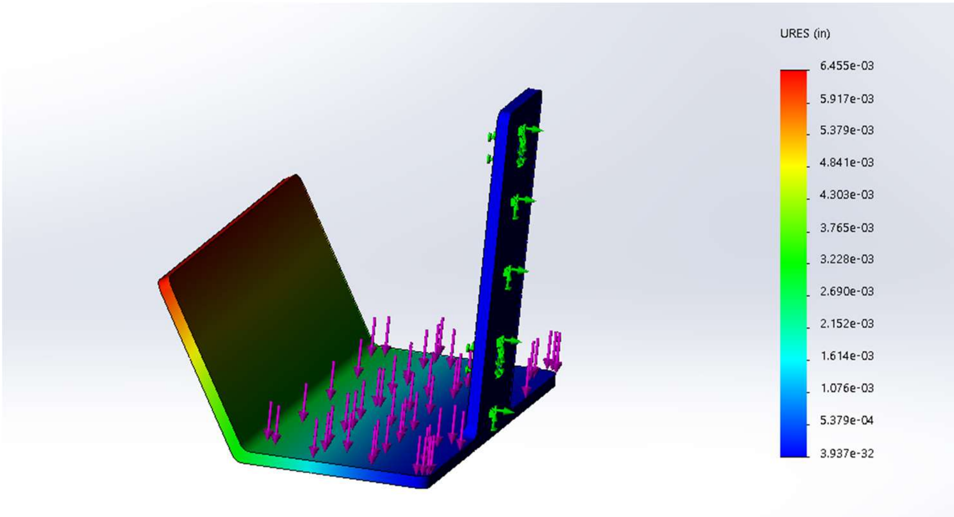
$c = \frac{d_e}{2} = .808\ in$

$M = (25 lb)(12 in) = 300\ lb\,in$

$I = \frac{2^4 - 1.75^4}{12} = .5518\ in^4$

$\sigma = \frac{Mc}{I} = \frac{(300 lb\,in)(.808 in)}{(.5518 in^4)} = 439.29\ psi$

Shelf Hook Deflection FEA Analysis: 120 lb load



Appendix F: Preliminary Analysis

Description of Hazard	Planned Corrective Action	Planned Date
Strap Failure	Ensure that the edges of the tube are not sharp enough to damage strap	2/11/2020
Connector Failure	Ensure that the connector it properly latched onto the hitch pin when installed	2/11/2020
Arm Failure	Possible braces for the arms when the rack is in the loaded configuration.	2/12/2020

Appendix G: DVP

Date: 1/30/2020		Team: 6-63	Sponsor: QL+			Description of System: Wheelchair Storage System						DVP&R Engineer: Mikio	
TEST PLAN										**TEST REPORT**			
Item No	Specification #	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES TESTED		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	1	Geometric test	Fits in the cab	Morcate	CP	1	Sys	12/4/2019	12/4/2019	pass	N/A	N/A	tight fit but in
2	1	Geometric test	Fits in the cab	Morcate	SP	1	Sys	2/13/2020	3/15/2020	pass	N/A	N/A	
3	3	Stow test	<2 min	Chloe	SP	1	Sys	2/13/2020	3/15/2020	pass	N/A	N/A	
4	4	Weight	<50 lb	Chloe	SP	1	Sys	2/11/2020	2/18/2020	pass	N/A	N/A	net weight 10lbs
5	5	# of custom parts	<50%	Mikio	SP	1	Sys	2/11/2020	3/10/2020	pass	N/A	N/A	35% custom parts.
6	6	ADA Reqs	100%	Cherry	SP	1	Sys	2/11/2020	REMOVED		N/A	N/A	no longer needed
7	7	Install test	<20 min	Cherry	SP	1	Sys	2/13/2020	3/10/2020	pass	N/A	N/A	5 min install
8	9	Noise test	survey	Mikio	SP	1	Sys	2/13/2020	3/10/2020	pass	N/A	N/A	minimal
9	1	Geometric test	Fits in the cab	Morcate	FP	1	Sys	5/5/2020	N/A		N/A	N/A	
10	3	Stow test	<2 min	Chloe	FP	1	Sys	5/5/2020	N/A		N/A	N/A	
11	4	Weight	<50 lb	Chloe	FP	1	Sys	4/30/2020	N/A	pass	N/A	N/A	net weight 10lbs
12	5	# of custom parts	<50%	Mikio	FP	1	Sys	4/30/2020	N/A	pass	N/A	N/A	35% custom parts.
15	6	ADA Reqs	100%	Cherry	FP	1	Sys	4/30/2020	REMOVED		N/A	N/A	no longer needed
16	7	Install test	<20 min	Cherry	FP	1	Sys	5/5/2020	N/A	pass	N/A	N/A	5 min install
17	9	Noise test	survey	Mikio	FP	1	Sys	5/5/2020	N/A	pass	N/A	N/A	minimal

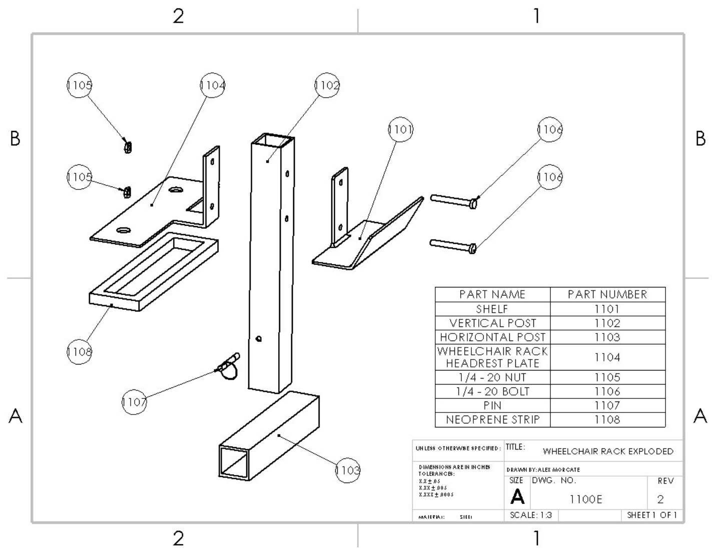
Appendix H: iBOM

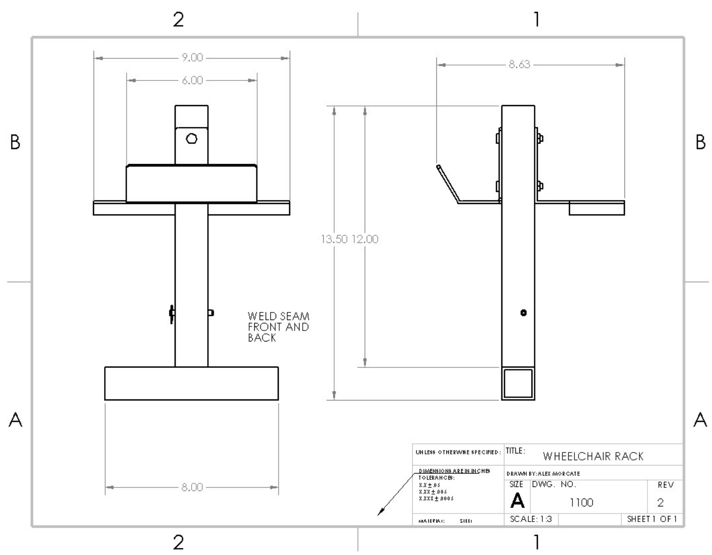
Indented Bill of Material (iBOM)									
Wheelchair Lift & Storage									
Assembly	Part Number	Description			Material	Vendor	Qty	Cost	Ttl Cost
		Lvl 0	Lvl 1	Lvl 2					
	1000	Final Assembly							0
	1100		Chair Storage						0
	1101			12 in 2" x 2"	Steel	Online Metals	1	15.29	15.29
	1102			8 in 2" x 2"	Steel	Online Metals	1	0	0
	1103			Head rest plate	Steel	Online Metals	1	26.25	26.25
	1104			Spray on Rubber		Amazon	1	10.99	10.99
	1105			bolts	Steel	Home Depot	1	3.7	3.7
	1106			Pin	Steel, zinc plated	Home Depot	1	1.94	1.94
	1107			Seatbelt Straps	Fabric	Amazon	2	13.99	27.98
	1108			Lock nuts	Steel	Home Depot	2	1.18	2.36
	1200		Wheel Storage						0
	1201			Wheel hook	Steel	Amazon	1	13.99	13.99
	1202			bolts	Steel	Home Depot	2	0	0
	1203			Lock nuts	Steel	Home Depot	2	0	0
	1204			Head rest plate	Steel	Online Metals	1	0	
							15		**102.5**

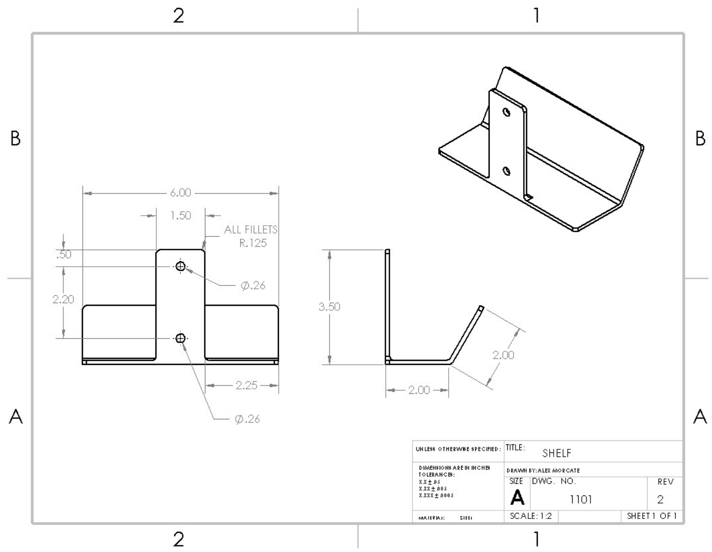
Appendix I: Links to Materials Purchased

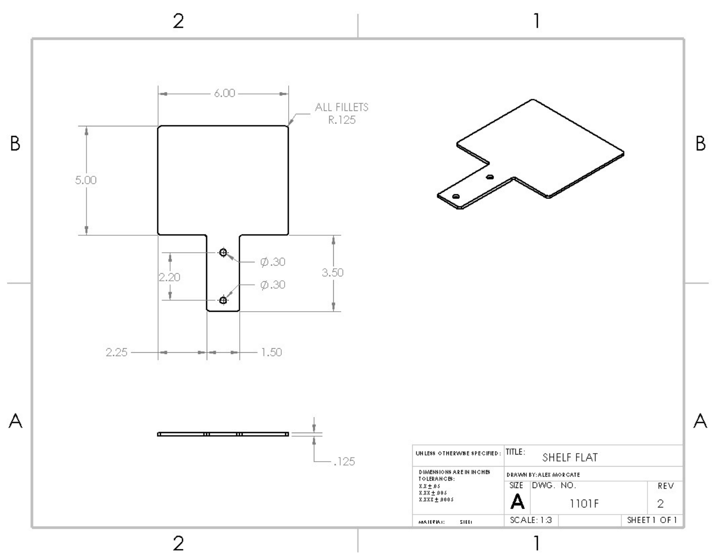
Car seat Connector Straps	https://www.amazon.com/gp/product/B07K1Y1MLL/ref=ppx_yo_dt_b_asin_title_o04_s00?ie=UTF8&psc=1
Spay on Rubber	https://www.amazon.com/gp/product/B003CT49AS/ref=ppx_yo_dt_b_asin_title_o04_s01?ie=UTF8&th=1
Wall Bike Rack (Wheelchair)	https://www.amazon.com/gp/product/B0743JGLD3/ref=ppx_yo_dt_b_asin_title_o00_s00?ie=UTF8&psc=1
Wall Bike Rack (Wheels)	https://www.amazon.com/dp/B07VHJB72G/ref=sspa_dk_detail_0?psc=1&pd_rd_i=B07VHJB72G&pd_rd_w=CgL9T&pf_rd_p=45a72588-80f7-4414-9851-786f6c16d42b&pd_rd_wg=ry1qv&pf_rd_r=27XH2VJH4S2HYSEBYB7S&pd_rd_r=4b80333f-50a6-4bb9-992a-2c44a8c1fe7d&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUEzUUpGUk5DVUVKUUVYJmVuY3J5cHRlZElkPUEwMDU4OtkwM09EQktISEtWVFdFUSZlbmNyeXB0ZWRBZElkPUEwNDA4NzY2MzU1SU1MNERVRUU3VCZ3aWRnZXROYW1lPXNwX2RldGFpbCZhY3Rpb249Y2xpY2tSZWRpcmVjdCZkb05vdExvZ0NsaWNrPXRydWU=
Head Rest Plate Material	https://www.onlinemetals.com/en/buy/cold-roll-steel/0-125-mild-steel-sheet-a366-1008-cold-roll/pid/13973
Steel Tube	https://www.onlinemetals.com/en/buy/material?q=%3Aname-asc%3AMaterial%3AHot%2BRoll%2BSteel%3AShape%3ATube-Square%3AAlloy%3AA500%252FA513%3AHeight%3A2.0%2522%3AWall%3A0.12%2522
Lock Nuts	https://www.homedepot.com/p/Everbilt-1-4-in-20-tpi-Coarse-Stainless-Steel-Nylon-Lock-Nut-3-Pack-800131/204274167?MERCH=REC-_-PLP_Search-_-NA-_-204274167-_-N
Bolts	https://www.homedepot.com/p/Everbilt-1-4-in-20-x-3-4-in-Chrome-Hex-Bolt-3-Pack-800394/207051782
Hitch Pin	https://www.homedepot.com/p/1-4-in-x-2-in-Zinc-Plated-Universal-Clevis-Pin-815418/204276164

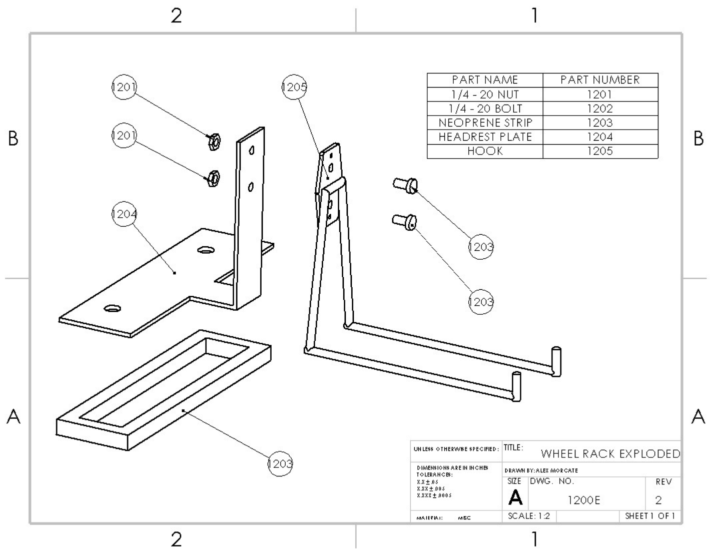
Appendix J: Drawing Package



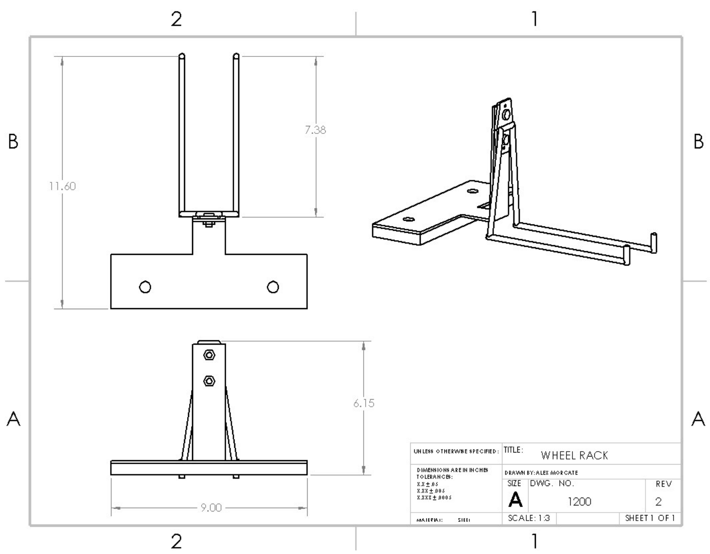


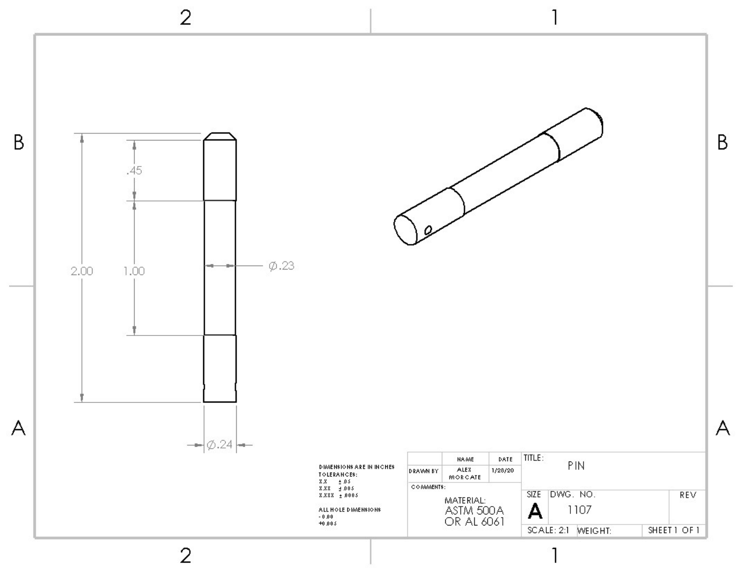

2
1
B
A
6.00
1.50
ALL FILLETS R.125
.50
2.20
Ø.26
2.25
Ø.26
3.50
2.00
2.00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
X.X ± .05
X.XX ± .005
X.XXX ± .0005
MATERIAL: STEEL
TITLE: SHELF
DRAWN BY: ALEX MORCATE
SIZE A
DWG. NO. 1101
REV 2
SCALE: 1:2
SHEET 1 OF 1


2
1
B
A
6.00
ALL FILLETS R.125
5.00
Ø.30
Ø.30
2.20
3.50
2.25
1.50
.125
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
X.X ± .05
X.XX ± .005
X.XXX ± .0005
MATERIAL: STEEL
TITLE: SHELF FLAT
DRAWN BY: ALEX MORCATE
SIZE A
DWG. NO. 1101F
REV 2
SCALE: 1:3
SHEET 1 OF 1



PART NAME	PART NUMBER
1/4 - 20 NUT	1201
1/4 - 20 BOLT	1202
NEOPRENE STRIP	1203
HEADREST PLATE	1204
HOOK	1205




2
1
B
B
.45
2.00
1.00
Ø.23
A
A
Ø.24
DIMENSIONS ARE IN INCHES
TOLERANCES:
X.X ±.05
X.XX ±.005
X.XXX ±.0005
ALL HOLE DIMENSIONS
-0.00
+0.005
NAME
DATE
DRAWN BY
ALEX MORCATE
1/28/20
COMMENTS:
MATERIAL:
ASTM 500A
OR AL 6061
TITLE:
PIN
SIZE
A
DWG. NO.
1107
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
2
1

Minerallac Company

Product Specification Sheet

40125J	1/4-20 HEX NUT ZP

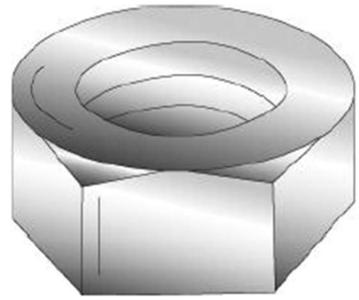
UPC: 085937080349

UNSPSC: 31161727

Commodity: Hexagonal nuts

Country of Origin:

Not Available

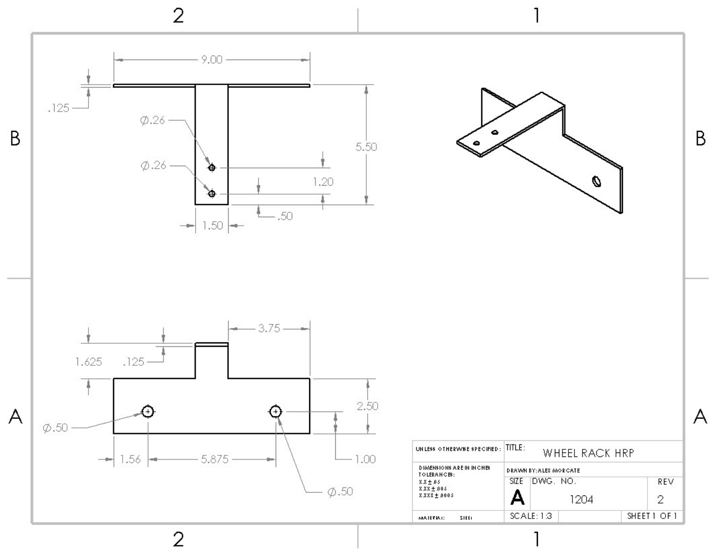


A six-sided internally threaded fastener with flat tops and chamfered corners.

Product Attributes

Brand Name	Minerallac Company
Sub Brand	Cully
Type	Machine Screw Nut
Special Features	N/A
Application	Designed to be used specifically with machine screws.
Standard	N/A
Material of Construction	Steel
Finish	Zinc Plated
Nut Type	Hexagonal Nut
Thread Size	20 TPI
Thread Type	Coarse
Thread Direction	Right Hand
Height	0.186" IN
Width	7/16 IN
Grade	Grade A
Size	1/4
Color	Silver
Rockwell Hardness	N/A

Item Status:	Active
Standard Qty:	100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Ø.26
Ø.26
5.50
1.20
.50
1.50
3.75
1.625
.125
2.50
Ø.50
1.00
1.56
5.875
Ø.50
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
X.X ± .05
X.XX ± .005
X.XXX ± .0005
TITLE:
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DRAWN BY: ALEX MORCATE
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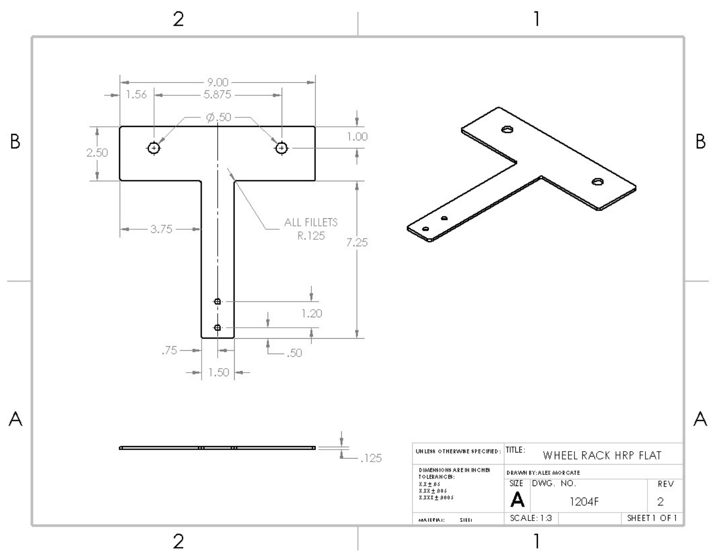
A
DWG. NO.
1204
REV
2
SCALE: 1:3
SHEET 1 OF 1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1.56
5.875
Ø.50
2.50
1.00
ALL FILLETS
R.125
3.75
7.25
1.20
.75
.50
1.50
.125
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
X.X ± .05
X.XX ± .005
X.XXX ± .0005
TITLE:
WHEEL RACK HRP FLAT
DRAWN BY: ALEX MORCATE
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DWG. NO.
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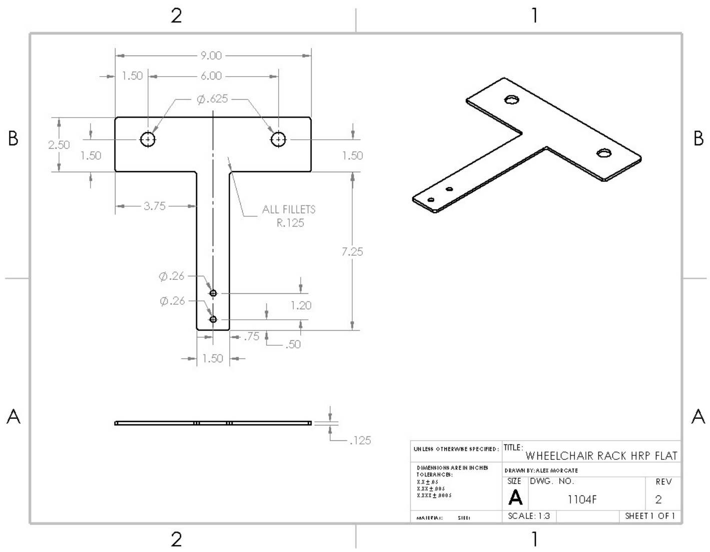
REV
2
SCALE: 1:3
SHEET 1 OF 1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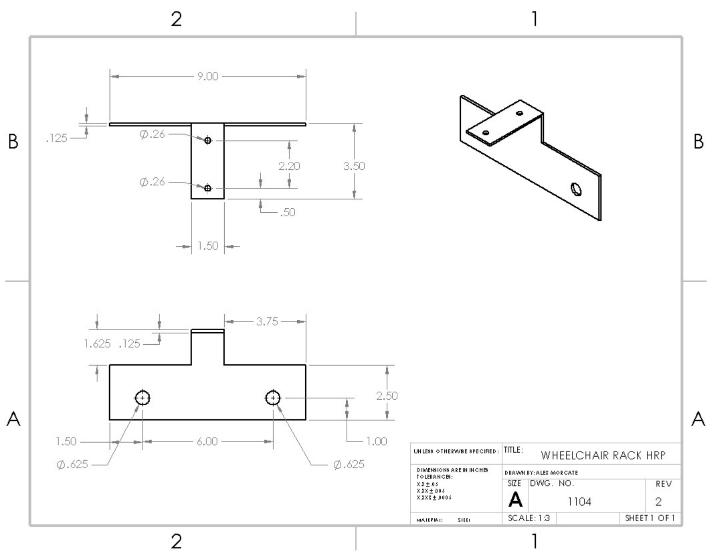
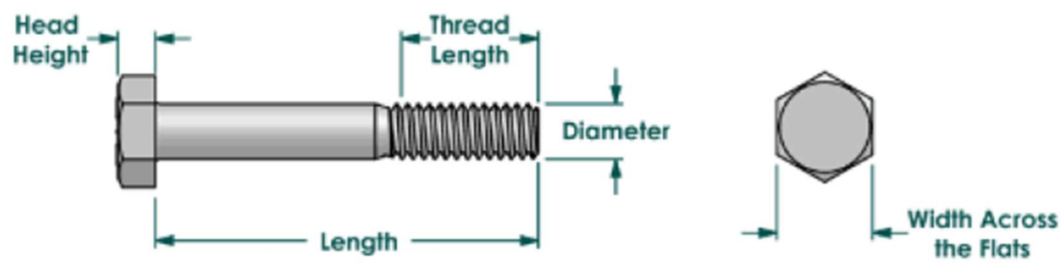
B
A
9.00
1.50
6.00
Ø.625
2.50
1.50
1.50
3.75
ALL FILLETS
R.125
7.25
Ø.26
Ø.26
1.20
.75
.50
1.50
.125
TITLE:
WHEELCHAIR RACK HRP FLAT
SIZE
A
DWG. NO.
1104F
REV
2
SCALE: 1:3
SHEET 1 OF 1

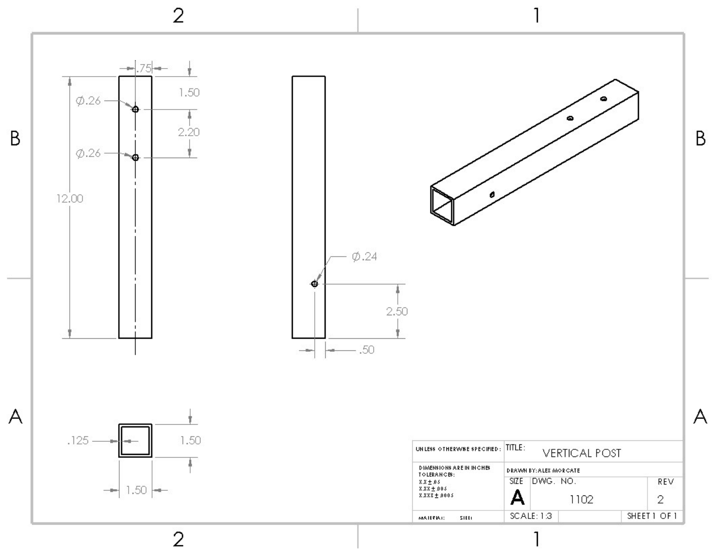

2
1
B
A
9.00
.125
Ø.26
Ø.26
2.20
3.50
.50
1.50
3.75
1.625
.125
2.50
1.50
6.00
1.00
Ø.625
Ø.625
TITLE:
WHEELCHAIR RACK HRP
SIZE
A
DWG. NO.
1104
REV
2
SCALE: 1:3
SHEET 1 OF 1

Product Images

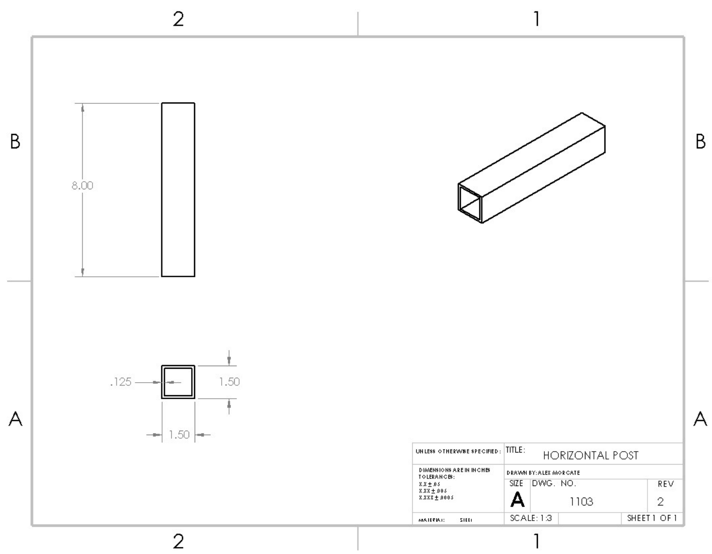


Product details

Bolt Depot Product #:	14
Units:	US
Category:	Hex bolts
Subcategory:	Hex bolts
Material:	Steel
Plating:	Zinc
Thread direction:	Right hand
Thread density:	Coarse
Diameter:	1/4"
Thread count:	20
Length:	8"
Dimensional standard:	ASME B18.2.1
Head style:	Hex
Drive type:	External hex
Head height:	5/32"
Width across the flats:	7/16"
Fully threaded:	No
Thread length Min:	1"



2
1
B
A
.75
1.50
2.20
Ø.26
Ø.26
12.00
Ø.24
2.50
.50
.125
1.50
1.50
UNLESS OTHERWISE SPECIFIED:
TITLE:
VERTICAL POST
DRAWN BY: ALEX MORGATE
SIZE
DWG. NO.
REV
A
1102
2
SCALE: 1:3
SHEET 1 OF 1



2
1
B
A
8.00
.125
1.50
1.50
UNLESS OTHERWISE SPECIFIED:
TITLE:
HORIZONTAL POST
DRAWN BY: ALEX MORGATE
SIZE
DWG. NO.
REV
A
1103
2
SCALE: 1:3
SHEET 1 OF 1

Appendix K: FMEA

System/Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities
Top strap/prevent sway	device sways	damages car; hurts Rory	7	material isnt rigid; no tensioning	Research material strength; test tensioning method	7	Material test
Super structure/support weight	doesn't support weight	chair falls; chair damage; car damage	9	material buckles; too thin material	Research material strength; load cases	3	Material test
Sturcture with velcro/prevent vibratation	wheelchair rattles from vib	noise from vibration, damage to car	3	poor tensioning; not strapped down properly	Research material strength; test tensioning method	5	Noise test
Super structure/prevent sway	device sways	damages car; hurts Rory	7	material isnt rigid; no tensioning	Research material stiffness; test tensioning method	7	Deflection test
Arm/holds chair	doesn't hold chair	chair falls; chair damage; car damage	9	attachment point breaks; arm breaks	Research material strength; load cases	4	Load test
Arm/folds	arm doesn't fold	gets in way of Rory	2	improper manufacturing	Clearance test; rotation testing	1	Load test
Wheel & cushion rack/holds components	doesn't fit components	components need to be placed elsewhere; rack just becomes an	2	improper manufacturing; incorrect measurements and sizing	Load cases; proper measurement	3	See if components fit
Wheel & cushion rack/prevent sway	rack sways	wheels fall out, noise	5	improper tensioning	Research material strength; test tensioning method	7	Tension test; Noise test

System/Function	Detection	RPN	Recommended Action(s)	Responsibility & Target Completion Date
Top strap/prevent sway	2	98	Material test	1/16/2019
Super structure/support weight	2	54	Material test	1/16/2019
Sturcture with velcro/prevent vibratation	2	30	Noise test	1/16/2019
Super structure/prevent sway	2	98	Deflection Test	1/16/2019
Arm/holds chair	2	72	Load test	1/16/2019
Arm/folds	1	2	Load test	1/16/2019
Wheel & cushion rack/holds components	1	6	See if components fit	1/16/2019
Wheel & cushion rack/prevent sway	2	70	Tension test; Noise test	1/16/2019

Appendix L: Project Budget

Item	Quantity	Unit Cost	BOM Part Number	Vendor	Vendor Part Number
12" x 24" 1/8" thick A1008 Cold Roll Steel Sheet	1	26.25	1104, 1204	Online Metals	13973
1.5" x 1/8" thick A500/A513 Hot Rolled Square Steel Tube	1	15.29	1102, 1103	Online Metals	10343
Rustoleum 248656 Automotive Professional Rubberized Coating	1	10.99	1105	Amazon	248656
Belt Latch Connector Child Car Safety Seat Connector	2	13.99	1108	Amazon	723585467081
Heavy Duty Garage Storage Utility Hooks (2-pack)	1	13.99	1201	Amazon	B07DC3MHXH
¼"-20 x ¾" Chrome Hex Bolt (3-pack)	2	3.70	1106,1202	Home Depot	800394
¼"-20 tpi Coase Stainless-Steel Nylon Lock Nut (3-pack)	2	1.18	1109, 1203	Home Depot	800131
¼" x 2" Zinc-Plated Universal Clevis Pin	1	1.94	1107	Home Depot	815418
Shipping & Handling		20.64	1102, 1103, 1104, 1204	Online Metals	N/A

Appendix M: Wheelchair Storage User Manual

This user manual provides instructions and guidelines to follow to ensure correct installation and use of our wheelchair storage system. It also includes important safety information. Refer to Figure 1 below for suggested storage orientations.

Hazards

If the wheels or wheelchair are not placed properly onto the device, both items have the potential of falling off while the car is in motion which can cause damage to them.

If the wheelchair and wheel storage systems are not installed correctly, they also have the potential of damaging the inside of the truck cab or any passengers sitting in the back seat.

PRIOR TO INSTALLATION

We recommend that you remove the cushion on the 40% seat. This will provide more room for the wheelchair frame and wheels. The seat is secured by two bolts (see Figure 5) at the front of the seat below the cushion can be removed with a 14mm socket wrench. If you wish to use a seat cover in the back seat the cover should be installed before the storage device.

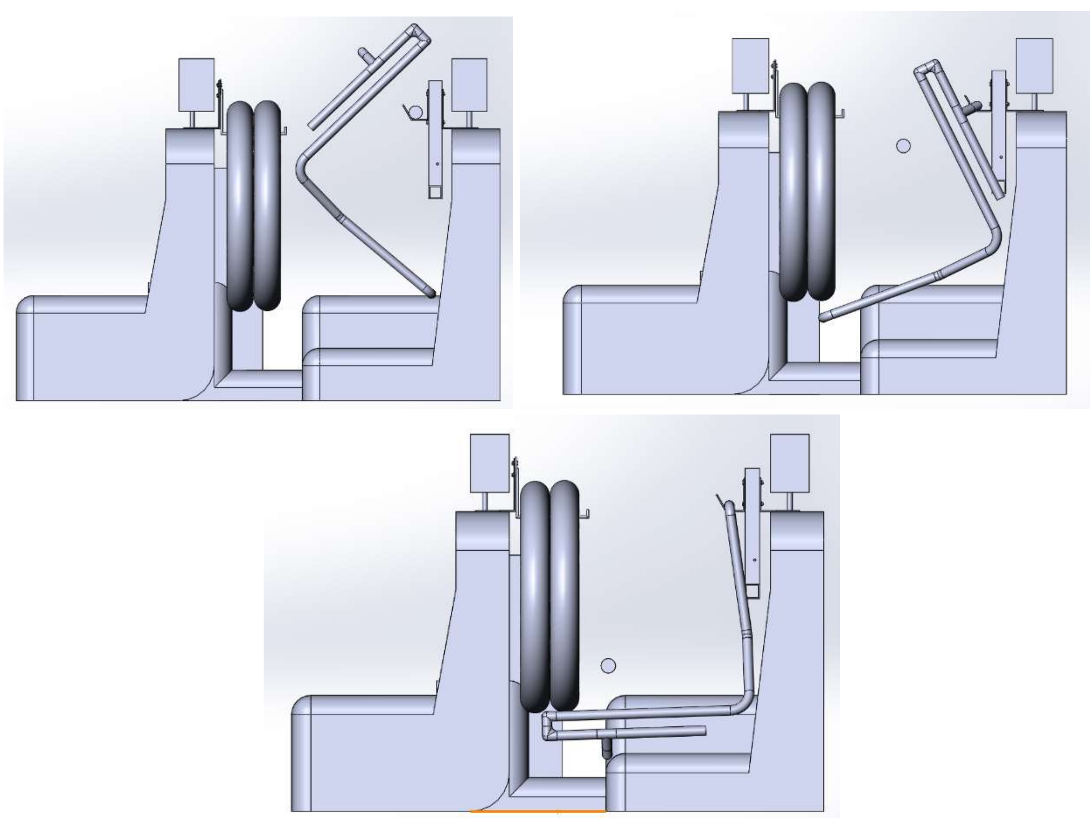


Figure 1. Wheelchair storage system set-up with three potential orientations of the frame

Installation Instructions

1. To install the wheelchair rack, first remove the headrest of the desired backseat. Slot the T-shaped headrest plate through the pegs of headrest so that structure (shown in Figure 2 below) rests on the top of the seat. Push headrest back into place.

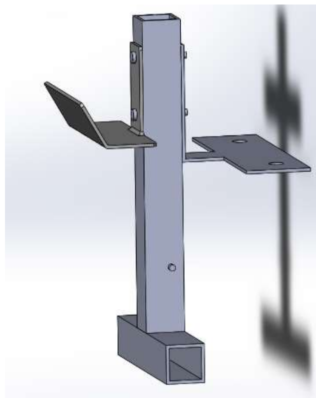


Figure 2. Wheelchair Storage System

2. Feed the child car seat connector (see Figure 6) attached to the vertical bar over the headrest and buckle it to the hook located on the back of the seat. See figure 5 for child safety seat hook locations.
3. Place the wheelchair onto hooks and secure with the provided bungee cord if necessary.
4. Feed the remaining child car seat connector through the horizontal tube of the T frame and attach the buckles to the hooks at the bottom of the seat.
5. Remove the headrest of the driver's seat or front passenger's seat and slot the T-shaped headrest plate for the wheel rack (shown in Figure 3) through the pegs of the headrest. Push the headrest back into place.

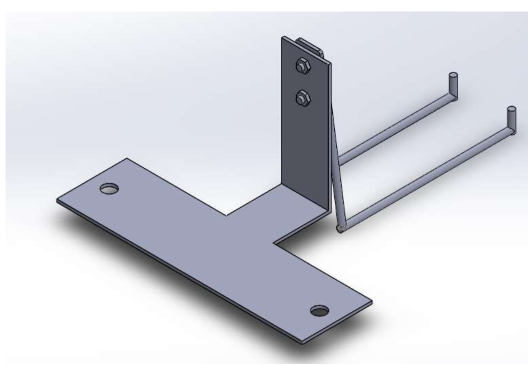


Figure 3. Wheel Storage System

6. Place wheels on hooks and secure with the provided bungee cord if necessary.

Usage

This device is intended to securely your specific wheelchair and is designed for a maximum load of 50 pounds. By using the provided straps, the rack and wheelchair should be secure. If the wheel storage rack is not remaining upright a strap can be used to adhere it to the headrest. For a visual of this process see Figure 4 below.

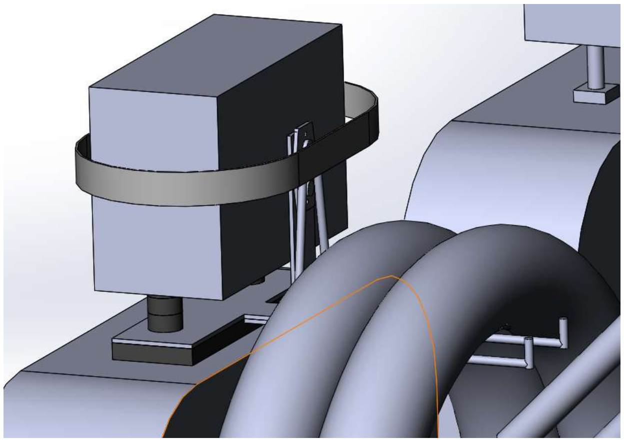


Figure 4. A strap such as the one provided can be used to hold the headrest plate against the headrest and prevent movement.

Part Replacement

If hooks on the wheel rack need to be changed or taken off, a 7/16 inch socket wrench and allen wrench can be used to remove the bolts.

Reference Images

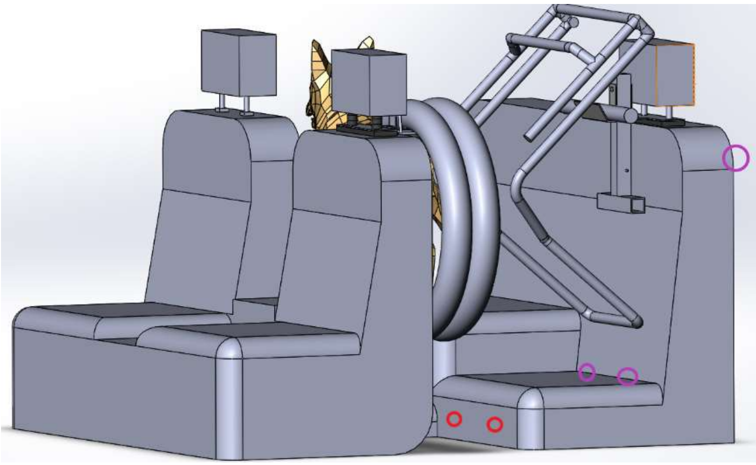


Figure 5. Red circles indicate the approximate locations of the bolts securing the 40% seat cushion. Purple circles indicate the approximate locations of child safety seat attachment points

Figure 6. Child car seat connector