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Final Project Report for a Lighter Mobility Cart

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Interoffice Memorandum

TO:	Richard Baldwin, Member of Board of Directors of the Texas-San Antonio affiliate of Mobility Worldwide and Chair of the Design & Standardization Committee of Mobility Worldwide
	Eliseo Iglesias, Team Advisor
	Dr. Darin George, Senior Design Administrator
	Panel of External Judges
FROM:	The Cartologists: Anne Wellford, Sam Mielke, and Hanna Rafferty
SUBJECT:	Final Project Report for Weight Reduction of a Mobility Cart
DATE:	April 23, 2020

The Cartologists are submitting this final report for senior design. This project aims to help make Mobility Worldwide's mobility carts more manageable to transport by decreasing the weight of the cart. This report gives an overview of our final design modifications to the Mobility Worldwide cart, which make the cart 10.14 lbs lighter than the original design. In the design process, we split the cart up into four subsystems and then modified and simulated each subsystem as well as the overall cart. Physical testing was then done for the first prototype of the cart, and the results of this testing were evaluated in order to make adjustments for the final prototype. Due to Bexar County's shelter-in-place orders in response to the COVID-19 pandemic, we were not able to complete our physical testing for the final prototype. However, based on our first prototype physical testing and our comparison of first and final prototype simulations, we are confident that our final design would yield a working prototype.

Thank you for considering our final project report. Please contact our point of contact, Anne Wellford (awellfor@trinity.edu) if you have any comments, questions or concerns. We hope that you enjoy learning about our exciting project, which will help thousands of people across the globe.

Mobility Cart - Mobility Worldwide

Final Project Report for a Lighter Mobility Cart

The Cartologists

Sam Mielke, Hanna Rafferty, Anne Wellford

May 1, 2020

Executive Summary

This report outlines the overview of our final cart design and evaluates the design's compliance to the project requirements, constraints, and objectives. This report also includes recommendations, future improvements and tests that to be completed after the shelter-in-place order has been rescinded in Bexar County.

Our final design saves 10.41 lbs in Fusion 360. This means that we met the major requirement of our design since the cart is 10% to 20% lighter than the original reference cart weight of 100 lbs. Our design changes include reducing the gauge of some of the parts of the cart (the main beam and gooseneck of the chassis and the handlebars). Additionally we reduced the amount of wood on the basket and chair by reducing the width or thickness of some parts or removing non-load bearing portions that withstood our loading conditions in simulations and physical testing. The major design changes include changing from a wood to a fabric chair back as well as going from a rigid wood trailer to a lighter, removable trailer on the basket. A full discussion of our design changes with pictures can be seen later in the report.

In this report, we analysed our test results to determine how well the final design met the requirements. We conducted finite element simulations that evaluated the cart's four subsystems, tractor, chassis, basket, and chair, as well as the whole cart. The physical tests for the first prototype are discussed and the simulation results for the final prototype. Due to the COVID-19 shelter-in-place order, the Cartologists were unable to physically test the final prototype. However, based on the results from the physical testing for the first prototype and Fusion 360 simulation results for the final prototype, we were able to confidently meet the majority of our requirements. The only requirement and constraint that was not met was that the cart should cost no more than the reference cart (~$300). The final prototype has a projected cost 1.2% higher than the reference cart. However, our sponsor at Mobility Worldwide indicated that a slight cost increase is acceptable as long as it reduces weight, and/or adds a valuable feature. Additionally, the cost estimate could be lower depending on discounts from buying in bulk or from local suppliers.

We will also provide Mobility Worldwide a drawing package of our final design. With it they can build and evaluate the final prototype. Additionally, future work should include building, testing and evaluating our two options for the basket trailer, which secures items in the back of the cart, described in detail in Appendix C. The two methods are a slidable plate, or a net/fabric mesh. Both methods are presented in the report for Mobility Worldwide's evaluation and final consideration.

Introduction

Mobility Worldwide is a non-profit organization that assembles mobility carts for users in developing countries, where there is limited or nonexistent access to assistive technology. The carts are shipped and distributed to those in need all over the globe. In the past, some users declined to receive a cart because it was too heavy to transport back to their home. In order to increase the amount of new users that can access the mobility carts as well as ease the construction and shipping process for the volunteers, the Cartologists were tasked with reducing the overall weight of the cart without sacrificing the strength, endurance, and capabilities of the Standard Large Crank Mobility Cart (SLCMC).

We were required to meet the functional, non-functional, and interface requirements to have a successful project. The functional requirements included that the cart shall be able to hold a person up that weighs up to 335 lbs, shall use a hand cranked design for locomotion, and shall be able to be driven in reverse. The cart shall have equal braking distances to the SLCMC on both flat and inclined surfaces. The non-functional requirements include that the cart shall only be made with the tools available in the San Antonio Mobility Worldwide Shop. The material cost per cart shall be no more than that of the reference cart (~$300). The cart shall have at least 2.57 ft^3 of storage space. The new cart shall require a user or Mobility Worldwide volunteer the same amount of assembly and disassembly time as the original. The seat, wheels, and front end must be detachable from the cart's chassis. Components shall be able to be purchased from a brick-and-mortar hardware store, unless a justification from Mobility Worldwide is provided. The major interface requirements include that the cart seats shall be adjustable in height and forward/backward position. Additionally, the cart seat shall be cushioned to lengthen time of 'comfortable' use of the cart.

The main applicable constraints for this project include that the final design must be solely hand powered and operated in addition to having both a hand and parking brake. The final design must weigh between 10% and 20% lighter than the original cart weight of 100 lbs. The final design must adhere to current Mobility Worldwide nationwide practices. In addition, an average volunteer must be able to build the cart. The final design also must be as comfortable as the reference cart to not impede users from using the cart for extended periods of time. There is no strictly defined method for measuring comfort of the mobility cart or the effectiveness in preventing bed sores. Medical literature such as "A Randomized Control Trial to Evaluate Pressure Reducing Seat Cushions for Elderly Wheelchair Users" (Geyer et al.) states that cushions are effective in the prevention of pressure ulcers, but these articles do not specify the thickness or type of cushions. To determine the maximum weight that the cart should be able to support, the Hybrid III 95th large percentile crash test dummy was chosen to represent an average cart user’s weight. The hybrid weighs 223.3 lbs +/- 3.6 lbs (“49 CFR Subpart E - Hybrid III Test Dummy”); with a 50% safety modifier, the minimum supported weight is 335 lbs.

Our design contains multiple changes to the reference cart that have reduced the weight of the cart while maintaining the structural stability of the cart and meeting all the constraints, requirements, and objectives for the cart. Some of these changes are reducing parts to a smaller gauge. Additional changes reduce the amount of wood on the cart. Other changes such as the back of the basket and chair back replace whole wood sections of the cart with lighter materials. These changes are discussed at length in the next section.

Overview of the Final Design

For ease of design, the Mobility Worldwide cart was broken into four major subsystems: the tractor, chair, basket, and chassis. The tractor is the metal steering column and wheel at the front of the cart. The chair includes the seat bottom, seat back and the metal bracket attaching to the basket. The basket includes the wooden structure under the chair on top of the chassis. The chassis is the steel frame under the basket and includes the axles and the two back wheels. Figure 1 shows the original cart to be used as a visual reference containing the four subsystems. This cart, the Standard Large Crank Mobility Cart (SLCMC) from Mobility Worldwide, will be referred to as the "reference cart" throughout this report.

Figure 1. Mobility Worldwide reference cart

Mobility Worldwide provided this physical cart to be used as a reference cart as well as CAD drawings of all the parts and assemblies corresponding to the physical reference cart. Our design changes to the cart were tested with both finite element simulations in Fusion 360 and with physical testing. In the simulations, the subsystems were able to be tested separately because constraints in the modeling software were designed to accurately represent the cart. Isolating the subsystems also allowed us to better understand the behavior of each subsystem and the effects of our design changes. Additionally, the subsystems were tested separately to reduce run time and errors due to model complexity. For the physical testing, the subsystems were tested separately, because the interactions between subsystems are critical in the structural stability of the cart; therefore, testing subsystems individually would not give an accurate representation of the cart.

We tested a variety of designs using the Finite Element Analysis (FEA) tool in Fusion 360. The objective was to select a final design for each subsystem to be implemented in the physical prototype testing. These designs were compared to the reference cart based on safety factor, stress [ksi], displacement [mils], weight savings [lb], and cost [$]. Decision matrices with a weighing factor for each of these categories were used to compare the potential design solutions with the reference cart. The goal was to identify a design with the most weight savings, cost savings, strength, rigidity and safety. The FEA was originally used as a tool to narrow down design ideas and support the physical testing results. However, because of the COVID-19 shelter-in-place order, physical testing could only be completed for the first prototype and not the final prototype. FEA served as a stand in for physical testing for the final prototype.

The first prototype was constructed in the Mobility Worldwide shop in San Antonio using their tools and assistance from their volunteers. Rodger, a volunteer who does the majority of the welding for the carts in San Antonio, welded the first prototype chassis and tractor pieces. Additionally, Bill, the lead chair and tractor assembly volunteer at the San Antonio Mobility Worldwide shop, helped us assemble the tractor and seat bottom with our design changes. Richard and Bob, who both work on various components of the cart, helped in the assembly of the basket and the fabrication of the modified welded pieces on the tractor. The San Antonio shop generated jigs to help guide the volunteers to create and assemble the cart components with ease and consistency.

Overall, nine significant design changes were implemented to create the final prototype cart including:

- reducing the gauge size on the chassis
- reducing the gauge size on the handlebars on the tractor
- removing the wood spacer from the tractor
- replacing the back of the basket with L-brackets
- shortening the chassis and basket by an inch
- planing the chair bottom
- tapering the unnecessary wood from the basket
- decreasing the size of the wooden supports on the side of the basket
- fabric chair back

Chassis Gauge Down

By reducing the gauge of the main beam of the chassis and the gooseneck from 14 gauge to 16 gauge rectangular steel beam, we reduced the weight of the cart by 0.90 lbs. The same welding techniques and equipment that are currently used can still be used in implementing this design. Figure 2 shows the two components of the chassis with the decreased gauge size.

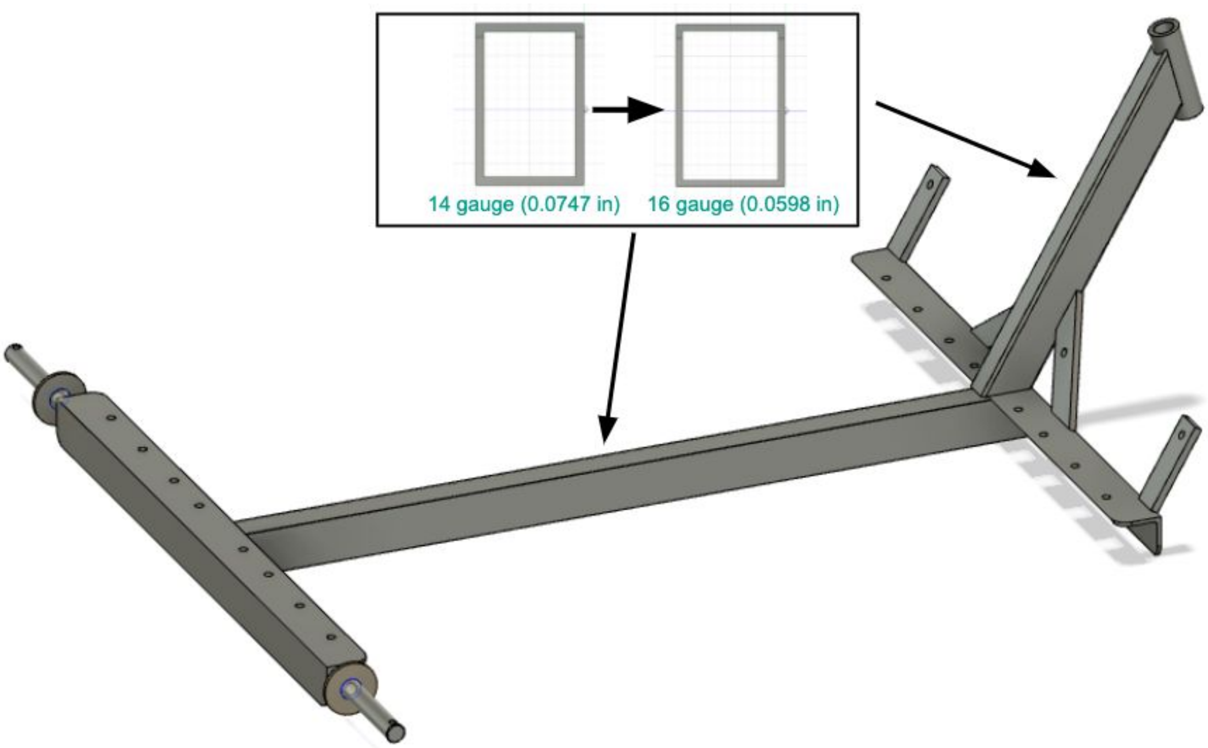


Figure 2. Decreased gauge size of gooseneck and main beam on chassis

The second design change decreased the gauge of the handlebars on the tractor. We decreased the thickness of the two bars by half, resulting in a weight savings of 0.31 lbs.

Handlebars Gauge Down

Similar to the gauge down on the chassis, the same equipment and techniques for welding and bolting the handlebars can still be used. In Figure 3, the top left handlebar shows the original design, while the lower left design shows the lighter version that we implemented in our final prototype.

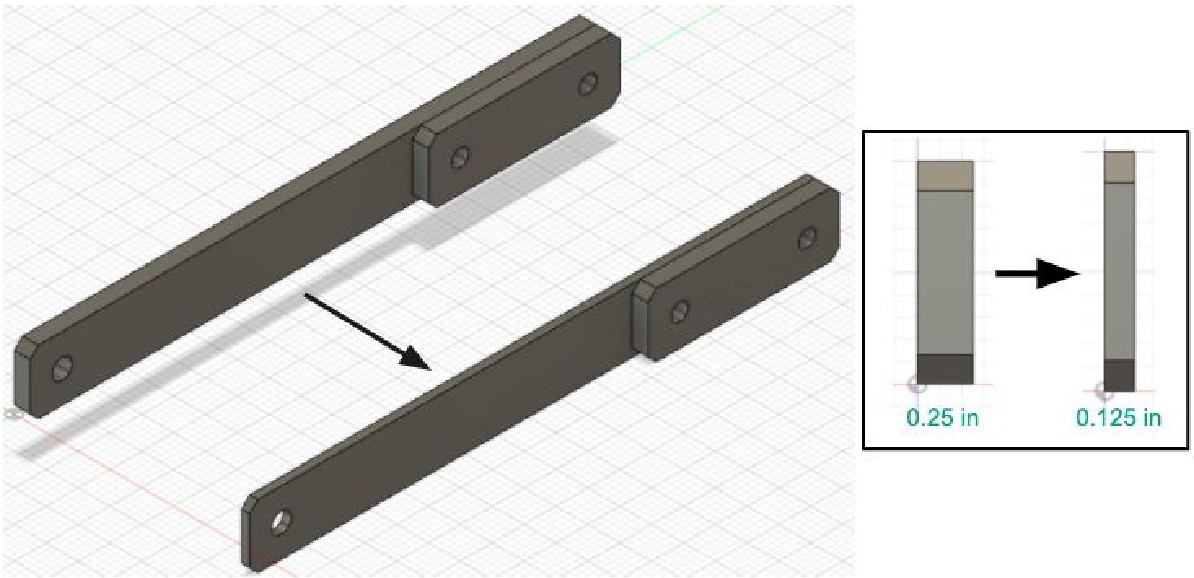


Figure 3. Decreased gauge size of handlebars

Wood Spacer Removed

For the next design change, we removed the wood spacer that is used in the main post of the tractor to prevent the bolts on the front of the tractor from being over torqued. In implementing this design, we encourage the volunteers to only tighten by hand. This will allow the tractor to be tightened without over torquing and thus warping the main post. By removing the wood spacer, there is a weight savings of 0.24 lbs. Figure 4 shows the original main post with the wood spacer in on the left and without the spacer on the right.

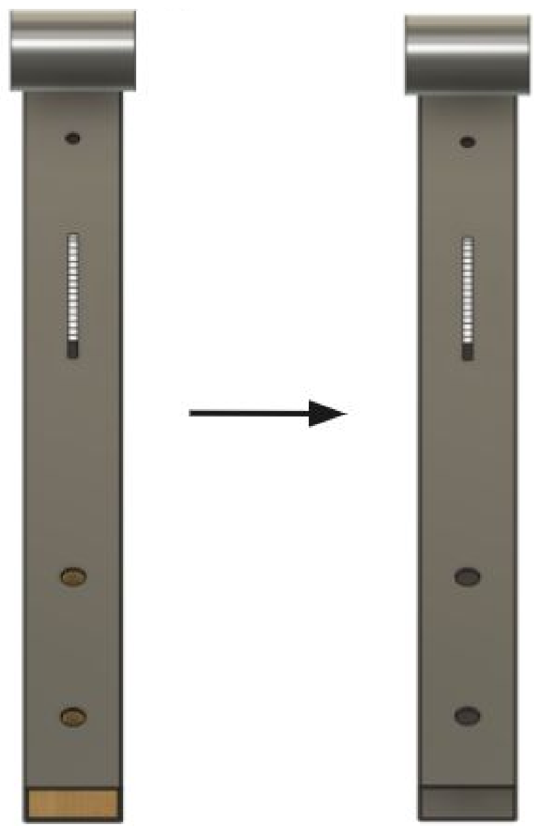


Figure 4. Removal of wood spacer from main post of the tractor

L-Bracket & Smaller Side Supports

For the basket, we made two major changes. The first included removing the back of the basket altogether and replacing it with two metal L-brackets for support, saving 1.42 lbs. The second design change was to decrease the size of the wood supports on the side of the basket. Previously, the side support board was a 1X6". This was replaced with a 1X4", which saved a total of 0.68 lbs. For both of these designs, the same table saw and drills can be used to fabricate and assemble the basket pieces. Figure 5 shows the updated basket with the design changes.

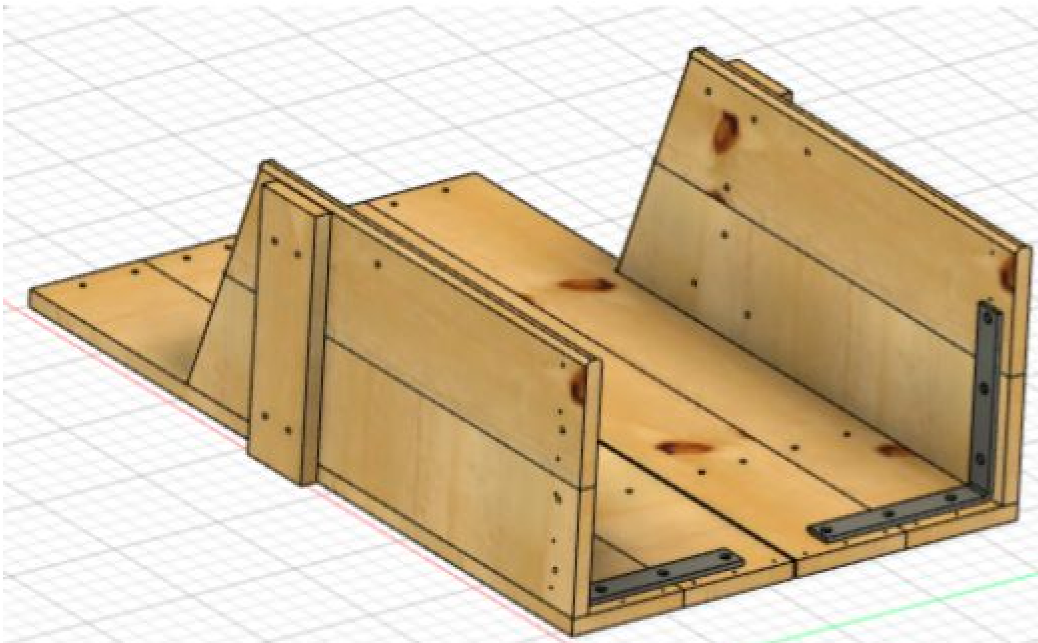


Figure 5. Replacement of basket back with L-brackets and smaller wooden side support

One Inch Shorter

Our design change to decrease the overall length of the cart by 1 inch saves approximately 0.44 lbs. Since the design only features dimensional changes, the same fabrication and assembly procedures can be used in implementing this design. Figure 6 compares the original cart on the left to the final prototype cart. There is an annotation showing where the inch was removed because the difference is hard to see since it is slight in comparison to the total length of the cart.

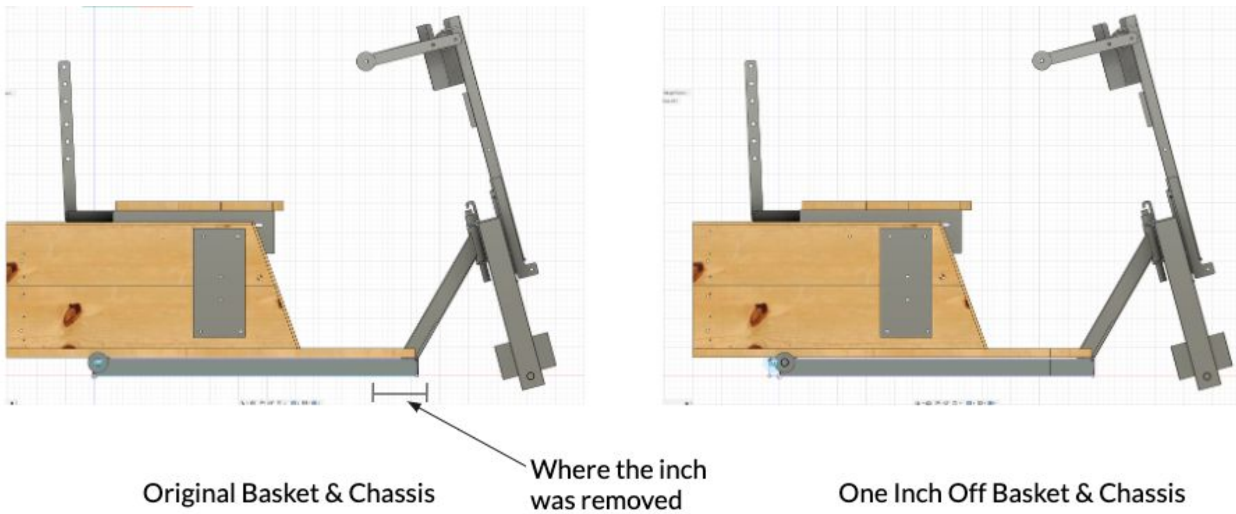


Figure 6. Comparison of original cart to the cart that is one inch shorter in length

Thinner Chair Bottom

For the next design change, we propose planing the chair bottom from ¾" to ½" for an approximate weight savings of 1.50 lbs. Mobility Worldwide does not currently have a planing machine in their shop. However, Mr. Baldwin has access to one and is willing to plane wood in order to implement this design. Figure 7 shows the original chair bottom thickness on the left compared to the planed bottom for the final design on the right.

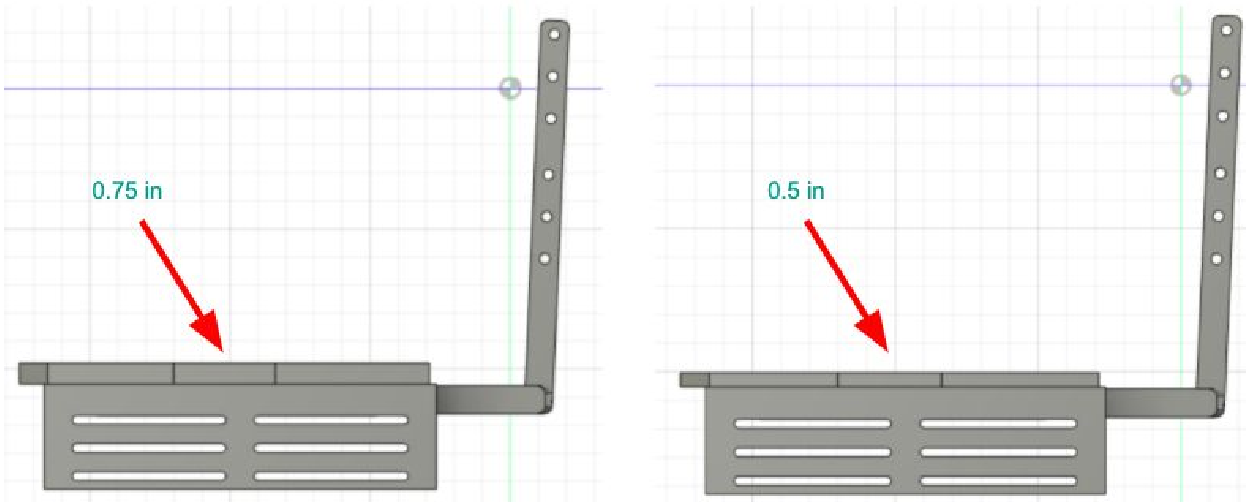


Figure 7. Comparison of original ¾" chair bottom to chair bottom with wood planed to ½"

Basket Tapers

Next, we identified areas of the basket that had excess wood that were not load bearing in order to remove unnecessary material. In doing so, we removed the diagonal cuts at the front of the basket by cutting them straight from the top. The back of the basket also had a triangular section removed in order to remove unnecessary material from the cart and possibly allow for easier access to the storage space. Overall, the taper design has an estimated weight savings of 1.10 lbs from Fusion 360. The same table saw and drills can be used to fabricate and assemble the basket pieces as what is currently used. Figure 8 shows the original side view of the reference cart, while Figure 9 shows the side view of the final prototype basket.

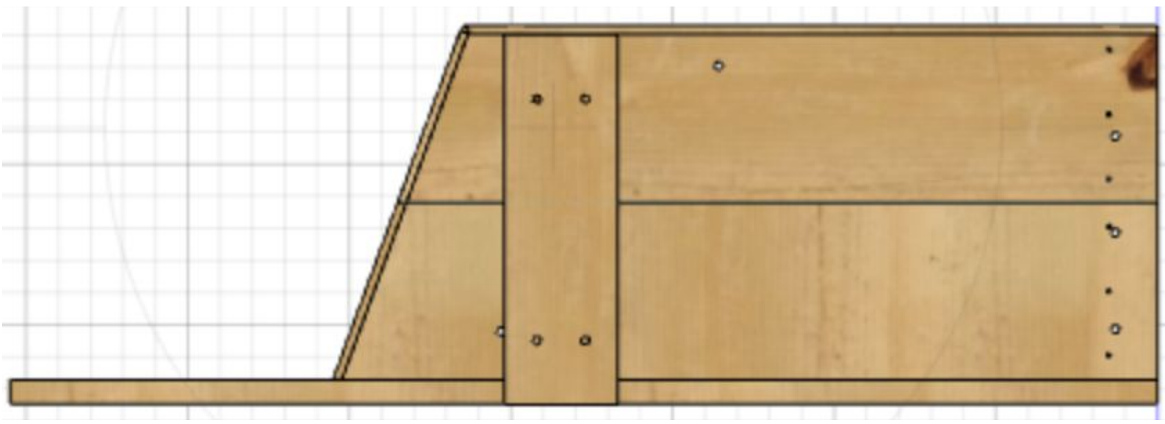


Figure 8. Original basket design with taper in front

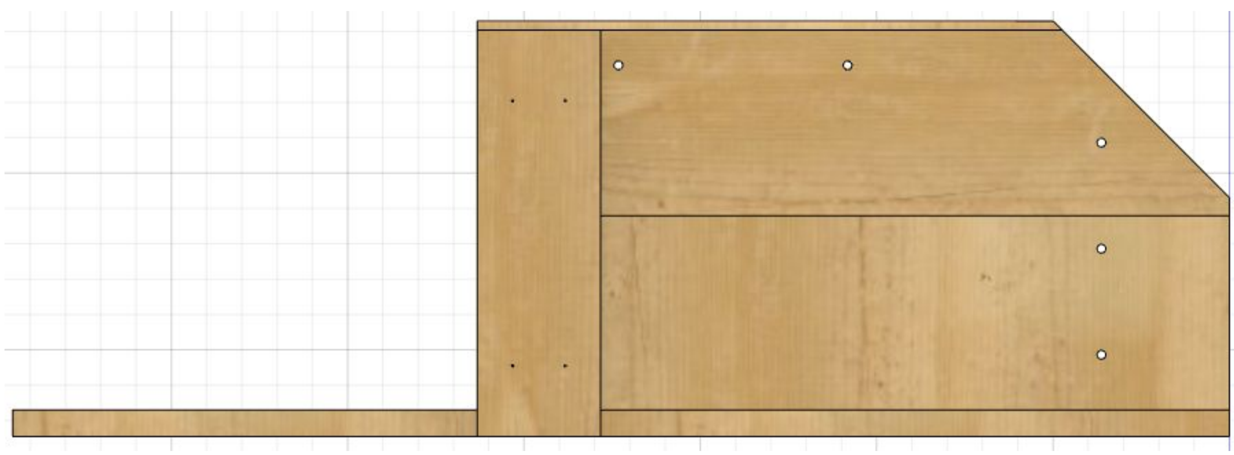


Figure 9. Basket with tapers in back and straight front

Fabric Chair Back

For our final design change, we propose removing the wooden seat back and replacing it with a fabric back. Additionally, we added PVC pipes that extend above the metal supports and provide an attachment point for the fabric material. The seat back is the same height as the original wooden design. Additionally, for this design the existing metal supports are installed on the outside portion of the wooden posts under the seat bottom to expand the surface area of the seat back. The metal supports were attached on the inside of the wooden posts for the reference cart and the first prototype cart as seen in Figure 10.

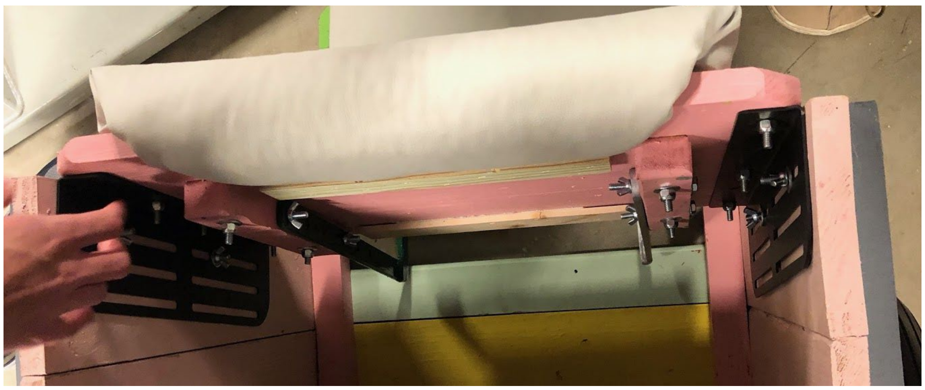


Figure 10. Chair bottom picture showing the metal supports attached to the wooden posts

Mobility Worldwide volunteers who sew the seat belts can use their sewing machines to create the seat backs that slip over the PVC pipes. By changing the wood chair back to the fabric back, there is an approximate weight savings of 3.55 lbs. Figure 11 illustrates the fabric back design for the first prototype, which doesn't include PVC. The sewing pattern for the final prototype will remain the same as the first prototype other than the updated dimensions. Figure 12 shows the fabric chair back design without the fabric portion, which would slip over the two PVC pipes. The fabric portion of the design is detailed in Appendix A.

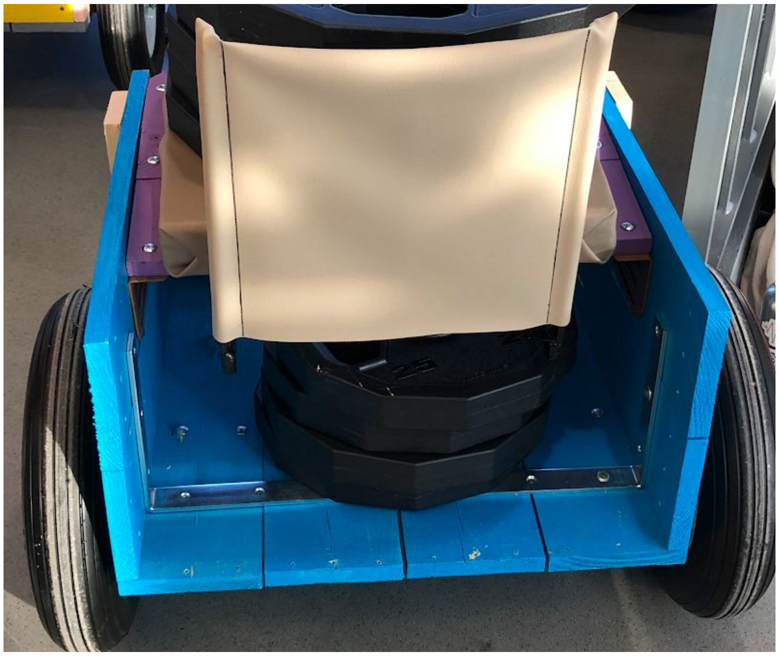


Figure 11. Fabric chair back design for the first prototype

Figure 12. Fabric chair back design without the fabric attached

By implementing all of these designs for the final prototype, there is an increase in price of $3.50 per cart. The only design change that adds cost is the L-bracket design. However, buying these parts in bulk, Mobility Worldwide currently does this, and working with local suppliers could easily result in a reduction in cost. Table 1 outlines the estimated cost associated with each design change where negative costs correlate to cost savings and a positive cost signifies an increase in cost.

Table 1. Estimated cost associated with each design change

Subsystem	Design Change	Cost Impact
Chassis	Gauge Down	-$1.29
	Inch Off	-$0.21
Tractor	Gauge Down Handlebar	-$0.41
	No Wood Spacer	-$0.23
Basket	Taper	-$0.74
	Smaller Wood Supports	-$0.36
	L-Bracket (No Trailer)	+$10.00
	Inch Off	-$0.37
Chair	Planing Bottom	$0.00
	Fabric Back	-$2.89
	Overall Estimated Cost Change:	**+$3.50**

Design Evaluation

Our design evaluation included both simulations and physical tests. The interface requirement that states that the cart may have an attachment point for a person to push on from the back end was not explored due to the shelter-in-place order. .

The following non-functional requirements were met during the construction of our prototype and, therefore, did not need to be explicitly tested:

- Requirement 1: Cart shall only be made with the tools available in the San Antonio Mobility Worldwide Shop.
    - Standard tools are limited to hand tools, steel welding equipment, drill presses, electric saws, and lathes.
- Requirement 2: Components shall be compatible with those in Mobility Worldwide's shop, unless a sponsor accepted justification is provided.
- Requirement 3: Components shall be purchasable from a brick-and-mortar hardware store, unless a sponsor accepted justification is provided.
- Requirement 4: The seat, wheels, and front end must be detachable from the cart's chassis.

In our project proposal, we stated that a test plan would be developed to measure corrosion (Requirement 5). However, since there was no change in material in our design, it was decided that comparing the corrosion levels of the reference cart and the final cart design would not give relevant results. As for the requirement that the cart shall be able to be exposed to inclement weather without a loss of forward and backward movement (Requirement 6), we have not made any significant changes in the design that would be affected by weather. Once again, because the cart is made of the same materials and will have the same painting and powder coating processes, we decided that completing an inclement weather test would not give relevant results. Because the reference cart successfully withstands weather conditions, we expect that the same weatherizing procedures would be followed for the final prototype. The proposed design uses the same tires and only has a small change in the tractor, so it is not expected to behave differently in various weather conditions. Similar to the corrosion test, we assume that because our modified design uses the same material as the reference cart, a weather test is not needed. As for the requirement that the material cost per cart shall be at a maximum \$300 (Requirement 7), this requirement was evaluated by doing a cost analysis based on prices from Triple S Steel, Home Depot, Lowes, and other brick-and-mortar hardware stores. This analysis can be seen in Table 1 of the previous section.

The following requirements were tested with simulations and physical testing, and are discussed in the rest of this section of the report.

- Requirement 8: Cart shall have at least 2.57 ft^3 of storage space.
- Requirement 9: The final design must weigh between 10% and 20% lighter than the original weight of 100 lbs.
- Requirement 10: Cart shall be able to hold a person up that weighs up to 335 lbs.
- Requirement 11: Cart shall be able to be disassembled and reassembled within the same time duration as the SLCMC.
  - The seat, wheels, and front end must be detachable from the cart's chassis.
- Requirement 12: Cart shall use a hand cranked design for locomotion.
- Requirement 13: Cart shall be able to be driven in reverse.
- Requirement 14: Cart seats shall be cushioned to lengthen time of 'comfortable' use of the cart.
- Requirement 15: Cart shall have equal braking distances to the SLCMC on both flat and inclined surfaces.

Requirement 8: The cart shall have at least 2.57 ft^3 of storage space.

Test: Storage Space Test

Test Overview

We used the measuring tool in Fusion 360 to measure the storage space in simulations, since we could not do physical testing for the final cart prototype due to the COVID-19 shelter-in-place situation.

Objectives

The goal of this test is to make sure that the new cart design does not decrease the storage space of our final design when compared to the reference cart.

Design Features Evaluated

This test evaluated the basket to address the requirement that the cart shall have at least 2.57 ft^3 of storage space. The 2.57 ft^3 number came from measurements of the model in Fusion 360.

Test Scope

We used the Fusion 360 measuring tool to accomplish this task for the final prototype testing.

Test Plan

We measured the height, length, and width of the storage space from the inside of the cart. Then we multiplied these numbers together to evaluate the volume of the available storage space.

Assumptions

This test assumes that the measuring tool in Fusion 360 is accurate. This test also assumes that the storage space of the cart is the length of the side boards of the basket multiplied by the width of the basket and the height from the floorboards to the chair bottom. Any volume taken up by posts on the inside of the basket is accounted for. We did not count the volume taken by the L-brackets into the 2.77 ft^3 calculation, because we assumed their impact on the volume measurement to be negligible in relation to the total calculation. Finally, we didn't include into our calculation that the open back design allows for objects to stick out the back of the cart, thus allowing for more things to fit in the storage space area. For example, an open back allows for items such as crutches to stick out, storing more than what a volume measurement may suggest.

Acceptance Criteria

An acceptable design is one where the storage space of the new cart design is greater than or equal to 2.57 ft^3.

Test Results & Evaluation

In Fusion 360, the reference cart had a storage space of 2.57 ft^3. The final design prototype has two trailer back designs, which can be seen in Appendix C, and have different storage space capacities. The fabric/mesh trailer back design has a storage space of 2.83 ft^3. The plate trailer back design has a storage space of 2.70 ft^3. Both designs for the final prototype cart increase the storage space when compared to the Fusion 360 value, thus this requirement was met by our design.

Requirement 9: The final design must weigh between 10% and 20% lighter than the original weight of 100 lbs.

Test: Weight Test

Test Overview

This test describes how we used a scale to measure the weight of the cart for the first round of physical testing. Then we used Fusion 360 to calculate the weight of the cart based on the densities in the Fusion 360 software for the final design testing.

Objectives

The objective of this test was to ensure that the cart meets the targeted weight requirement stating that the final design must weigh between 10% and 20% lighter than the original weight of 100 lbs.

Features Evaluated

This test evaluated the weight of the prototype cart after all subsystem design modifications.

Test Scope

For the first round of physical testing, the test was limited to the completed reference cart and the completed prototype cart and was only required to be accurate to the tenth of a pound. The cart did not have any external loads applied or added weights. For the final prototype, we used the weight measurements from Fusion 360, since we could not do physical testing for the final cart prototype due to the COVID-19 shelter-in-place situation.

Test Plan

The cart was weighed using the scale that is available in the Trinity Maker Space. This scale is capable of weighing items of the physical size and weight of the cart. The scale was calibrated before use and tested with a known weight. Since the scale was calibrated before weighing the cart, only one measurement was necessary for the prototype and the reference cart. The weights were then compared and evaluated by our acceptance criteria. For the final design test, the weight measurements were obtained from the Fusion 360 software then compared and evaluated by our acceptance criteria.

Assumptions

By completing this test, we assumed that the scale in the Trinity Makerspace takes consistent measurements and that our calibration was accurate. Additionally, we assumed that the two carts have uniform materials with uniform material properties outside of the changes that we made. For our final prototype, we are assuming that the Fusion 360 material properties such as the material densities and masses are accurate representations of the physical version of the model.

Acceptance Criteria

The prototype cart is considered acceptable if it weighs between 10% and 20% lighter than the reference cart.

Test Results & Evaluation

When measured with a physical scale, the reference cart weighed a total of 99.5 lbs, and the first prototype cart weighed 93.5 lbs. This is a 6 lbs weight savings, translating to a 6% lighter cart, so the design did not meet the criteria range for the prototype to be 10% to 20% lighter than the reference cart. For the final prototype, we were not able to physically build and weigh the cart in the Trinity Makerspace. Based on the calculations for weight savings using Fusion 360, the final prototype cart weighs 10.14 lbs less than the original cart.

One limitation to keep in mind is the variance between each cart. For the first prototype, we estimated that the weight savings would be approximately 7.91 lbs using Fusion 360, when in reality the weight savings was only 6 lbs. Since wood is a non-uniform material, the weight of each cart can vary greatly. We evaluated the density of a few individual pieces of the cart and compared the density to that of Fusion 360. The calculated average density was 0.023 lbs/in^3 with a standard deviation of 0.003 lbs/in^3 while the Fusion 360 density for pine was 0.021 lbs/in^3. Because of the magnitude of the standard deviation, we deemed that the variance in wood density is not consistent enough to reliably predict the weight. With that being said, the final prototype weight of 10.14 lbs lighter than the reference cart is a good, educated estimate, but may vary when physically built.

Requirement 10: Cart shall be able to hold a person up that weighs up to 335 lbs.

Test: Tractor Finite Element Analysis

Test Overview

This test compared different tractor designs under a static load of 335 lbs using the Finite Element Analysis modeling software in Fusion 360.

Objectives

The goal of this test was to compare the safety factor, stress [ksi], and displacement [mils] of the final tractor design to the reference tractor. This test addressed the requirement that the cart shall be able to hold a person up that weighs up to 335 lbs.

Features Evaluated

This test evaluated the strength of the tractor.

Test Scope

The test was done using the Finite Element Analysis modeling software in Fusion 360. We applied a distributed static load to the tractor, replicating the weight of a 335 lb person sitting on the cart. For our simulations, we removed the wood spacer in the main column and decreased the gauge of the crank arms.

Assumptions

In this test, we assumed that we accurately placed constraints on the models to simulate the cart realistically. Because the handlebars experience a dynamic load, which we did not explore in Fusion 360, we assumed that the handlebars were welded in place and under a 25 lb load each. In doing so, we simulated a worst case scenario of loading to ensure that the handlebars would not deflect significantly. Additionally, the load from a person sitting on the chair transferred to the tractor is not straightforward since the load is experienced at an angle and a portion of the load is distributed to the back wheels as well. As a result, we simulated a horizontal load coming away from the connection point with one third of the 335 lb load of the person to ensure that the tractor could withstand the worst case loading scenario.

Test Plan

The instrument that we used for this test was Fusion 360's Finite Element Analysis tool. For the loading scenario, we applied gravity in addition to a load at the connection point between the chassis and the tractor where the force of a person sitting on the chair would act. Additionally, we examined the strength of the crank arms of the tractor by applying a 50 lb force downward on the handles with the assumption that the crank arms are welded in place. These forces can be seen in Figure 13.

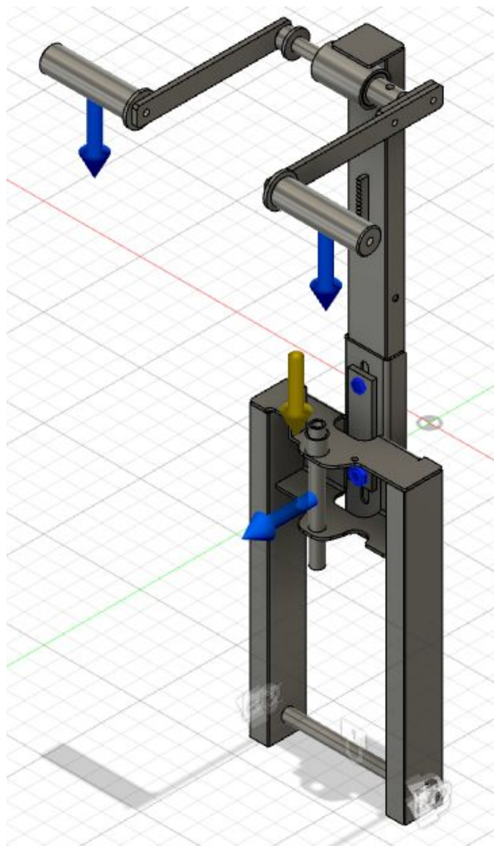


Figure 13: Applied loads on the tractor in Fusion 360 simulation

We compared the results of the FEA of the designs given to us by Fusion 360 to evaluate the final design.

Acceptance Criteria

The final prototype design was considered acceptable if the safety factor, and stress, and displacement were not significantly different from the reference cart.

Test Results & Evaluation

Tables 2 and 3 show the results of the tractor simulations. For the designs in Table 2, we decided to go with the "No Wood Spacer" design, because it reduces the weight of the cart by 0.24 lbs without significantly the safety factor, stress, or displacement values relative to the reference cart. The reference and prototype cart FEA results are displayed in Figures 14 and 15, respectively. These figures contain both displacement results and stress concentration results. Table 3 evaluates the smaller gauge steel design for the handlebars. The stress and safety factors of the smaller gauge handlebars are slightly worse than the reference results, with a displacement 0.007 inches further for the smaller gauge. The reference and prototype handlebar deflection FEA results are depicted in Figures 16 and 17, respectively. We decided to accept the smaller gauge handlebar design because we thought that the stress and safety factor values were still within a reasonable range for the cart to operate successfully in addition to the weight savings of 0.31 lbs. Overall, these simulation results allowed us to select the smaller gauge handlebars and remove the wood spacer for the final cart prototype.

We recognize that these testing results are not entirely accurate because the safety factor of the reference cart is less than 1. Because the safety factor is a ratio of the working stress over yield stress, the design as shown by Fusion 360 fails because the analysis shows that the yield stress is greater than the working stress. This is likely due to meshing issues with Fusion 360. Based on our results from the physical tests for the first prototype that are described later in the report, the cart does not fail in these stress conditions. Therefore, we evaluated the safety factor parameter results while keeping this limitation in mind.

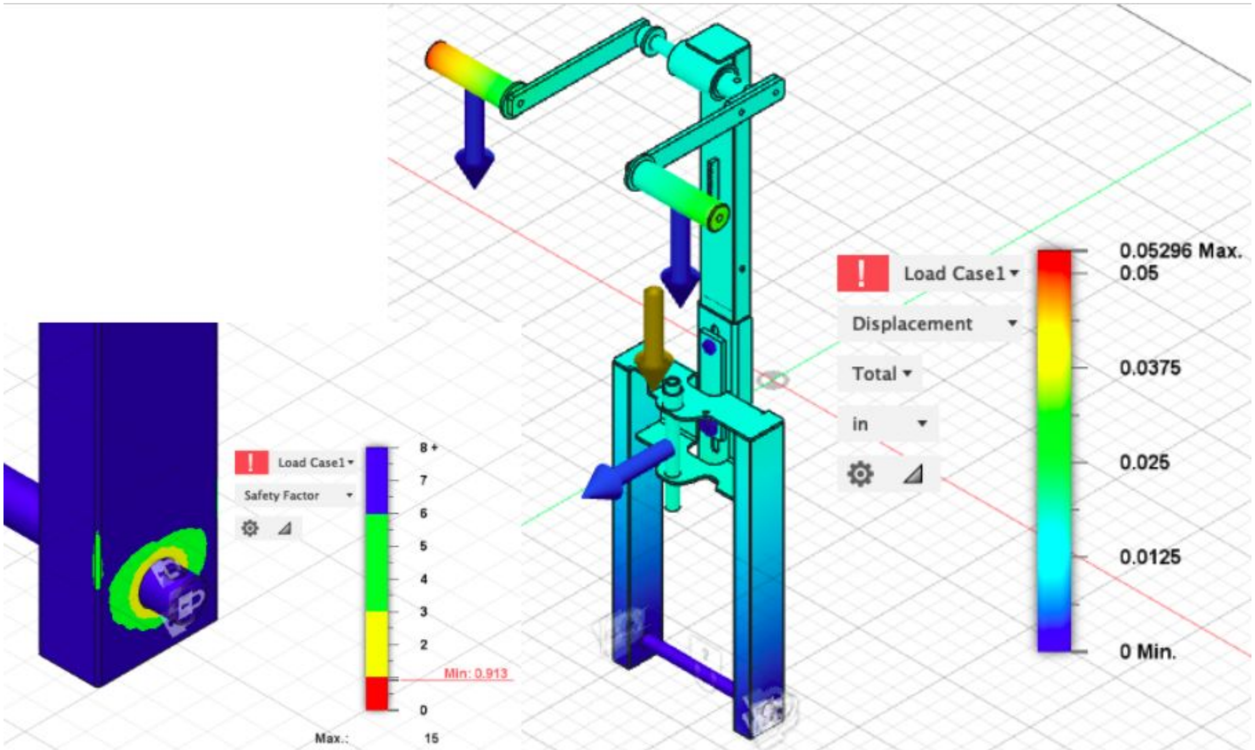


Figure 14: Deflection results for reference tractor on the right and maximum stress location on the left in Fusion 360 simulation

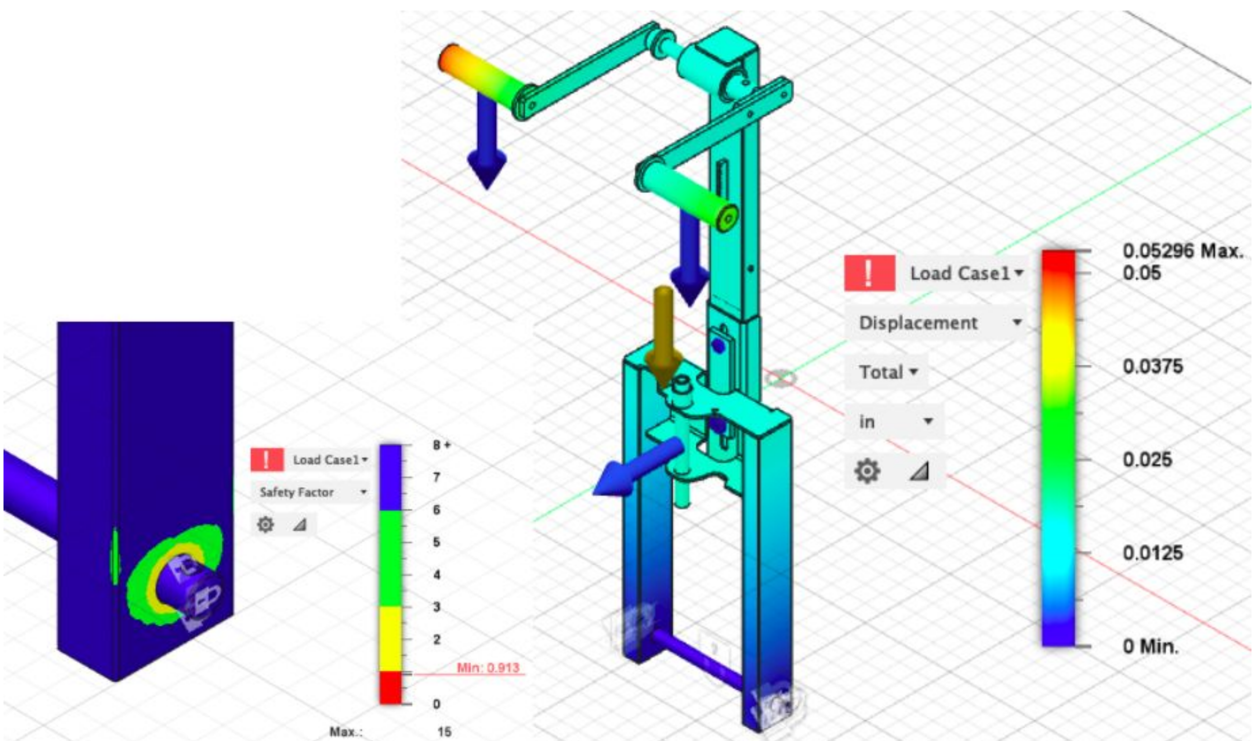


Figure 15: Deflection results for prototype tractor on the right and maximum stress location on the left in Fusion 360 simulation

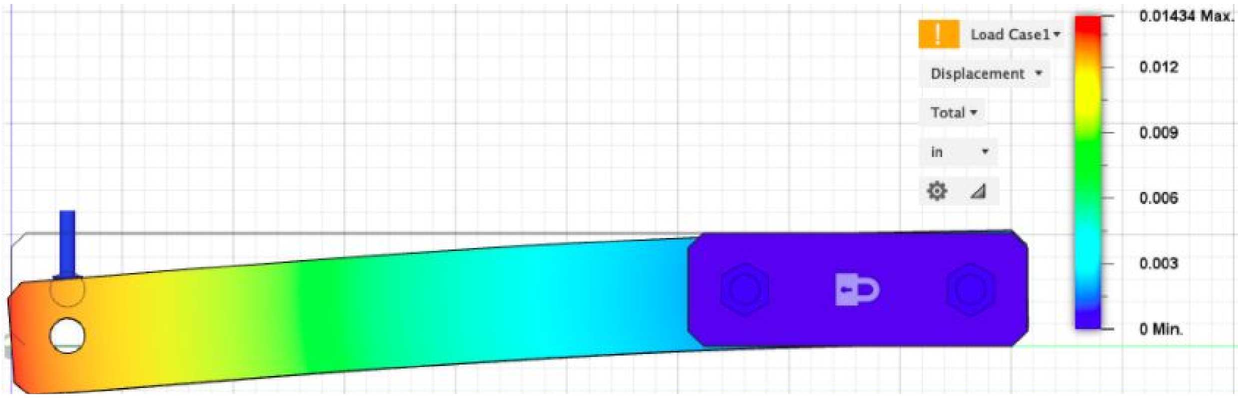


Figure 16: Deflection results for reference tractor handlebar in Fusion 360 simulation

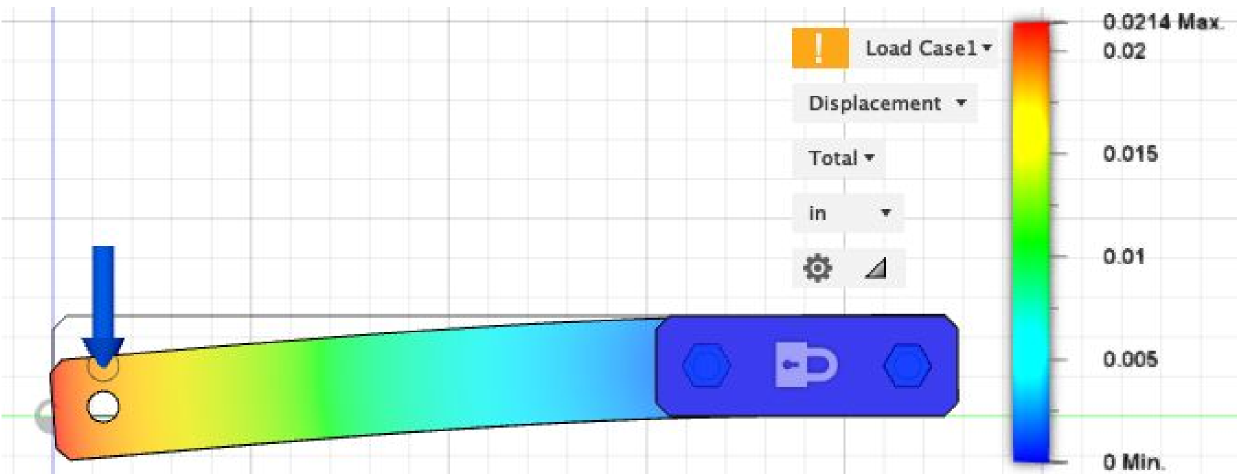


Figure 17: Deflection results for prototype tractor handlebar in Fusion 360 simulation

Table 2: Tractor without wood spacer

	Reference	**No Wood Spacer**
Safety Factor	0.91	0.91
Stress	32.88 ksi	32.88 ksi
Displacement	0.053 in	0.053 in
Weight Saving [lb]	0.00	0.24

Table 3: Tractor handlebar results

	Reference Crank	**Gauge Down Crank**
Safety Factor	1.35	1.31
Stress	153.1 psi	157.6 psi
Displacement	0.014 in	0.021 in
Weight Savings	0.00 lbs	0.31 lbs

Test: Basket Finite Element Analysis

Test Overview

This test compared the final basket designs and the reference basket design under a static load of 335 lbs using the Finite Element Analysis modeling software in Fusion 360.

Objectives

The goal of this test was to compare the safety factor, stress [ksi], and displacement [mils] of the final basket design to the reference basket. This test addressed the requirement that the cart shall be able to hold a person up that weighs up to 335 lbs.

Features Evaluated

This test evaluated the strength of the final basket design.

Test Scope

The test was completed using the Finite Element Analysis modeling software in Fusion 360. We applied a distributed static load to the 'simulation seat', replicating the weight of a 335 lb person sitting on the cart. The most significant obstacle was that wood cannot be simulated in Fusion 360, so MDF was selected as the closests alternate material to use for the wood spacer located inside of the main post of the tractor. MDF is weaker than wood, so this consideration was taken into account while comparing simulation results.

Assumptions

In this test, we placed constraints on the models to approximate the cart's loading conditions. Since the basket gains a significant amount of rigidity from the seat being attached, we assumed that adding a wood piece ('simulation seat') in place of the seat would better replicate the actual behavior of the subsystem. Additionally, we assumed that the use of MDF would accurately depict the behavior of the wood-base components. Unfortunately, pine wood cannot be simulated in Fusion 360 due to its non-uniform properties. Another major assumption that we made was to use contacts to connect the basket pieces. In doing so, the basket bolts are assumed to have perfect, effectively welded, connections at the contact points. This assumption was necessary since the bolt tool did not accurately represent the cart because stress concentrations and maximum deflections occured at bolted locations where the stress would not realistically be concentrated. Another assumption that was made was that the 335 lb load on the 'simulation chair' would accurately represent the distribution of weight a person sitting in a chair, even though a person may not have a uniform distribution of weight across their buttocks.

Test Plan

The instrument that we used for this test is Fusion 360's Finite Element Analysis. Gravity and a 335 lb load was applied to the 'simulation seat' where the force of a person would act. These forces can be seen in Figure 18.

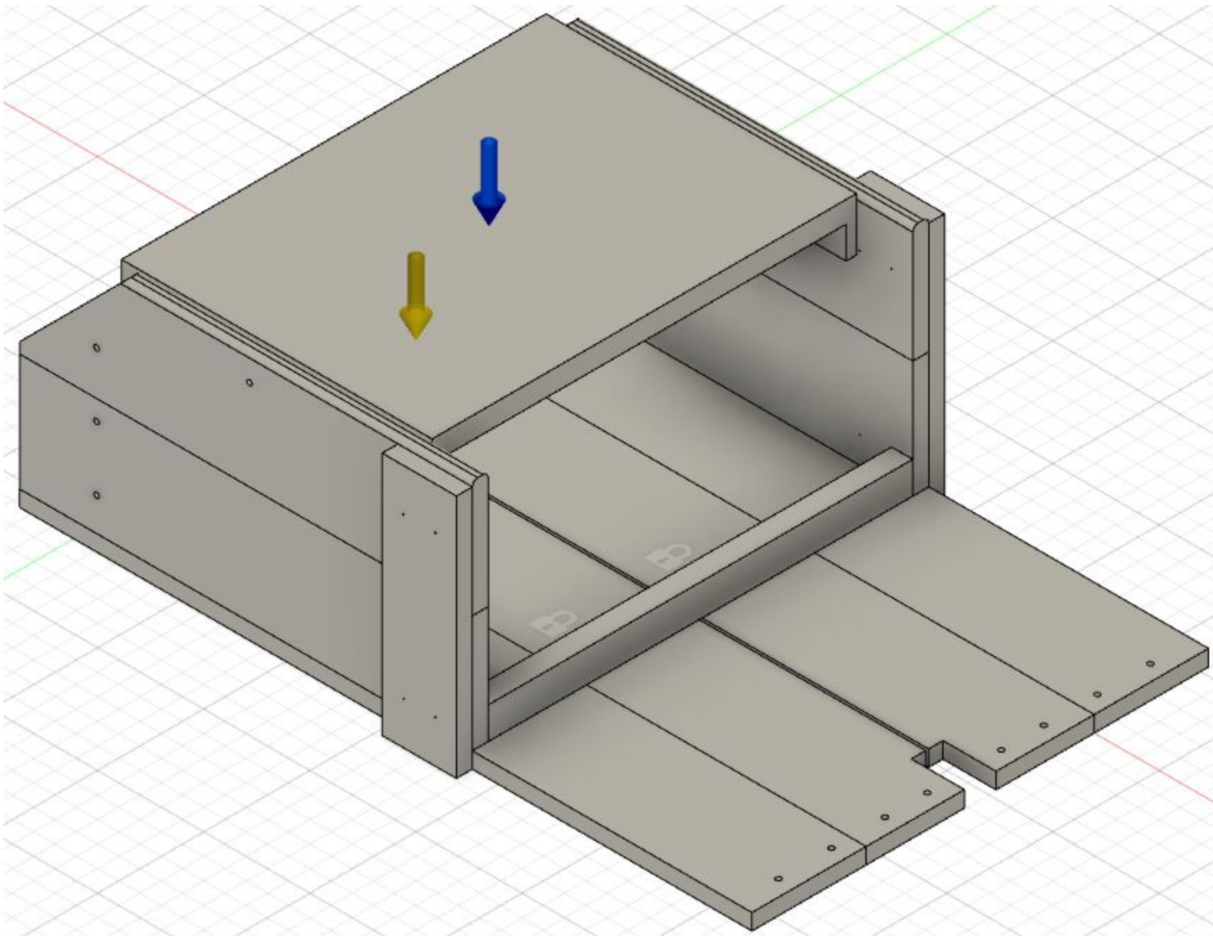


Figure 18: Applied loads on the basket in Fusion 360 simulation where the yellow arrow represents gravity and the blue arrow represents the distributed 335 lb load on the simulation chair bottom

Acceptance Criteria

The final prototype design was considered acceptable if the safety factor, and stress, and displacement were not significantly different from the reference cart.

Test Results & Evaluation

Table 4 shows the comparison of the reference and final basket designs. The overall weight savings for the final basket design is 3.53 lbs based on the Fusion 360 data. The major cause for concern was that both the reference and prototype designs exhibited the most deflection and stress when a distributed load of 335 lbs was placed on the seat; however, we know that the physical chair is capable of supporting this much weight. Based on the material used for the ‘simulation chair’, the overall strength of the basket varied. We decided to make the chair out of MDF and ensure that the basket behaves correctly. After some investigation, we suspected that the bolt tool in Fusion 360 was unreliable, so we used contacts, essentially welding all of the surfaces to one another.

Figures 19 and 20 detail the results from the FEA on the basket, displaying that the final prototype basket has similar behavior and results to the reference cart. The safety factor of 1.117 for the final prototype may seem low, but there are two reasons that we still accept these designs. First of all, because the simulation uses MDF, which is a weaker material, we think that the physical version will be significantly stronger. In the Fusion 360 library, MDF has a yield strength of 1120 psi, and pine has a yield strength of 6000 psi in bending (Tsoumis), the yield strength of wood is direction dependent. Additionally, the point of lowest safety factor and maximum deflection is on the chair, so the safety factor of the actual basket is significantly higher.

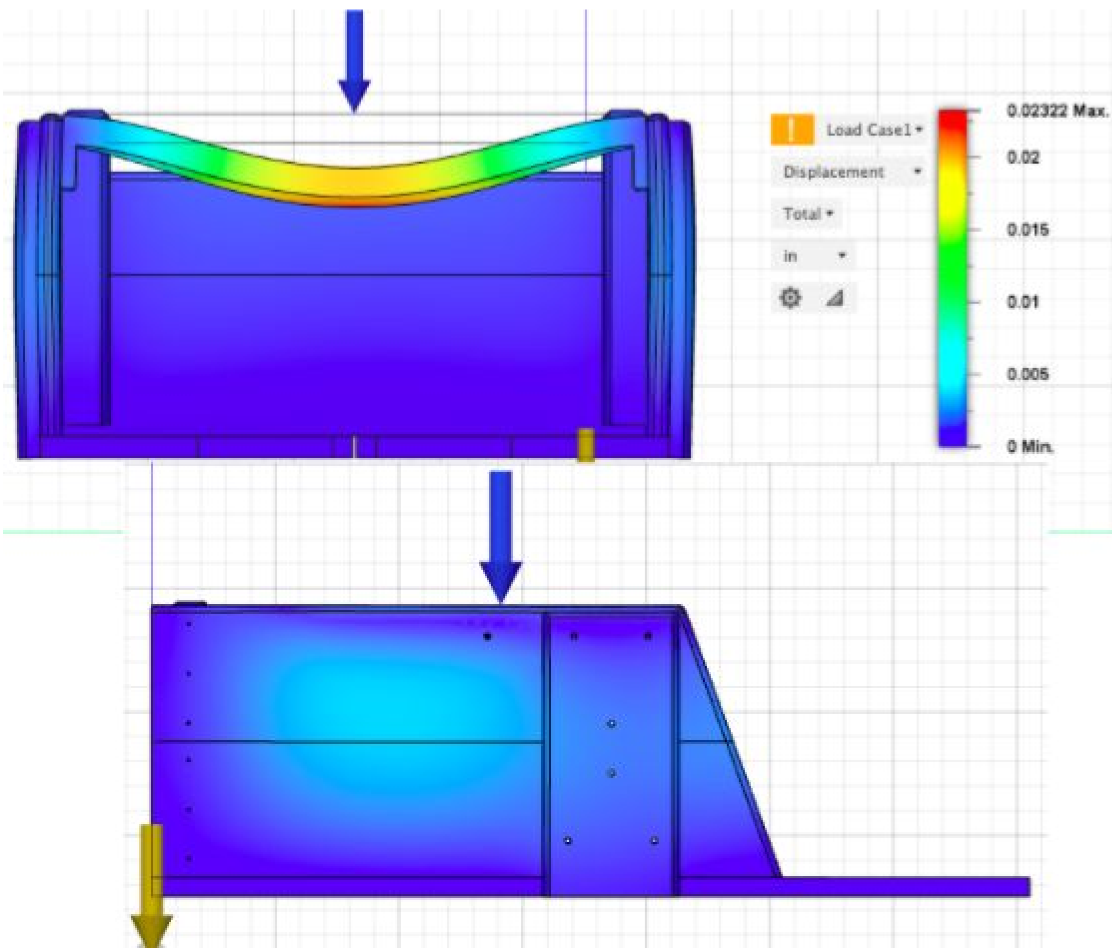


Figure 19: Displacement data from reference basket simulation results

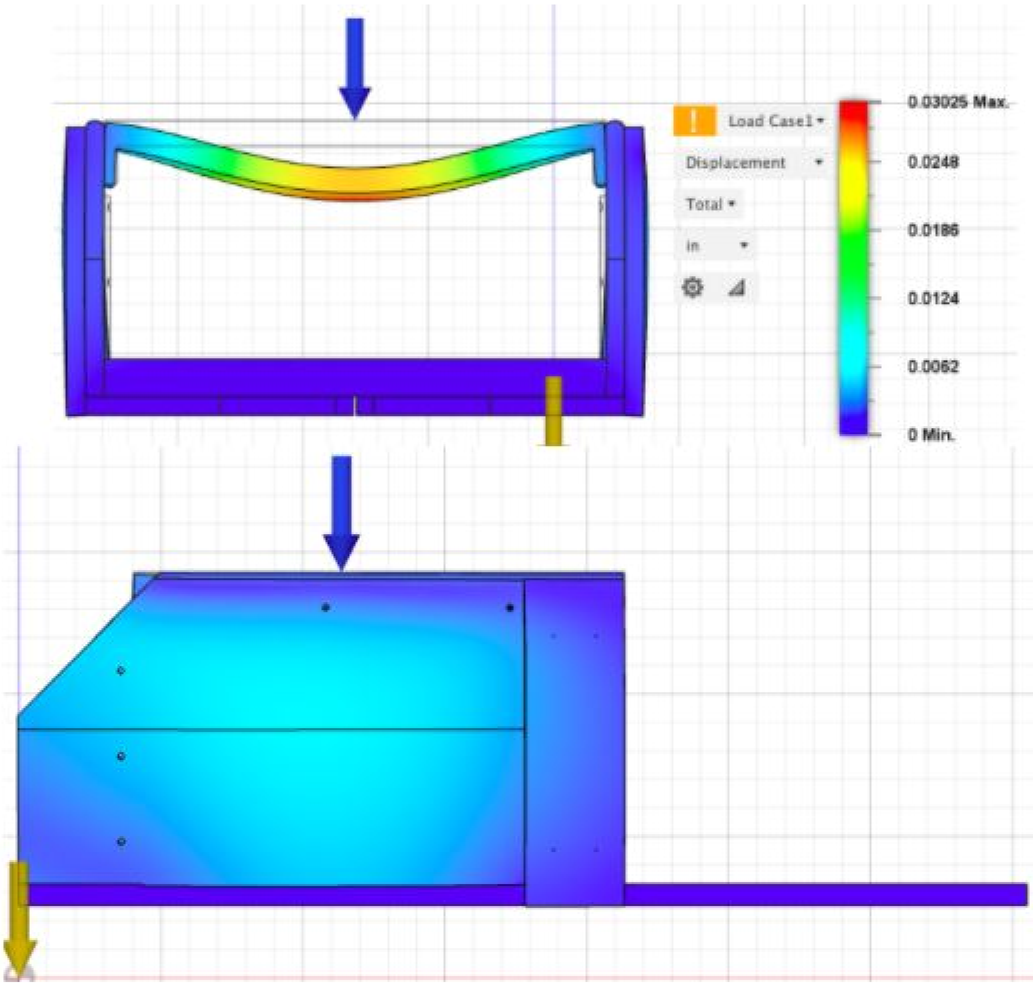


Figure 20: Displacement data from final prototype basket simulation results

Table 4: Comparison of simulation results for the reference and final design basket

	Reference Basket	**Final Design Basket**
Safety Factor	2.623	1.117
Maximum Stress	426.9 psi	5198 psi
Maximum Displacement	0.0232 in	0.0303 in
Weight Savings	0.00 lbs	3.53 lbs

Test: Chair Finite Element Analysis

Test Overview

This test compared the final chair designs and the reference Mobility Worldwide basket design under a static load of 335 lbs using the Finite Element Analysis modeling software in Fusion 360.

Objectives

The goal of this test was to compare the safety factor, stress [ksi], and displacement [mils] of each design to the reference chair and to each other. This test addressed the requirement for the cart's ability to hold a person up that weighs up to 335 lbs.

Features Evaluated

This test evaluated the strength of the chair subsystem.

Test Scope

The test was done using the Finite Element Analysis modeling software in Fusion 360. We applied a distributed static load to the chair, replicating the weight of a 335 lb person sitting on the cart. The most significant obstacle was that wood cannot be simulated in Fusion 360, so MDF was selected as the closests alternate material to use for the wood spacer located inside of the main post of the tractor. MDF is weaker than wood, so this consideration was taken into account while comparing simulation results.

Assumptions

In this test, we assumed that we accurately placed constraints on the models to simulate the real life cart realistically. Additionally, we assumed that the use of MDF would accurately depict the behavior of the system since pine wood cannot be simulated in Fusion 360 due to its non-uniform properties. Another major assumption that we made was that although the chair is bolted, we had to make contacts between them, effectively welding them together. If the bolt tool was used in Fusion 360 for the chair assembly, the stress concentrations and maximum deflections occured at bolted locations where the stress would not realistically be concentrated. Another assumption that was made was that the 335 lb load on the chair would accurately represent the distribution of weight of a person sitting in a chair, even though a person may not have a uniform distribution of weight across their buttocks. Finally, we assumed that a person leaning back on the chair could be simulated by putting an evenly distributed load along the PVC for the final prototype and across the wood seat back for the reference cart.

Test Plan

The instrument that we used for this test is Fusion 360's Finite Element Analysis. We also completed a cost analysis of the different designs. Gravity and a 335 lb load was applied to the chair bottom to simulate a person sitting on the chair. Additionally, a load of 100 lb was applied to the seat back to approximate a person leaning back on the chair. These forces can be seen in Figure 21. The FEA results (safety factor, stress [ksi], and displacement [mils]) based on these forces were used to evaluate the design.

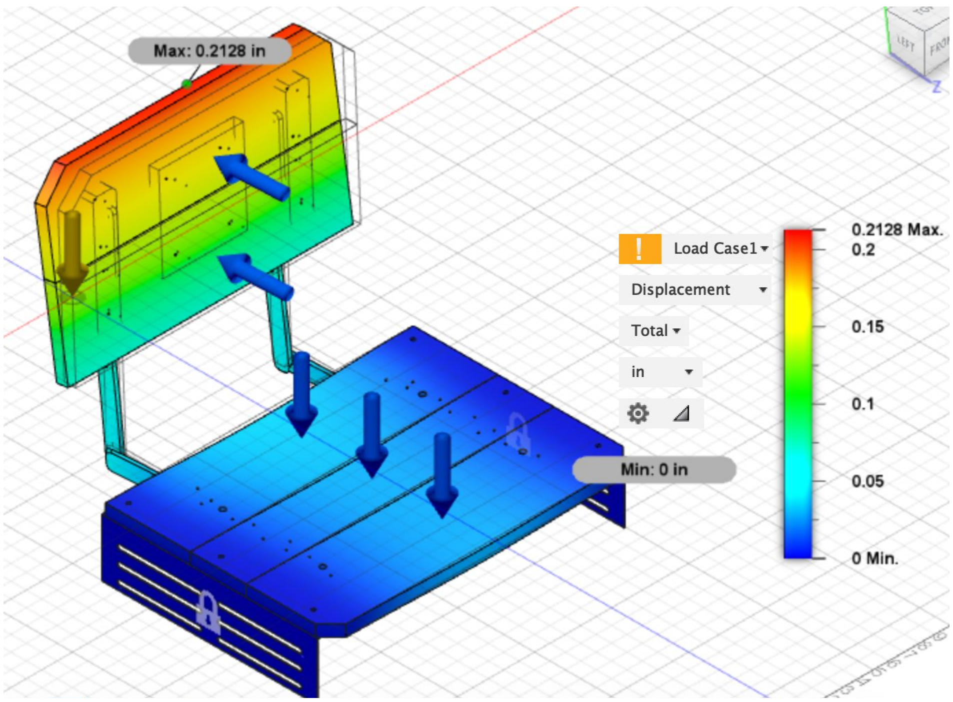


Figure 21: Displacement results with applied loads (335 lb on seat bottom and 100 lb on seat back) on the reference chair in Fusion 360 simulation

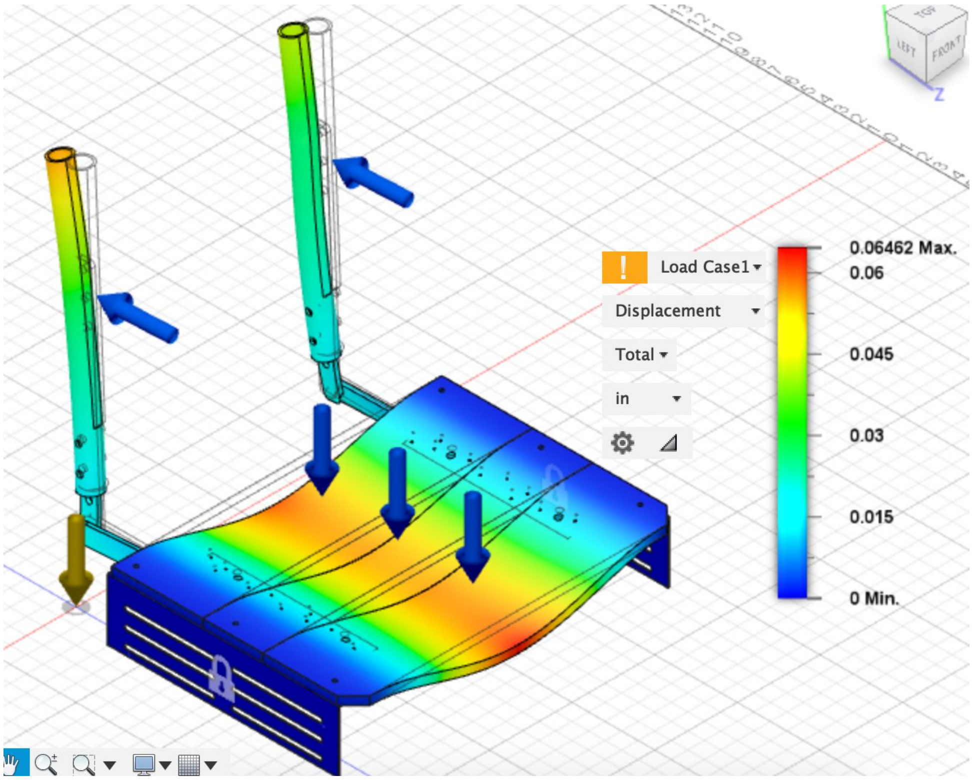


Figure 22: Displacement results with applied loads (335 lb on seat bottom and 100 lb on seat back) on the final prototype chair design in Fusion 360 simulation

Acceptance Criteria

The final prototype design was considered acceptable if the safety factor, and stress, and displacement were not significantly different from the reference cart.

Test Results & Evaluation

Table 5 shows the chair design comparison when a 335 lb distributed load was applied on the seat bottom and there was no load on the seat back. Table 6 shows the chair design comparison when there was a 335 lb distributed load applied on the seat bottom and a 100 lb distributed load on the seat back. For the final prototype chair, the thickness of the chair was decreased from 0.75 inches to 0.5 inches, and the wood back design of the reference cart was replaced with a fabric backing supported with two PVC pipes. The weight savings from this design change is 3.55 lbs. Table 5 compares the seat bottom change in thickness. The safety factor went from 2.869 to 1.525. However, this is an acceptable safety factor, when considering that MDF is significantly weaker than the pine wood that is used in the physical cart. The actual safety factor values are expected to be significantly higher. For the load case seen in Table 6, the final prototype chair design had a slightly higher safety factor and slightly lower displacement. These results demonstrate that the changes to both the seat bottom and the seat back would support a 335 lb person putting a 100 lb load on the seat back. This design was accepted, because it met the requirement for the cart's ability to hold a person up that weighs up to 335 lbs.

Table 5: Chair simulation results for 335 lb force on the chair

	Reference Chair	**Final Prototype Chair**
Safety Factor	2.869	1.525
Stress	12549 psi	14378 psi
Displacement	0.0244 in	0.0651 in
Weight Savings	0.0 lbs	3.55 lbs

Table 6: Chair simulation results for 335 lb force on the chair and 100 lb force on the seat back

	Reference Chair	**Final Prototype Chair**
Safety Factor	1.411	1.473
Stress	18713 psi	15591 psi
Displacement	0.2128 in	0.0646 in

Test: Chassis Finite Element Analysis

Test Overview

This test compared the final chassis designs and the reference Mobility Worldwide basket design under a static load of 335 lbs using the Finite Element Analysis modeling software in Fusion 360.

Objectives

The goal of this test was to compare the safety factor, stress [ksi], and displacement [mils] of each design to the reference chair and to each other. This test addressed the requirement for the cart's ability to hold a person up that weighs up to 335 lbs.

Features Evaluated

This test evaluated the strength of the chassis subsystem.

Test Scope

The test was done using the Finite Element Analysis modeling software in Fusion 360. We applied a distributed static load to the chassis, replicating the weight of a 335 lb person sitting on the cart.

Assumptions

In this test, we assumed that we accurately placed constraints on the models to simulate the real life cart realistically. Another assumption that was made was that the distributed 335 lb load on the main beam and two angle bars of the chassis would accurately represent the distribution of weight of a person sitting on the cart.

Test Plan

The instrument that we used for this test is Fusion 360's Finite Element Analysis. Gravity and a 335 lb load was applied to the chassis, where the force from the person and the cart would be translated onto the chassis from the basket. These loads on the chassis can be seen in Figure 23. The simulation results (safety factor, stress [ksi], and displacement [mils]) based on these forces were used to evaluate the design.

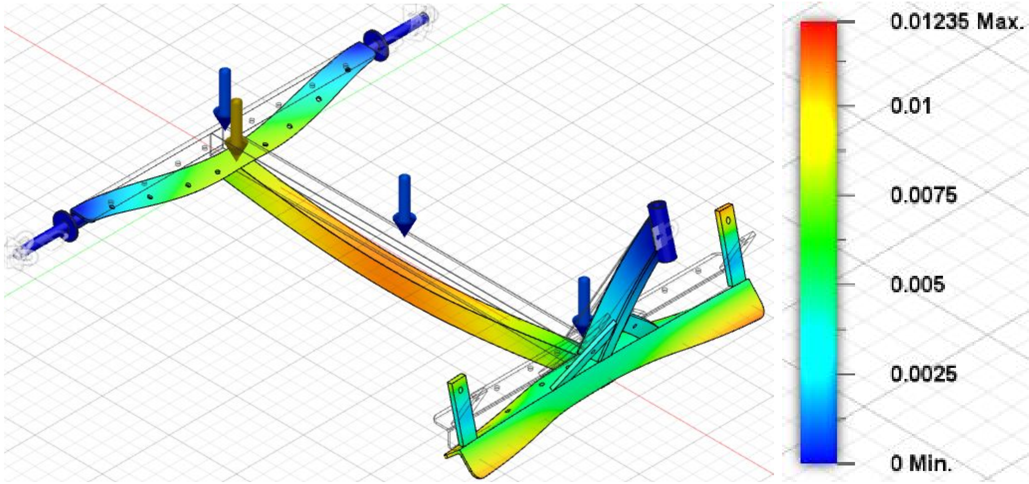


Figure 23: Deflection results in inches for the reference chassis in Fusion 360 simulation

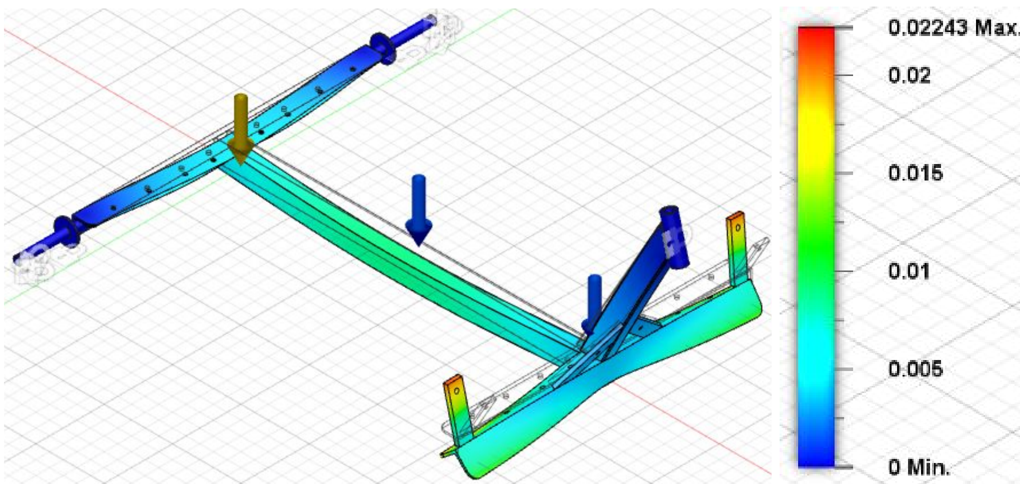


Figure 24: Deflection results in inches for the prototype chassis in Fusion 360 simulation

Acceptance Criteria

The final prototype design was considered acceptable if the safety factor, and stress, and displacement were not significantly different from the reference cart.

Test Results & Evaluation

Table 7 shows the chassis design comparison. The reference chassis is the original design, and the final prototype chassis is the gauge down on the main beam and the gooseneck. The weight savings from this design change is 0.90 lbs. The safety factor decreased from 2.164 to 1.871. The displacement increased by 0.01 inches. Based on the marginal changes in the safety factor, stress, and displacement, this analysis shows that the cart would support the load of a 335 lb person. This design was accepted, because it met the requirement for the cart's ability to hold a person up that weighs up to 335 lbs.

Table 7: Chassis simulation results

	Reference Chassis	Final Prototype Chassis
Safety Factor	2.164	1.871
Stress	16634 psi	19237 psi
Displacement	0.0124 in	0.0224 in
Weight Savings	0.0 lbs	0.90 lbs

Test: Complete Cart Finite Element Analysis

Test Overview

This test compared the reference cart with the final prototype cart, both under a static load of 335 lbs using Fusion 360.

Objectives

The goal of this test was to compare the safety factor, stress [ksi], and displacement [in] of the final cart to the prototype cart. This test addressed the requirement that the cart shall be able to hold a person up that weighs up to 335 lbs.

Features Evaluated

This test evaluated the strength of the whole cart.

Test Scope

The test was done using the Finite Element Analysis modeling software in Fusion 360. We applied a distributed static load of 335 lb to the cart in addition to the force of gravity. The 335 lb was split into a 235 lb load applied to the seat bottom and 100 lb applied to the seat back to represent a person sitting on the chair. The scope is limited due to a variety of assumptions discussed below. The two most important assumptions are that the wood in the model had to be replaced with MDF, and that bolting was replaced with surface mates.

Test Plan

The instrument that we used for this test was Fusion 360's Finite Element Analysis. We took the model and replaced the wood components with MDF by changing their material properties in Fusion 360. This was done because Fusion 360 does not allow simulations containing materials with amorphous properties, such as wood. We then assigned the load cases discussed in the test scope. For the fabric back design we put the 100 lb load split across the back support members, which is shown in Figure 25. We then included the effects of gravity and compared the reference cart and final prototype FEA results from Fusion 360, which gives a report showing the safety factor, displacement, and stress along the model.

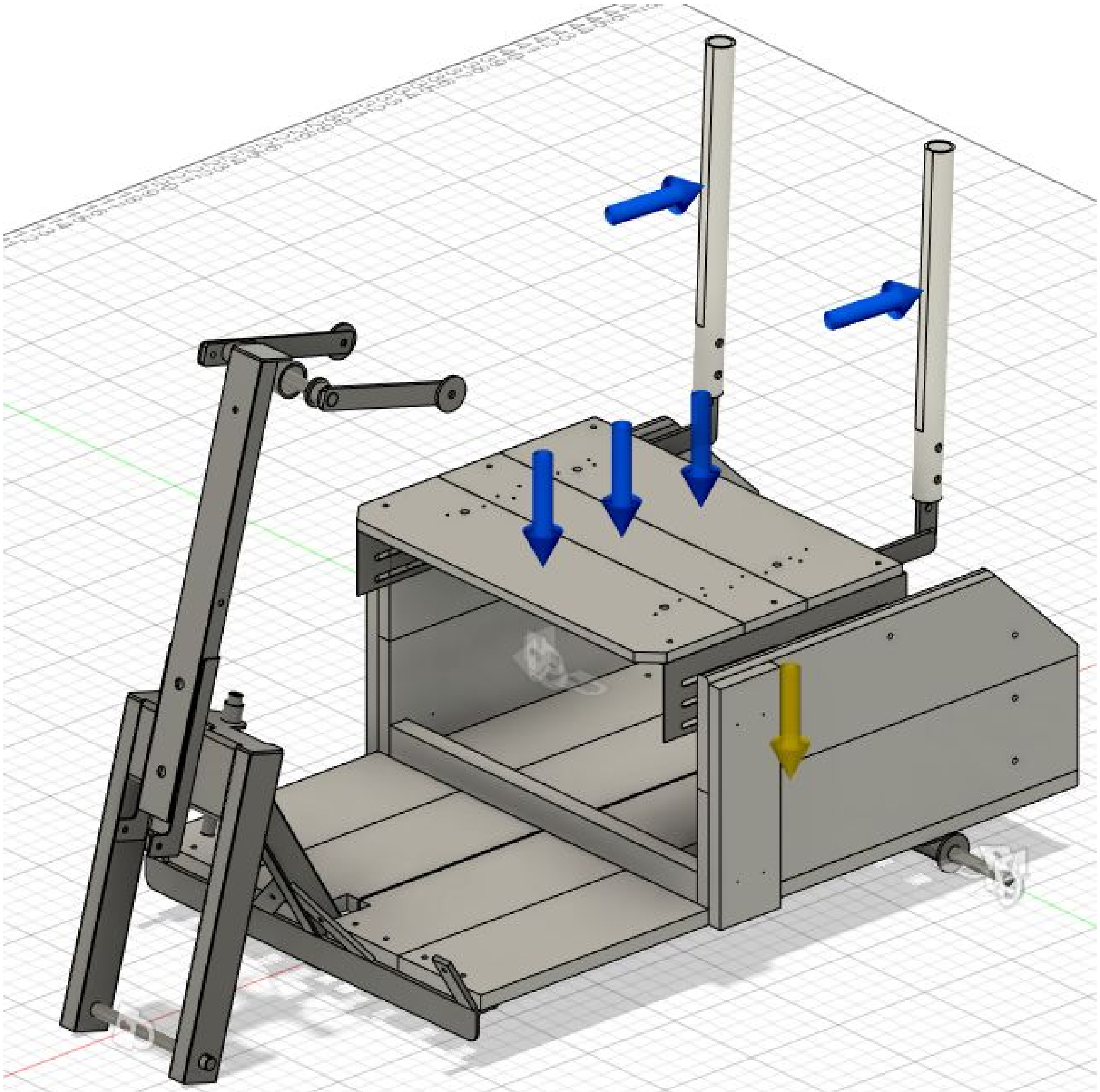


Figure 25: Applied loads on the final prototype cart in Fusion 360 simulation

Assumptions

A key assumption made was that MDF is an acceptable alternative in simulation to wood. This was done because Fusion 360 does not allow simulations with wood because of its non-uniform properties. MDF was chosen because it is known to be weaker than wood, so the safety factor estimates should be conservative. Another assumption that was made is that the bolted areas could be replaced with surface mates, which treat the faces of two contacts as fused together. This was made because the built-in bolt tool of Fusion 360 was causing simulation results that did not match reality. It was found that treating the two surfaces as fused together gave much more realistic deflection behavior. Additionally, we assumed that our constraints on the model simulated the carts realistially. The maximum displacement was 0.23 inches on the tractor facing edge of the seat bottom; in our physical testing of the first prototype, there was no observable deflection. This leads us to believe that the behavior of the carts in simulation is correct, but the magnitude of the results may be off.

Acceptance Criteria

The final prototype design was considered acceptable if the safety factor, and stress, and displacement were not significantly different from the reference cart.

Test Results & Evaluation

The reference cart FEA produced a safety factor of 1.13, a maximum stress value of 31.7 ksi, both located along the metal bracket that connects the chair to the basket, and a maximum displacement of 0.23 inches located at the top of the chair, in the direction of the applied load. The deflection results are shown in Figure 26, from the figure you can see the U-shaped deflection in the chair bottom, and the bending on the back of the chair. These behaviors speak to the validity of the model, as the chair in the cart is expected to have a U-shaped deflection when a distributed load is applied.

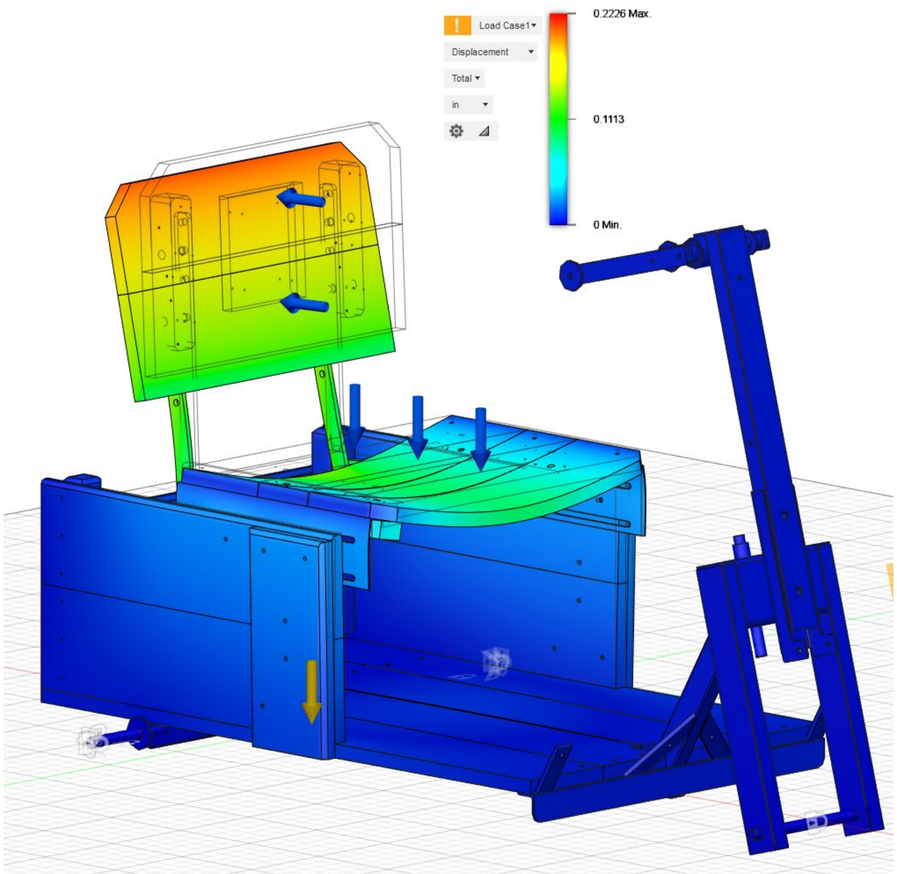


Figure 26: Reference cart deflection in Fusion 360 simulation

The FEA on the final prototype cart showed a safety factor of 0.64 and a maximum stress value of 55.8 ksi that were both located along the metal bracket. The maximum displacement of 0.24 inches was located at the top of the PVC pipe in the direction of the applied load. Figure 27 shows the deflection results of the final prototype. Again there is a U-shaped deflection in the chair, although this time it is a larger deflection, represented in the image as a deeper bend, due to the reduction of material on the seat bottom. This again speaks to the validity of the behavior of the model.

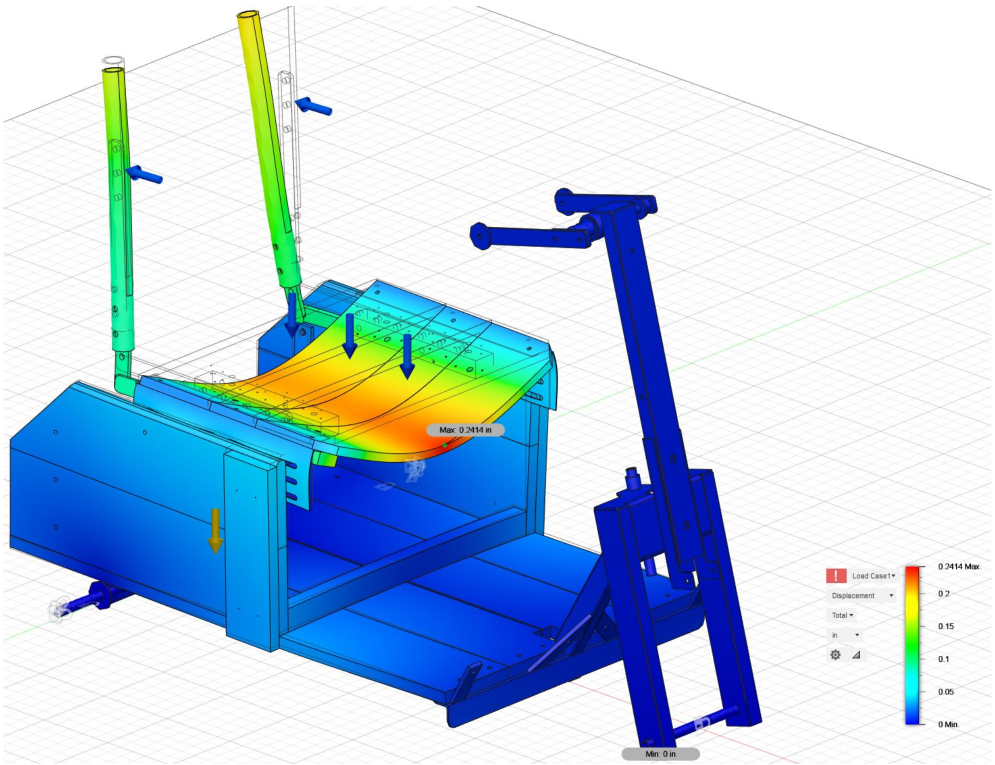


Figure 27: Prototype cart safety factor Fusion 360 simulation

The preceding analysis of this design demonstrates an acceptable level of strength and durability due to two key pieces of evidence. The first being the difference of 0.01 inches of deflection between this cart and the reference cart along the top edge of the seat. Additionally, no observable deflection on the reference cart was encountered in physical testing. The other key piece of evidence is found in Figure 28. This shows the side of the chair where the metal grating is bolted to the wooden sides of the basket. In this image, the red represents an area where there is a low safety factor and a high stress value. This may have resulted from artificial stress concentrations produced by the automatic meshing tool within the FEA package within Fusion 360. To account for this, the minimum safety factor for the seat bottom was calculated at 3.37 for the reference cart and 2.13 for the final prototype. Therefore, we are not as worried about the low safety factor and relatively high stress value.

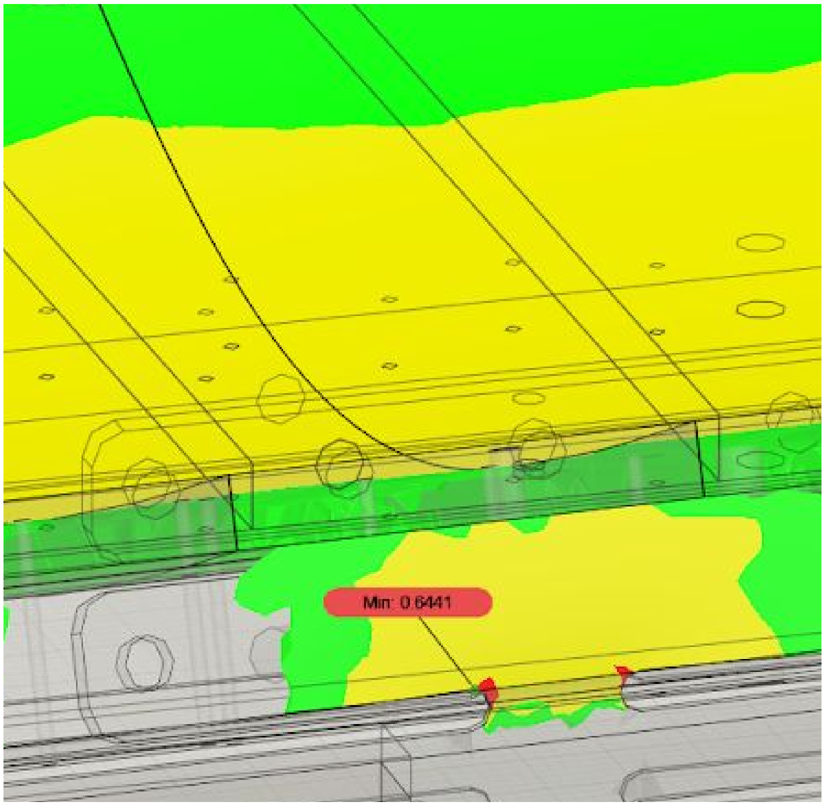


Figure 28: Safety factor close-up of seat connection on final prototype

Test: Static Load Test

Test Overview

The static load test was designed to ensure that the physical cart can hold a static load of 335 lbs without failure. This test was completed for the first prototype and was not able to be completed for the final prototype for the COVID-19 shelter-in-place situation. However, the results of this test for the first prototype are necessary in supporting our simulation results for the final prototype.

Objectives

The objective of this test was to ensure that the prototype cart is able to meet the requirement of supporting a 335 lb static load without noticeable deformation or failure.

Features Evaluated

This test evaluated the whole cart and addressed the requirement that the cart shall be able to hold a person up that weighs up to 335 lbs.

Test Scope

This test evaluated the cart's ability to hold 335 lbs fully on the chair and included a situation where the chair contained 225 lbs and the basket contained 100 lbs. The latter load case represents a situation where a small child or cargo would be in the back of a cart with an adult driving. This plan did not evaluate any failures that may be caused by creep or fatigue.

Test Plan

The reference and first prototype cart were placed on a flat surface. The first test was the application of 335 lbs onto the seat bottom. These weights were pre measured weights from a gym. Any apparent deformations were recorded with the use of a ruler with 1/16 of an inch graduations. Additionally the cart was inspected for any cracks. This process was repeated with 225 lbs on the seat and 100 lbs on the floor of the cart, representing a load in the basket. Any differences in behavior between the reference and the prototype cart was noted. These differences were documented in a testing journal.

Assumptions

An important assumption in this test was that the approximation of a human load by gym weights is appropriate. These gym weights apply their weight uniformly over the face of the weight against the cart, a person sitting in a chair may not have a uniform distribution of weight across their buttocks. A360 lbs total weight was applied in this test, which was a weight 1.5 times greater than the 95th percentile male (“49 CFR Subpart E - Hybrid III Test Dummy”). The loading condition is a conservative estimate that should compensate for not approximating the non-uniformity of typical load conditions. Additionally, any deflections that are not noticeable on a standard ruler with 1/16 of an inch graduations or by the human eye, were considered an acceptable amount of deflection. The finite element analysis results suggest that there would be visible deflections on the order of tenths of an inch before the stress, within the cart, reached the yield stress.

Acceptance Criteria

The first prototype cart was considered acceptable if our ruler measurements show deflections as much as or less than the reference cart. Additionally, the first prototype cart needed to be able to support the 335 lb weight without having any visible cracks or cupping.

Test Results & Evaluation

There was no observed deflection in any part of the cart when placing 360 lbs in the seat of both the first prototype and reference carts. This loading scenario is shown in Figure 29. For the portion of the test when 225 lbs was placed in the seat and 100 lbs was placed in the chair, as shown in Figure 30. Again there was no observed deflection in either cart. Based upon these results, we conclude that both carts can support the static load, therefore, meeting the acceptance criteria.

Since the final prototype was not constructed, this test could not be performed. Since the final design changes the thickness on the wood portions of the seat as well as other features of the cart, this test should be run on the final prototype when constructed.

Figure 29: Prototype cart static load test with 360 lbs of weight on the seat

Figure 30: Prototype cart static load test with 225 lbs of weight on the seat and 100 lb of weight in the basket

Test: Chair Back Static Load Test

Test Overview

This test was designed to evaluate the strength of the chair back.

Objectives

This test ensured that the modified chair design is able to support a user when they lean back in the chair regardless of their weight.

Features Evaluated

This test focused on evaluating the weight capacity of the chair back.

Test Scope

The cart was tilted on its back (the trailer) and weights were set in the center of the seat back. The purpose of this test was to demonstrate an approximation of the weight distribution of a person on the seat back. Additionally, this test examined the integrity of the chair back and the welds that hold the chair in place. Twelve individuals independently sat in the chair and leaned back on the seat back. The feedback from these individuals as well as our observation of the behavior of the seat back allowed us to evaluate the cart design with a more typical weight distribution on the seat back. One limitation is that only qualitative data can be taken when the individuals lean back on the seat.

Test Plan

The test was performed on both the reference and first prototype carts. We placed the cart on its back, creating a 90 degree angle between the chair back and the floor. Weights up to 100 lbs were applied to the middle of the chair back. These weights were obtained from the gym to ensure that the exact weight being applied to the seat back was known. If there were any observed deflections of components (not including the fabric) they were measured using a ruler, comparing the pre and post loaded positions. To do so, a ruler was held at the zero load position and once weight was added, a measurement of the change was recorded. Additionally, the chair was inspected for any cracks. The deflection results of the test were compared between the carts.

In addition, 12 volunteers independently sat in the chair and pressed their weight onto the back of the chair. The chair was then observed for any deflections, cracks, or signs of cupping. We compared the results between the carts.

Assumptions

In completing this test, we assumed that the seat back may have had some slight deflections that we could not see. However, the non-visible deflections incurred by the load were assumed to be insignificant. Additionally, we assumed that the 12 volunteers that leaned against the chair back were an accurate representation of the average Mobility Worldwide cart user.

Acceptance Criteria

In order for the prototype chair to pass this test, it needed to deflect similarly to the chair back on the reference cart within $1/16^{th}$ of an inch as determined by the resolution of a ruler. Additionally, it needed to be able to support the 335 lb weight without showing any signs of cracking or cupping.

Test Results & Evaluation

For the reference cart, 100 lbs was placed on the seat back while the cart was tilted on the back of the basket, and there was not any deflection observed, as seen in Figure 31. As for the first prototype, the 100 lb load was placed across the metal supports to test the welds, as seen in Figure 32. Similarly to the reference cart, the prototype did not experience any deflection. To test the strength of the fabric, 10 lb weights were added directly on the fabric in between the metal supports since the 10 lb plates were smaller, as seen in Figure 33. The fabric could support a weight of 20 lbs before it deflected to the point where it was resting on the floor since the seat was at a 90 degree angle resting a couple of inches from the floor.

Due to the situation surrounding COVID-19 shelter-in-place order, we were not able to physically test the chair back on our final prototype. Based on how the seat back performed in our simulations for the first prototype and the similar behavior for the final prototype, we expect that the final design would have a similar, positive result.

Figure 31: Reference cart with 100 lbs of weight on the chair back

Figure 32: Prototype cart with 100 lbs of weight on the metal supports

Figure 33: Prototype cart with 30 lbs of weight on the fabric

Requirement 11: Cart shall be able to be disassembled and reassembled within the same time duration as the reference cart is met

Test: Assembly/Disassembly Test

Test Overview

This test ensured that the assembly and disassembly of the modified subsystems in the prototype cart takes at most the same amount of time as the reference cart. Due to the COVID-19 shelter-in-place order, this test was not completed for the final prototype. However, it was completed for the first physical prototype.

Objectives

This test evaluated the requirement for the first prototype cart to be able to be disassembled and reassembled within the same time duration as the reference cart.

Features Evaluated

This test evaluated the modified subsystems on the cart and addressed the requirement that the cart must be able to be disassembled and reassembled within the same time duration as the reference cart.

Test Scope

For this test, we compared the assembly time of modified subcomponents. The subcomponents that were not evaluated were the tractor and the chassis since the modifications (decreasing gauge size) did not significantly change the assembly procedure of the subcomponent. The assembly portion of the test was only focused on the assembly duration for the completed components of each subsystem, disregarding the time to fabricate each component. The disassembly portion of the test recorded the duration of disassembly of the cart.

Test Plan

One member of the Cartologists assembled the reference cart and modified components. The first part of this test evaluated the design changes that were deemed to have a significant effect on assembly time, which included all changes except those made to the tractor and chassis parts (decreasing the gauge). A stopwatch was used to compare the assembly time of each design change on the first prototype and reference carts to isolate the time difference for each design change.

The second portion of this test assessed the disassembly of the cart. A stopwatch was used to measure the time it took to disassemble the reference and the first prototype carts.

Assumptions

In this test, we assumed that the speed at which the team member assembled and disassembled was roughly equivalent to the speed of an average volunteer. We also assumed that the chassis and the tractor assembly and disassembly durations would not be significantly different, because the changes on those subsystems were reducing gauges and removing the wood spacer.

Acceptance Criteria

If the modified components took the same or less time to assemble than the reference components, the design was considered acceptable. If the first prototype cart could be disassembled for shipping in the same or less time than the reference cart, then it was considered acceptable.

Test Results & Evaluation

For the assembly/disassembly test, we chose to test the modified chair back and the basket. The other design changes such as the gauge of the chassis main beam were determined to have a negligible effect on the assembly/disassembly time. The first prototype chair back took 1.03 seconds to disassemble while the reference chair back took 3 minutes and 40 seconds to assemble. During assembly, the first prototype chair back took 2.83 seconds and the reference chair back took 4 minutes and 5 seconds. Overall, the first prototype chair back took a significantly shorter amount of time than the reference chair back to assemble and disassemble.

Disassembling the back of the basket and posts on the reference cart took 4 minutes and 5 seconds, while removing the same portion of the first prototype cart with the L-brackets took 3 minutes. Assembling the back of the reference cart took 7 minutes and 55 seconds, while the back of the first prototype cart took 4 minutes. The first prototype assembly and disassembly took a shorter amount of time than the reference cart.

Since the modified components took less time to assemble and disassemble than the reference components, the first prototype passed the test. Due to the COVID-19 shelter-in-place order, this test was not completed for the final prototype. However, based on the results from the first prototype test and the changes that we made from the first prototype to the final prototype, we think that the final prototype would have similar results. This test should still be performed with the final prototype once the COVID -19 situation slows down and the final prototype can be built physically.

Requirements:

- **12: Cart shall use a hand cranked design for locomotion.**
- **13: Cart shall be able to be driven in reverse.**
- **14: Cart seats shall be cushioned to lengthen time of 'comfortable' use of the cart.**

Test: Comfort and Maneuverability Test

Test Overview

This test qualitatively measured the comfort and maneuverability of the cart.

Objectives

This test addressed the following requirements:

- Cart shall use a hand cranked design for locomotion.
- Cart shall be able to be driven in reverse.
- Cart seats shall be cushioned to lengthen time of 'comfortable' use of the cart.

Features Evaluated

This test evaluated the whole cart with a focus on the seat comfort and cart maneuverability.

Test Scope

Since comfort is a subjective variable, the test collected qualitative data comparing the reference and modified carts on their respective comfort levels. A Google form was distributed to at least 10 volunteers.

Test Plan

An obstacle course including turns, hills, bumps, dirt, and concrete was developed. The course also included driving in reverse and braking. All 12 volunteers drove both the prototype and the reference cart through the course. After they completed the course with both carts, we sent them a Google form asking for their height and weight as well as additional questions comparing the comfort and the ability of the cart to be driven in reverse and be operated by a hand crank.

Assumptions

Because comfort is a subjective variable to measure, we assumed that the survey results would reflect the relative comfort of each cart for comparison. Additionally, we assumed that each participant operated the cart in a uniform manner between each cart with the same understanding of the steering and braking mechanisms as an average Mobility Worldwide cart user. Another assumption we made is that the participants would not skew their qualitative results based on whether they were riding the reference or prototype cart based on differences in color and appearance.

Acceptance Criteria

If the modified cart design was generally perceived to be as comfortable or more comfortable than the reference cart, the design changes were accepted. Additionally, if the modified cart design was deemed as easy or easier to maneuver, then the design changes were accepted.

Test Results & Evaluation

In our survey, everyone answered that the cart was hand crank and could be driven in reverse, therefore satisfying those requirements. Our other requirement was that cart seats shall be cushioned to lengthen time of ‘comfortable’ use of the cart. We noticed that the seat back was too far back to lean on when people are driving the cart. So, we asked people to rank the comfort from 1 to 10, 1 being least comfortable and 10 being most comfortable, with two different questions: “How comfortable was the prototype/reference cart when you leaned on the seat back?” and “How comfortable was the prototype/reference cart throughout the obstacle course?”

Figure 34 shows a boxplot of the comfort data from the obstacle course question. Based on the boxplot, the data is shown to be relatively close, with the medians, the red line, being almost identical. A Kolmogorov-Smirnov test was performed on the data from the obstacle course. With a 95% confidence level, there is not a significant difference between the comfort of the reference and the prototype carts on the obstacle course.

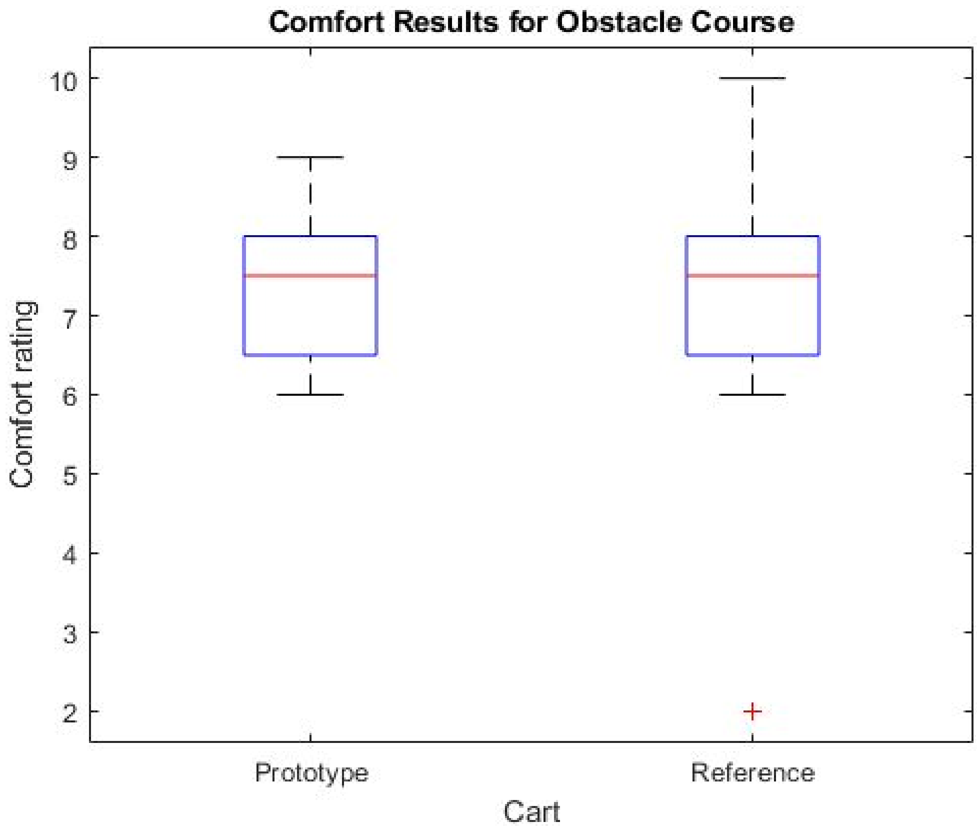


Figure 34: Survey results for obstacle course

Figure 35 shows a box plot of the comfort data from the seat back question. In the box plot, the medians are significantly different from each other, with the comfort level of the reference cart being higher or more comfortable. A one-sided paired-sample t-test was performed to compare the responses. With a 95% confidence level, the first prototype seat back was determined to be significantly less comfortable then the reference cart.

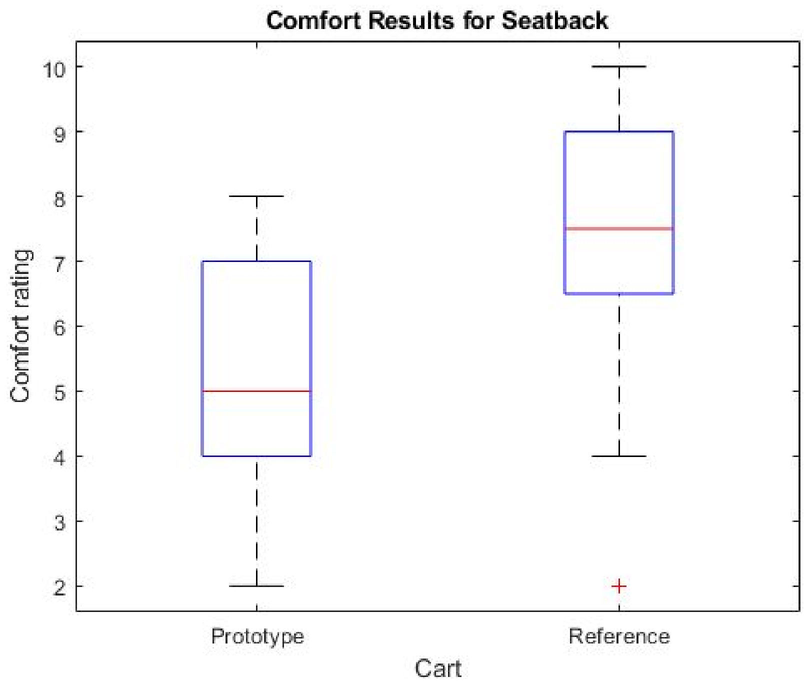


Figure 35: Survey results for seat back comfort

Figures B.1 through B.4 in Appendix B show the survey results for the 12 participants that drove the cart through the obstacle course. These results show that throughout the obstacle course, the pink (reference) and blue (first prototype) seat bottoms were not significantly different in comfort levels on average. However, when leaning back on the seat back, the first prototype cart was significantly less comfortable than the reference cart.

Due to the situation surrounding the COVID-19 shelter-in-place order, we were not able to physically test the comfort and maneuverability of our final prototype. Based on how the subsystems performed in our simulations for the first prototype and the similar behavior for the final prototype, we expect that the final design would have a similar, positive result. Additionally, the major complaint regarding our first prototype was that the chair back was not high enough or wide enough to support the rider's back. In our final prototype, we took this into account and increased the surface area of the chair back from 138 in^2 on the first prototype to 184 in^2 on the final prototype cart.

<u>Requirement 15: Cart shall have equal braking distances to the reference cart on both flat and inclined surfaces.</u>

Test: Braking Test

Test Overview

This test demonstrated that the prototype cart has similar braking characteristics to the reference cart.

Objectives

The test evaluated the requirement that the prototype cart has an equal braking distance to the reference cart on a flat surface.

Features Evaluated

The test evaluated the tractor subsystem and more specifically the braking system.

Test Scope

In this test the reference and prototype cart were set on a flat surface. The grade of the flat surface was unknown but not relevant when comparing the performance of the carts on the same surface. An attempt to make the velocity of the cart consistent was made by having the operator of the cart turn the hand crank the same number of times and at the same rate, before engaging the brake.

Test Plan

For this test an indicator ,in the form of an indentation on the ground, and a measuring tape were used. The cart was accelerated up to speed, and when the front wheel of the cart crossed the indicator, the brake was applied. The distance from the indicator to the front wheel of the stopped cart was measured to determine the braking distance. An attempt to make the cart's speed consistent each run was made by using the same driver, and having that driver turn the hand crank the same number of times. Additionally, the driver started each run from a specified starting location. The same driver was used to perform the test with the first prototype cart and the reference cart provided by Mobility Worldwide.

Assumptions

An assumption was that the relative braking performance between the carts could be maintained between a flat and inclined surface. Another assumption was that the velocity of a cart between runs could be maintained to a reasonable level by the cart's driver. We assumed that the cart's driver could reliably hit the brakes each time the cart passed the specified stopping location with a consistent amount of force on the brake. We also assumed that there was no appreciable change in braking behavior during the test. Breaking performance on an inclined surface was not tested due to an oversight by the Cartologists. However, due to the consistency in the behavior of the carts on a flat surface, we assume that we would have similar results on the inclined surface. This test should be performed on both a flat and an inclined surface for the final prototype.

Acceptance Criteria

The relative distance in braking between the reference and prototype cart was used to evaluate the performance of the first prototype cart. If the first prototype cart stopped either at the same distance as or at a shorter distance than the reference cart, then the first prototype cart was deemed acceptable.

Test Results & Evaluation

For the braking test, the braking distance of the first prototype and reference cart was recorded five times with the same driver (Hanna Rafferty). Table 8, shows the results of the testing, and the Excel calculated mean, standard deviation, and 95% confidence interval values.

Table 8. Data from Braking Test

Braking Test Distance		
Trial	Reference [in]	Prototype [in]
1	7.0	9.5
2	20.5	14.0
3	11.5	12.0
4	13.0	10.0
5	13.5	14.5
Mean:	13.1	12.0
Std Dev:	4.4	2.0
Confidence:	3.8	
95% CI:	9.3	16.9

The braking distance was found, within a 95% confidence, to be 13.1 ± 3.8 inches. Since the first prototype cart's mean braking distance of 12.0 inches falls within this range, its braking is not significantly different than the reference cart. As a result, there was not a significant change in braking behavior between the reference and first prototype carts, so the design modifications were considered acceptable.

This test should be repeated on the final prototype for both a flat and an inclined surface to confirm that our assumption was correct. The final prototype should pass this test as the final prototype is lighter than the first prototype, which should shorten braking distance. Additionally, the final prototype is an inch shorter which changes the center of gravity. Although our finite element analysis predicts the center of gravity to change less than 5/16 of an inch towards the rear of the cart, the braking should still be retested.

Conclusions

The physical testing results from the first prototype and the final prototype FEA were used to evaluate the final prototype. The first prototype was a working prototype, but did not fulfill all of the project objectives, constraints and requirements as stated in the Project Plan. The first prototype met 6 out of the 9 constraints and fulfilled 13 out of 15 requirements. The constraints and requirements that were un-fulfilled addressed the same issues, because the requirements were constraint driven. These constraints and requirements that were not met were:

- that the design must weigh between 10 and 20% lighter than the original cart
- that the material cost per cart shall be at a maximum $300
- that the design must be as comfortable as the original cart

The first prototype was only 6% lighter than the original cart, and had a unit cost that was approximately $2 more. As for the comfort requirement and constraint, users said that the seat bottom was as comfortable as the reference cart, but the seat back of the first prototype was considerably less comfortable than the reference cart.

The final prototype includes most of the design changes from the first prototype, but some designs were changed or added to meet the constraints and requirements that were not met in the first prototype. The weight requirements were met by:

- reducing the thickness of the the seat bottom boards from 0.75 inches to 0.5 inches thick,
- adding a taper to the back of the basket
- reducing the cart length by an inch as measured from front-axle to back-axle

The design changes for the final prototype resulted in a weight savings of 10.14 lbs, which is approximately 10% lighter than the reference cart, satisfying the weight requirement. To meet the comfort requirement, the focus addressed the specific complaints from the users in the comfort test. There were two main complaints about why the seat back was uncomfortable. One was that the metal bars holding the fabric on the seat back were too close together and were digging into users' backs. The other was that the seat back was too low on users' backs.

In an effort to address this issue, the metal posts were moved farther apart, and PVC pipe was attached over the metal bars in order to provide a higher chair back. Additionally, PVC pipe should be more comfortable to lean back on than metal bars because the PVC pipe is rounded. Due to the COVID-19 shelter-in-place order, we were not able to perform physical testing on the final prototype. However, we feel confident that these recommendations for the final prototype should address the comfort issues found with the first prototype.

Once the shelter-in-place order has been rescinded, we recommend re-evaluating the final proposed prototype with similar physical tests presented in this report. If the behavior of the final prototype is satisfactory after these tests, the last design change needed is a method to secure items in the back of the cart. This design change does not affect any load-carrying components. The two methods under consideration are a plate trailer back design and a fabric/mesh trailer back design. Both methods are presented in Appendix C for Mobility Worldwide's assessment.

Overall, the final prototype satisfies all constraints and meets all requirements except for one: the material cost per cart shall be at a maximum $300. The design changes brought the total cost of the cart to $3.50 higher than the reference cart. However, this should not be an issue for two main reasons. First, our sponsor has indicated that the slight cost increase could be deemed acceptable if it reduces weight, and/or adds a valuable feature. The high cost stemmed from the $10 L-brackets. These not only reduce the cart's weight by approximately 1.4 lbs, but they also allow for an openable back on the cart. This means that larger cargo can fit in the storage space, such as a user's crutches. Additionally, the cost should not be an issue since the prices used in the cost analysis were from individually purchased parts from a box hardware store. The actual price of these parts is likely to be less if purchased in bulk from specialty or wholesale retailers. The final prototype has a projected cost 1.2% higher than the reference cart. This is an acceptable cost increase that will not significantly impact Mobility Worldwide's production capabilities.

Thank you to Mobility Worldwide, Mr. Richard Baldwin, and the other San Antonio volunteers for your help and support throughout this project. We sincerely appreciate your assistance in fabricating the first prototype, supplying materials, providing a reference cart, and all of your suggestions along the way.

Appendix A: Setup, Operating, & Safety Instructions

This Appendix covers the changes needed to convert the reference cart provided by Mobility Worldwide to the final prototype. The changes necessary are split by subsystem, and listed below. It should be noted the drawing package contains all of the engineering drawings necessary to construct the cart. "FB" signifies the name of a part in our drawing package that has been modified from the original design, "TU" signifies the name of a part that was added for our design.

Chassis: The chassis modifications are a thinner gauge on the gooseneck and main tube and a reduction in length of an inch, as seen in Figure A.1. To achieve this FB-028 and FB-069 have to be modified. In FB-028 the main tube is modified by cutting it an inch shorter than reference, and reducing the gauge from 14 to 16. The gooseneck is kept the same length but is also reduced from 14 to 16 gauge.

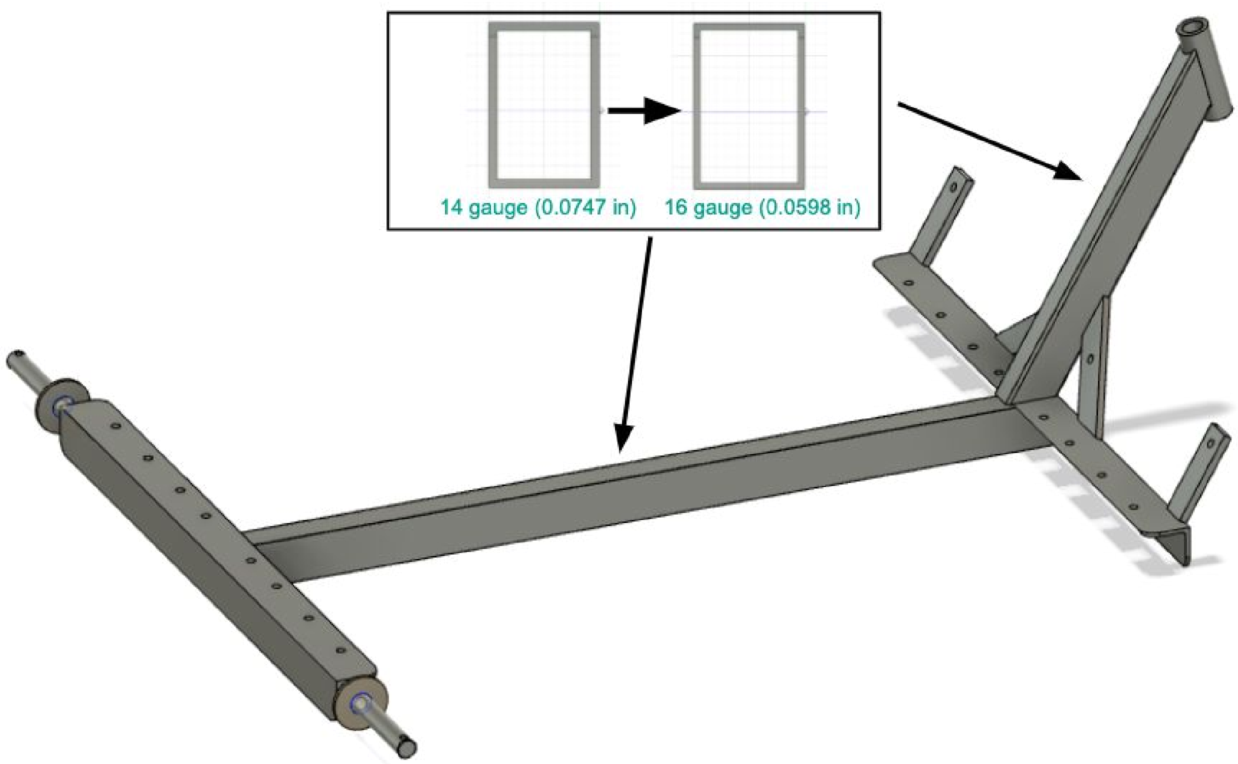


Figure A.1: Decreased gauge size of gooseneck and main beam on chassis

Basket: To construct the basket, the wooden pieces that make up the back of the cart are removed. These are FB-043, FB-078, and FB-079, the wood back posts, wood lower back boards, and wood top back boards respectively. Instead, two L-brackets, TU-003, are placed 3-inches away from the end of the cart, and screwed in as shown in Figure A.2. The floorboards, FB-073, and FB-074, have modified hole positions as shown in the drawing package. A different way to potentially add the L-brackets is to pre drill the holes in FB-073, and FB-074 at the 3-inch away point, and then align the L-brackets. Additionally, as shown in Figure A.2, FB-077 has an angle cut on it to reduce weight. The angle of the cut is 45 degrees from half an inch up on the side of the board. FB-131 the side joiner board is replaced with a wooden 1X4".

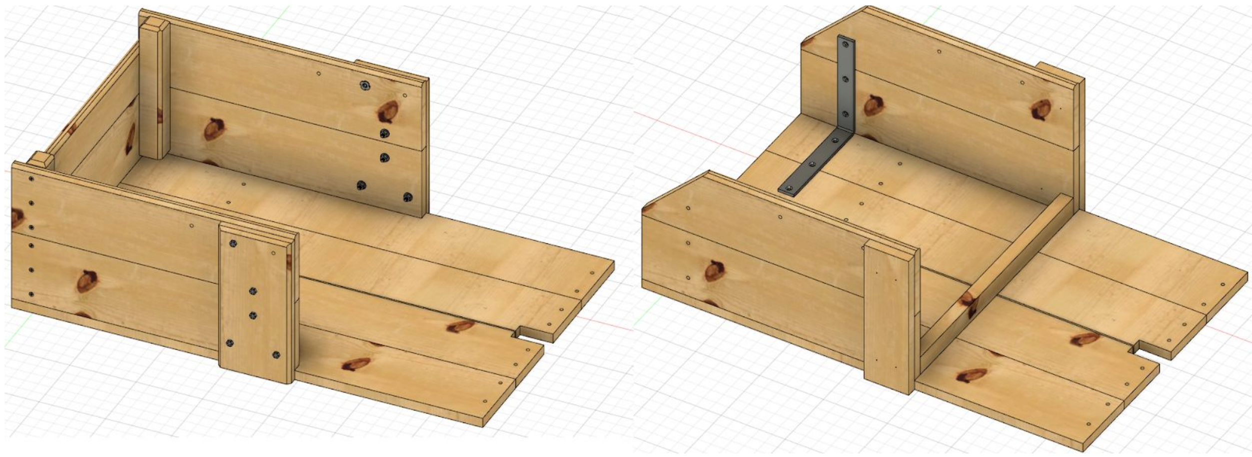


Figure A.2: Basket before and after modification

Tractor: The differences on the tractor are thinner gauge handlebars and the removal of the wood spacer (FB-054). The handlebars have been changed from ¼ inches thick, flat steel bar stock to ⅛ inches thick, shown below in Figure A.3.

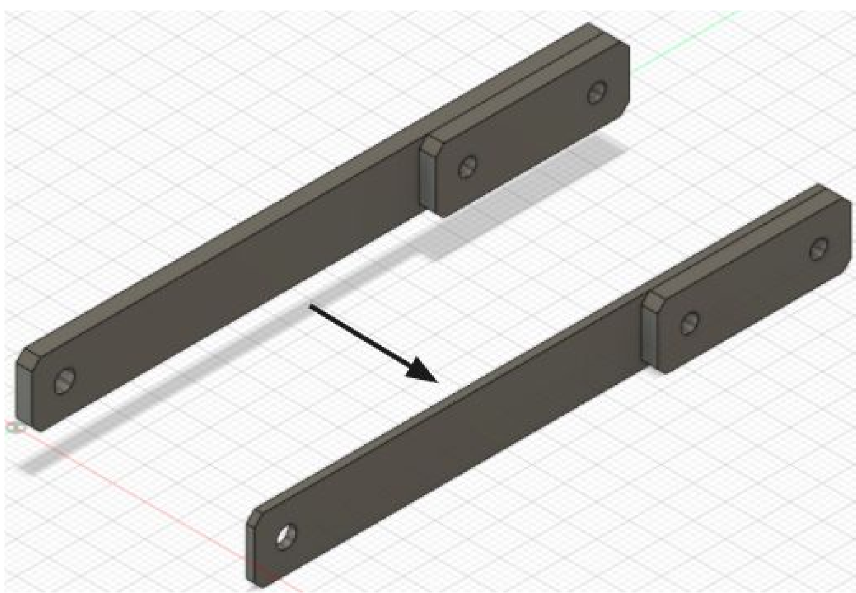


Figure A.3: Handlebar modification

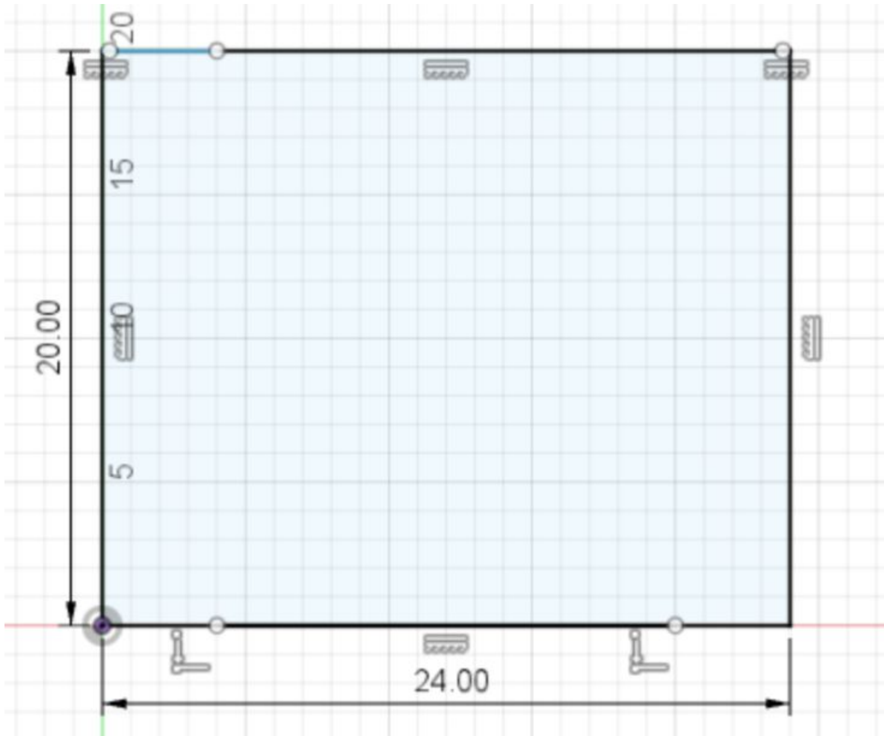
Chair: The differences on the chair are the planed lower boards and the fabric seat back. The three wood pieces that make the bottom of the chair need to be planed from ¾" to ½" thick. The codes for these pieces are FB-061, FB-060, and FB-133. The seat back was modified by taking off all the wooden components that were there previously, and bolting two PVC posts (TU-001) to the metal supports (WD-021 R & L). The chair modifications, except for the fabric, are shown in Figure A.4.

The PVC is bolted on using 1-1/2" bolts with a wingnut to secure the PVC. If cracking becomes an issue, saddle washers can be applied to both sides of the pipe. The bolt is mainly used to keep the pipe in place, preventing rattling and sliding, so the potential for cracking may come from over tightening. A substitute for PVC if it is unable to handle being the chair back is to use metal conduit, this will be slightly heavier but should not crack.

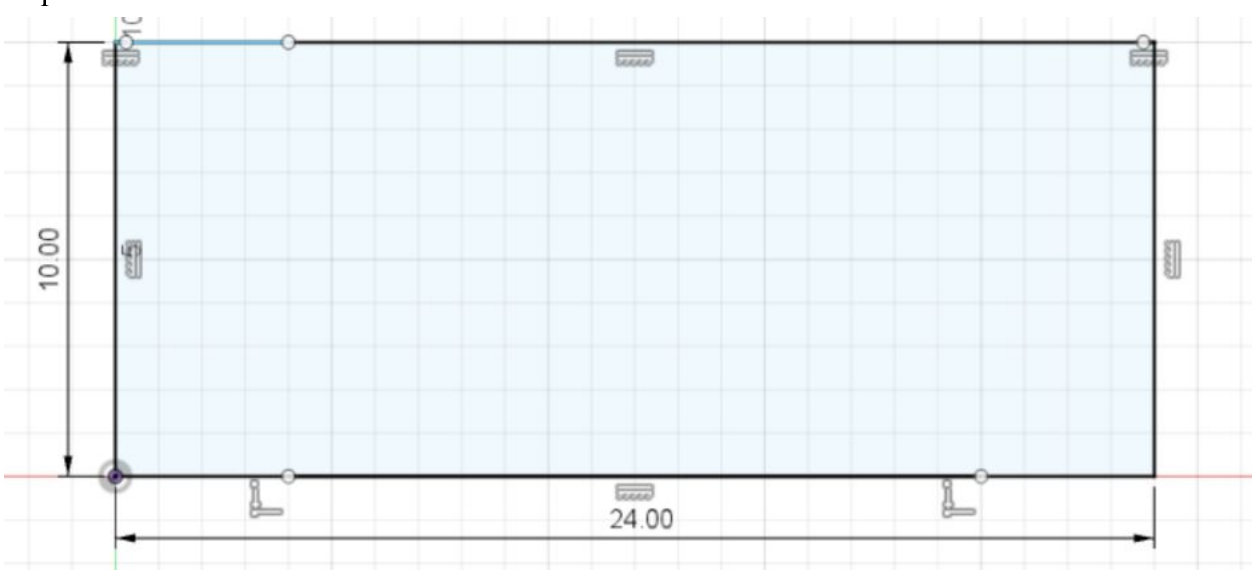
Figure A.4: Final Prototype Chair

Fabric Seat Back Instructions

Step 1: Cut a 20’’ X 24’’ piece of fabric.



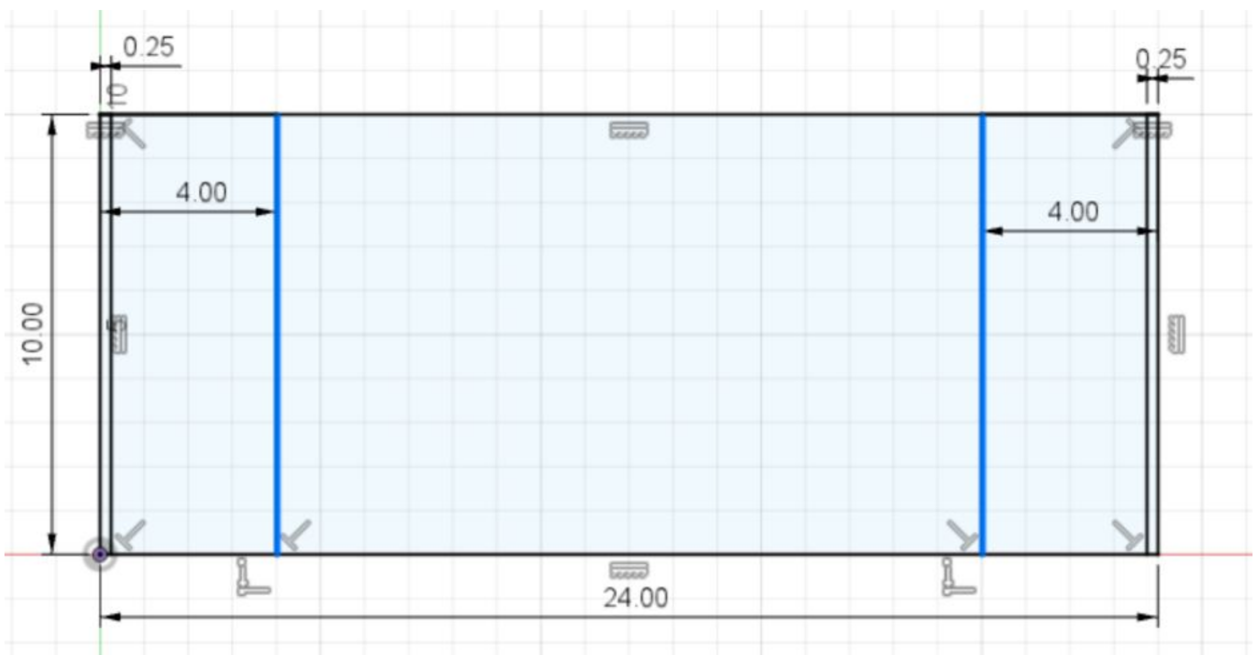
Step 2: Fold the fabric so that the fabric is inside out. The folded fabric will now be 10’’ X 24’’.



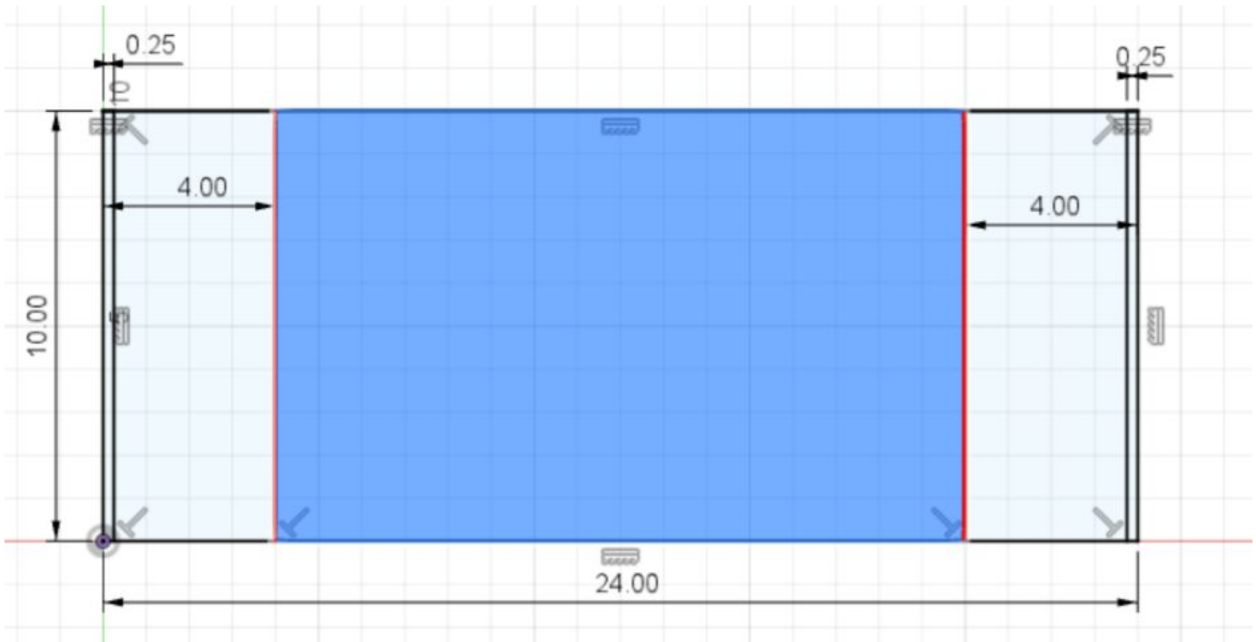
Step 3: Sew along the indicated blue lines. (Approximately 0.25 inches from the edge)

Step 4: Turn the fabric inside out.

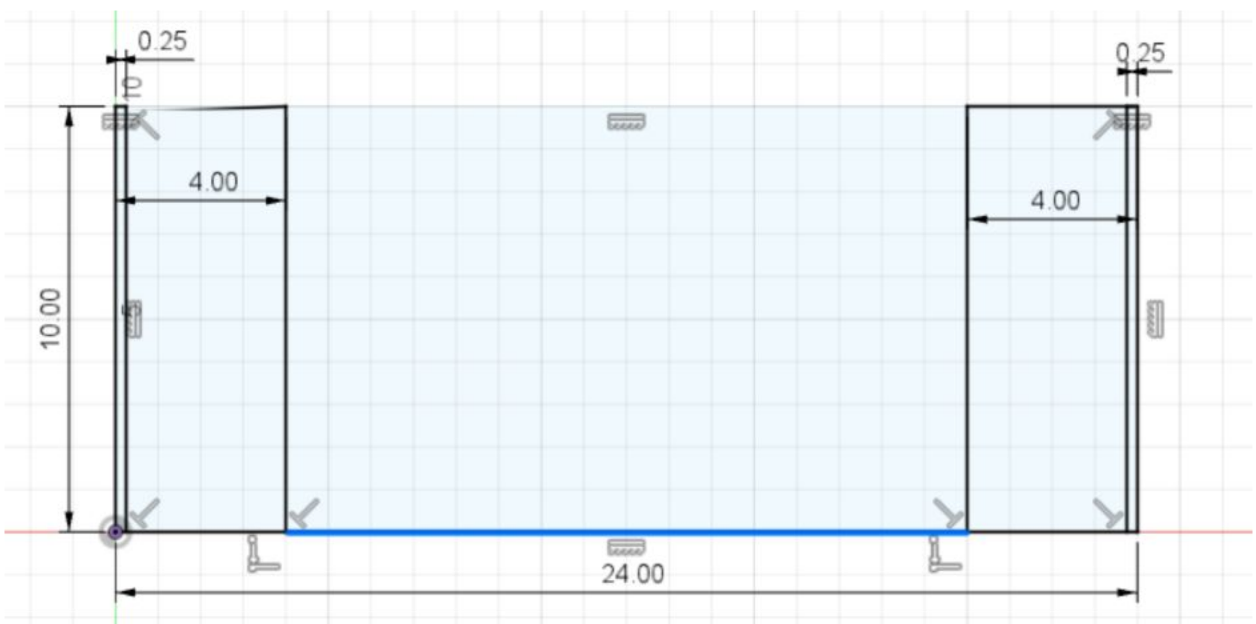
Step 5: Sew along the indicated blue lines. (Approximately 4 inches from the edge)



Step 6: Stuff the center area with cushioning. The center area is indicated by darker blue.



Step 7: Sew along the indicated line to seal the cushioning.



NOTES FOR FABRIC SEAT BACK SEWING INSTRUCTIONS:

- Backstitching should be done to improve the durability of the fabric seat back.
- The measurements are based on numbers from estimations.They will likely need to be adjusted once physical testing is done.

Appendix B - Survey Results for Comfort & Maneuverability Test

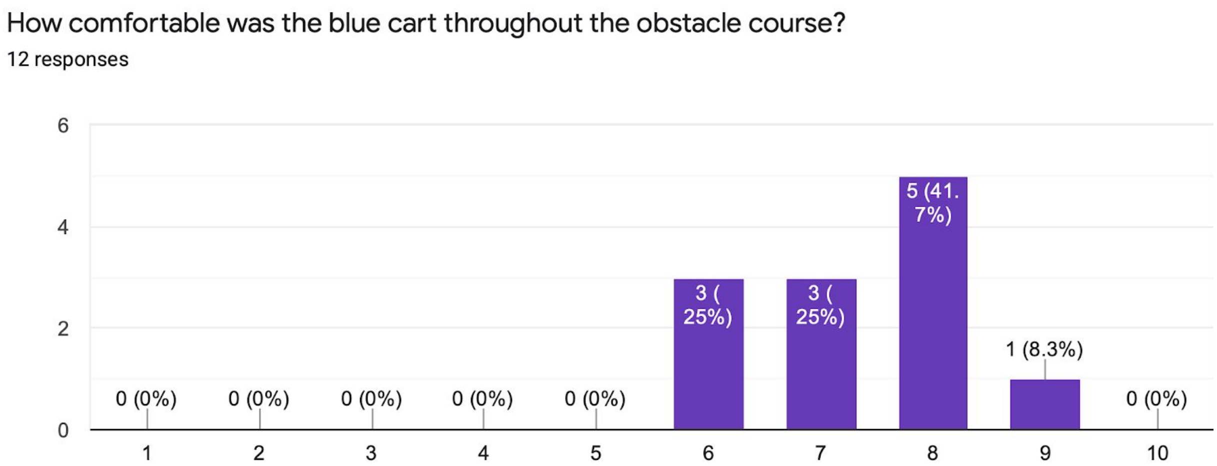


Figure B.1: Survey results for prototype cart

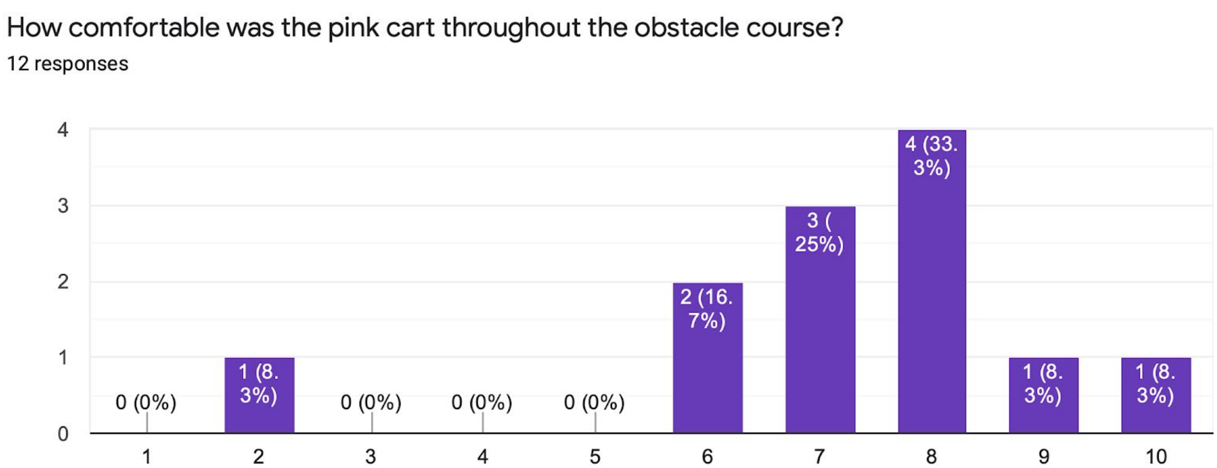


Figure B.2: Survey results for reference cart

How comfortable was the blue cart when you leaned on the seat back?
12 responses

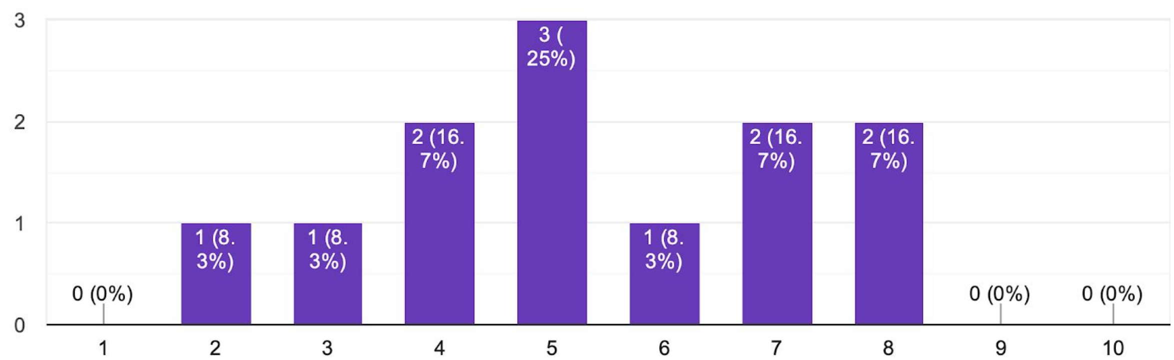


Figure B.3: Survey results for prototype cart

How comfortable was the pink cart when you leaned on the seat back?
12 responses

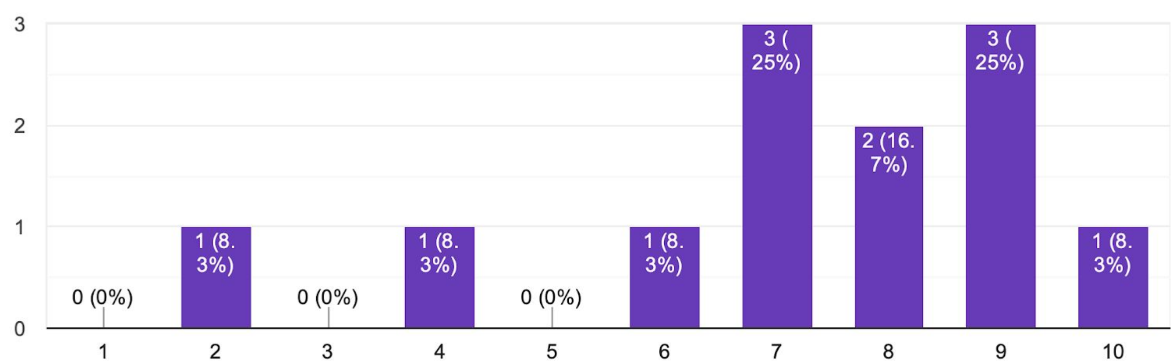


Figure B.4: Survey results for reference cart

Appendix C: Trailer Back Design Options

This section covers some recommendations for securing cargo in the basket of the cart. This is split into two main design types, a solid back plate or a fabric/mesh back.

The design for the solid back plate is shown in Figure C.1. Slots are cut into the wood that makes up the basket using a table saw. Then a plate is placed inside of these slots. The general positives of this design are that it should be sturdy, able to handle some shifting of the cargo, and it should be easily removable. Someone with limited mobility sitting in the chair can easily pull out the plate and lay it in the cart. This is to help in scenarios where someone might be putting an oversized item in the cart, preserving the benefit of having the back of the cart open. The negatives of this design type is that the plate adds different amounts of weight to the cart, depending on the material. Additionally, this design adds areas that could potentially rot (the slots and the plate) if not painted, although the wood is pressure treated. Even if painted, the plate might scratch the paint off with repeated use. Depending on material choice, the plate may break down over time.

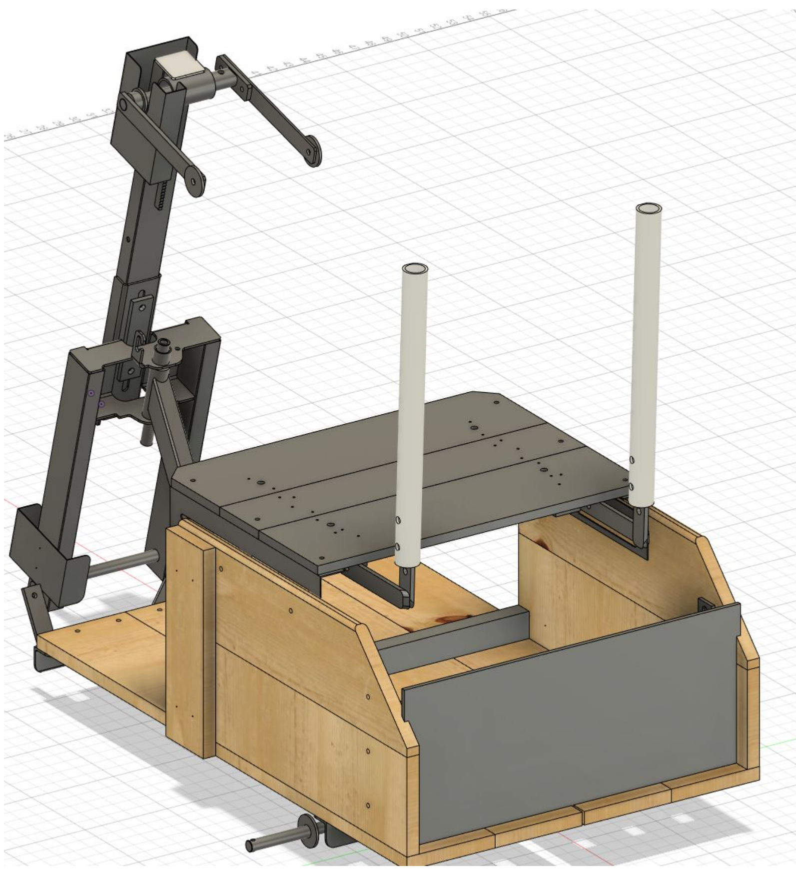


Figure C.1: Backplate Design

For the plate design, there are three materials that have been primarily explored, these materials are plywood, PVC roof paneling, and polycarbonate roof paneling. The back plate size used to calculate the cost and weight numbers is 9 x 25-½ inches, the size of the original cart's wooden backing. This size has not been optimized for functionality and weight. Plywood is an effective material, due to its low cost and high work-ability. The negatives surrounding plywood is that it can break down when subject to rain or a wet environment, would have a limited service life due to weathering and rot, and is relatively heavy. The limited service life of plywood could be mitigated by painting or otherwise sealing the material. Alternatively, the limited service life could be acceptable if it is treated as a replaceable part, due to the relative inexpensiveness of plywood. The cost per plate for ⅜" plywood is around $1.00, adding 1.35 lbs. For ¼" plywood the cost is somewhat greater than $1.00 due to it being slightly more expensive, and it adds 0.9 lbs of weight. PVC Roof Paneling is another choice of material as it is weather resistant and light. The negative is that it would require a wider slot to be cut in the wood, due to its corrugations, and can become brittle under UV radiation. The UV radiation can be mitigated by painting, but with regular use the edges may have the paint wear. It is projected to add 0.32 lbs to the cart but it costs $5.00. Polycarbonate Roof Panels are corrugated like PVC Roof Panels, cost the same amount, and add roughly the same weight 0.31 lbs vs 0.32 lbs. The main advantage is that they do not have UV embrittlement. At this time, looking at either plywood or polycarbonate is recommended.

The fabric/mesh back design involves using fabric or mesh as the securing means for the cargo in the basket of the cart. Doing so would provide a lighter trailer replacement than the plate back, but it might be weaker and less durable than the plate back. Using the fabric or mesh could prevent riders from carrying cargo that is heavier and may rip the fabric tailgate. The fabric/mesh back could be attached either with velcro or with hooks. For the velcro attachment design, one side of the velcro would go along the insides of the basket and the other side of the velcro would go along the fabric. For the hook attachment design, the hooks would be placed at the top of the basket back and where the floorboard and side boards meet. Due to the COVID-19 shelter-in-place order, this design was not fully explored, but the Cartologists think that a fabric/mesh back is a valid option to secure cargo in the basket.

Bibliography (MLA)

"49 CFR Subpart E - Hybrid III Test Dummy." *Legal Information Institute*, Cornell Law School, 25 July 1986, www.law.cornell.edu/cfr/text/49/part-572/subpart-E.

Geyer, Mary, et al. "A Randomized Control Trial to Evaluate Pressure-Reducing Seat Cushions for Elderly Wheelchair Users." *Advances in Skin & Wound Care*, vol. 14, no. 3, 2001, pp. 120–129., https://insights.ovid.com/crossref?an=00129334-200105000-00008.

Tsoumis, George T. *Science and Technology of Wood: Structure, Properties, Utilization*. Van Nostrand Reinhold, 1991.

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<tr><td colspan="3">The undersigned agree that the proposed project is realistic and achievable, and that the team can accomplish the stated goals of the project.</td></tr>
<tr><td></td><td>Date Received</td><td>Date Approved</td></tr>
<tr><td>Team Members:
Sam Mielke
Hanna Rafferty
Anne Wellford</td><td>4/29/2020</td><td>4/29/2020</td></tr>
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