Innovative Cargo Rack Solutions

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by

Travis McCart
Brian Plummer
Whit Ratcliff

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Innovative Cargo Rack Solutions
Final Design Report

by
Travis McCart
Brian Plummer
Whit Ratcliff

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Executive Summary

This report describes the process of designing, building, and testing a lowering mechanism for a roof-mounted SUV cargo box. It provides a detailed problem description and a specific list of requirements that our design must comply with. Existing products and concepts are presented which meet one or more of our design requirements. Six design concepts are discussed and down-selected to three for further development. A final design has been chosen and described in detail. A team management plan is included to specify member responsibilities and a schedule details major deadlines and goals. Manufacturing processes and testing procedures are described in detail. The resulting prototype is discussed, evaluated, and future improvements are presented. Further development of the design is described and conclusions based on the prototype’s performance have been provided.
Chapter 1: Introduction

Problem Statement

SUV roof-mounted cargo boxes enable additional cargo items to be stored above the vehicle in a secure, weather-tight box. Loading these boxes can be difficult, especially if your cargo is difficult to lift or if your vehicle is tall.

A prototype cargo box needs to be developed which enhances accessibility via a mechanism that lowers the carrier to a level where it can be loaded and unloaded while standing on the ground. Also, present cargo rack systems increase the height of the vehicle significantly and can prevent the vehicle from parking in a garage due to vertical interference. A secondary objective for this project is to permit garage parking without requiring the cargo box system to be uninstalled first.

List of Requirements

The following is a list of requirements our sponsor and team feel the cargo rack should be designed around.

- Mechanism weight shall not exceed 45lbs
- Cargo box shall fit 2 large suitcases - 32" X 16" X 19" & have a volume exceeding 11 ft^3
- Mechanism shall not increase vehicle height by more than 6" when in loading configuration
- Shall last at least 10 years with 50 loading cycles per year with minimal maintenance
- Shall withstand wind loads at 60 mph with minimal road noise
- Must be able to translate from loading to stored configuration with 100lbs of cargo
- Shall survive environment temperatures of 32 to 100°F
- Shall withstand a snow load of 20 psf
- When loading, no part of cargo shall be lifted more than 5 ft above ground
- When transitioning from stowed to loading position, the operator shall not be required to exert more than 50 lbs
- Safety factor between design loads and yielding: 2
- Safety factor between design loads and ultimate loads: 3
- Shall only integrate with vehicle without permanent vehicle modifications, such as drilling and bolting through vehicle roof

Design Specifications

We used our list of requirements as well as input from our sponsor to develop the design specifications outlined in Appendix F.
Chapter 2: Background

Existing Products

After extensive research, no existing products or patents could be found which ease loading of roof-mounted cargo racks. However, several products were found which meet a similar purpose. The following is a list of these products.

Yakima EZ Loader Car Roof Rack

Yakima developed a parallel four-bar sliding system for lowering bikes, skis, and cargo boxes off to the side of the vehicle, but never put the product into development because of "irreconcilable engineering issues." The rack would first slide on rails towards the side of the vehicle. As the rack began to pass over the rails, the four bar mechanism would begin lowering the rack until it was in the loading position. Springs and dampers would be incorporated into the four bar linkage to assist the user by reducing the force to operate the rack. The idea behind this product satisfies the basic requirements of this project, but was unsuccessful mechanically.

Figure 2. Yakima EZ Loader

Thule Hullavator

The Hullavator is designed to ease the loading of a kayak onto an SUV. While driving, the kayak is stowed on the roof of the vehicle. In the loading position, the rack sits on the side of the vehicle and the kayak is loaded sideways as seen in Figure 3 below. To transition to the loading position, the kayak rotates 90 degrees away from the vehicle on a constant pivot, and then lowers vertically via a pair of four bar mechanisms. Dampers mounted diagonally inside the four bar mechanisms ease user input and make the device safer. The Hullavator is designed to support a load of 75 pounds. The sideways orientation of the rack in its loading position prevent it from easily being adapted to other applications.

Figure 3. Thule Hullavator
The Safari Condo is a rack which slides to the back of the vehicle and then pivots to the ground. It is designed to carry a variety of items including bikes, cargo boxes and kayaks. When the rack is in its loading position, it is supported by the roof of the vehicle on one side, and the other side has a leg that rests on the ground. This system makes access to one end of the rack much easier however the other end remains at the original height on top of the roof. The angle of the rack could also make it difficult to load.

**Figure 4. Safari Condo**

Off-the-Shelf Product Implementation

Research on existing products and parts has been done to see if it would make sense to use some of these products in our design rather than designing and building them ourselves. Off-the-shelf products may be used when they will reduce manufacturing costs or if the part is too complex to design ourselves. Other companies may have the tooling already set up to create parts that would otherwise cost us too much to manufacture or take too long to manufacture.

**Rack Feet**

Rack feet attach the load bars of the rack to the roof of the vehicle. Thule makes a few different style of feet that will attach their rectangular load bars to practically any roof. Most of these do not require any permanent modification to the vehicle. Making our product compatible with Thule's feet would allow the customer to easily find the parts needed to mount our rack to their specific vehicle. Otherwise, we would have to design different mounting systems for different roofs, which would be time consuming and costly. The critical dimension we must design to in order to use Thule's system is the cross section of the load bar. Thule's load bar is rectangular with a width of 1.3 inches and a height of .96 inches.

**Figure 5. Examples of Thule Feet**
Spring and Damper

A spring and damper will likely be included in the final design in order to reduce the user's input force and control the movement of the cargo box. Using a spring and damper will allow us to control the speed of the box when it is lowering and ensure that it will lower safely. Spring and dampers come in many variations, but the one we would likely use is a gas spring because of its simplicity and availability in different sizes and different forces. A gas spring will need to be sized in order to fit the geometry of our system and to output the required force to assist the user in lifting the box. Gas springs are readily available from companies such as Stabilus and Camloc.

Figure 6. Examples of Spring and Dampers

Other Possibilities

The wheels that roll along the load bar and support the carriage will probably be deep groove sealed ball bearings. These bearings are available in hundreds of sizes and variations so it should be no problem to find the ones that fit our application. Sealed bearings will ensure that the carriage rolls smoothly and they will last a very long time even under load. Some sort of off-the-shelf latching mechanism may be used to secure the rack in its loaded position. Rotary latches are one possibility to perform this function. They would be used with a rotating handle that connects to the latches with rods. When the handle is rotated out, the latches would release, allowing the carriage to move.
Chapter 3: Design Development

Method of Approach

To begin this project, we decided to break the problem down into the major actions that need to be performed and try to come up with solutions for each of them, employing functional decomposition. At the end of this process we developed six system ideas by forming different combinations of these components. We each took two designs and split up to develop them further. These 6 ideas are presented in the ideation section below.

Ideation

During an open-ended brainstorm session, the team arrived at the following list of potential ideas on how a cargo box could translate to a more easily loaded position while minimizing user effort:

Idea #1 – The Slide and Tilt

This mechanism depicted in Appendix D in Figure 34, allows easier access to the cargo box by sliding it behind the vehicle and rotating it down to a lower level. During normal driving, the cargo box is securely stored near the back of the roof on top of the crossbars. When the user wants to lower the box the mechanism slides on the rails towards the rear of the vehicle. As the cargo box clears the back of the vehicle, the support bar rotates back until it reaches a level that...
the user can easily access. Rollers will help the system slide on the rails. A spring and damper will ensure that the cargo box does not rotate too fast, and will assist the user when lifting the box back up.

Idea #2: The Fold-up

This device allows the cargo box to move from the roof to the side of the vehicle to allow easier access to the box as well as allowing the vehicle to be driven into garages with low clearance. A sketch of this concept is shown in Figures 3 and 36 of Appendix D. During normal driving, the cargo box is stored above the roof rack system on the driver's side of the vehicle. When the user wants to lower the box, the device goes through two stages of motion. First, the device rotates from horizontal to vertical about pin joints on the passenger side of the rack. Once the vertical position is reached, the four bar linkage unfolds and lowers the box so that it is along the side of the vehicle. Pressurized cylinders running across the four bar linkage will assist the user when raising the cargo box and prevent it from lowering too quickly.

Idea #3: The Sliding Parallel Four Bar

This mechanism, shown in Figure 37 of Appendix D, slides on lateral mounted rails on the roof of the SUV. The design consists of four main components: the rails, the sliders which clamp to the rails with bearings and connect to one end of the parallel bars through vertical mounting holes, the parallel bars which connect the cargo box to the sliders and keep the cargo box level, and the cargo box. When stowed, the cargo box rests on the rails and the parallel bars are horizontal. A roller connected to one end of each rail permits the cargo box to slide smoothly in the lateral direction for loading and unloading. When translating to the loading position, the cargo box, parallel bars and sliders translate horizontally on the rails until the cargo box is just over the side of the vehicle. At this point the parallel bars come in contact with the rail end-rollers and the cargo box continues to translate laterally and starts translating vertically as well. The parallel bars keep the cargo box level while the sliders, also translating across the rails, come in contact with lateral dampers and slow the vertical descent of the cargo box. At loading position, the cargo box is no more than five feet off the ground and the sliders are resting against the fully compressed lateral dampers. To stow the cargo box, the user gently pushes up on the box while the compressed lateral dampers push laterally on the rollers, easing user effort.

Idea #4: The Sliding Cantilever

Similar to the previous design, rails are mounted laterally on the vehicle on which the sliders translate. As shown in Figure 38 of Appendix D, the cargo box still rests and slides on the rail end-rollers. The main difference between these two ideas exists in the connection of the cargo box to the sliders. Rather than using a parallel four bar mechanism, this idea uses horizontal bars rigidly mounted to the cargo box and mounted to a pivot on the sliders. When moving the cargo box to the loading position, the sliders translate on the rails and the box and horizontal bars slide on the end-rollers and gently translate and rotate down to the side of the vehicle. The cargo box is not held parallel to the ground. Similar to the previous design, the sliders contact horizontal dampers, slowing the descent of the cargo box and easing user effort when stowing.
Idea #5: Folding linkage with locking joint

This idea involves two sets of links that both rotate around axes that are parallel to the forward and reverse direction on the vehicle. As you can see in Figure 3 of Appendix D, the first pivot point, mounted to the car, is fixed on the passenger side roof rail. The first set of the pivoting members are attached here. Then the other members are attached to on the other ends of the first members. The joints between the two sets of members have a locking mechanism in them to allow the second set of links to sit horizontally in the stowed and loading positions. The cargo box is attached to the second set of members on the top so it can be loaded while horizontal when the mechanism is in the loading position. The pivot axis that is attached to the roof rails has an extension that connects to the other rail to minimize the moment reaction on the pivot support. It also has telescoping lift bars to help the operator lift the loaded rack by increasing the moment arm they apply to the load.

Idea #6: Offset Four-bar Linkage

This design is a rotating four-bar mechanism to lower the cargo box to a more accessible height. A sketch of this system is shown in Figures 32 and 33 of Appendix D. There will be a set of pivot points mounted on the passenger roof rail that will act as the fixed member in the four-bar system. Attached to these pivots are essentially two beams that are identical to each other. On the other end of these beams is the fourth link which connects them. The distance between the pivots on the mounting member is the same as that on the cargo box holding member. The two pivoting beams rotate in separate planes so they will not hit each other during rotation. The mounting link is L shaped so that when the rack is moving around, the cargo box can stay horizontal without interfering with the links, and when the box is stowed it sits above the links. This mechanism will have a spring attached to the mounting and pivot links in a configuration that will aid the operator in raising the load. There would also be a locking mechanism on the structure to prevent the assembly from pivoting around when it is not supposed to.

Down-Selecting and Final Design Concept

After speaking with our sponsor, Mr. Allwein, we each chose one of our two ideas to pursue further. During a team bonding exercise we made rough prototypes of designs using K'Nex. These K'Nex models are shown in Figures 43 to 46 of Appendix E. In preparation for our Preliminary Design Review, as described in Appendix B, we developed more in depth sketches and basic calculations to get rough size estimates for our parts. After this, we had a design review where we decided which of our ideas best accomplishes our goals and meets the engineering requirements. In our preliminary design review, we compared the sliding cantilever idea, the fold up idea, and the offset four bar idea. We found that the four bar idea created too many problems because of how far it rotated. It was very unstable at the top point of the arc it moves in when we modeled it with the K'Nex. It also presented the problem of interacting with the box at the top of the arc, because it would be another two feet above the top of the vehicle. The fold-up
The sliding cantilever idea presents the simplest solution so we began to further develop the idea. We proceeded to solid model the design and develop code to solve for various geometries as a function of one angle so we could quasi-statically model the forces.

We began to worry that the user input to lift the box would exceed the specified limit of 50 lbs. We brainstormed methods to give the user some mechanical advantage. One concept we wanted to pursue was a way to move the box closer to the pivot point, thus increasing the moment arm that the user applies to lift the box. This led us to come up with the crank slider idea. Over the next week after the brainstorming session, we continued to develop this idea, as well as an additional variation of the cantilever design, in parallel in case the original idea turned out to be infeasible.

### Design Variations

After downsizing to one concept to pursue, the team looked at different variations in order to determine the most feasible design. Solidworks models were created to visualize the different systems and compare them. Although some of these alternative ideas are not going to be implemented in the final design, it was important that we at least considered them. This led to a better understanding of the design and what we could do to improve it further.

**Variation #1**

This design was generated because we were concerned that some of the stresses in the original design may be too great for the materials available. In addition, it would also reduce the user input force. This variation uses the same main sliding and pivoting mechanism as the original design, but it also includes a feature to support the load on the side of the vehicle using a padded bar and a sliding mechanism which allows the load to be located closer to the pivot point when raising or lowering. This sliding mechanism would make the moment around the pivot to be smaller, meaning the user would have to input less force when moving the box between the loading and stowed positions. Images describing the motion can be seen below in Figure 8.
The main advantages of pursuing this idea were that the stresses on the entire rack system would be reduced because of the added support on the side of the vehicle and that the user input force would be reduced by shortening the moment arm created by the weight of the box. However, this design also had some consequences that discouraged us. First of all, adding another point of contact between the rack and the vehicle added to the complexity of setting up the system. The point of contact would have to occur at different locations on different vehicles so it would have to be adjustable somehow. Also, many vehicle owners may not like the idea of having some of the load being supported by the side of their vehicle, an area not designed to be loaded.

Another disadvantage to this variation is the added complexity of the sliding mechanism. This would add another degree of freedom to the motion and we would need to make sure to control this movement so that it is safe and reliable. We would need to develop a way to lock the slider at different positions and a way to assist the user in raising and lowering it. Also, we would need to design the system in a way that it does not interfere with the rest of the rack's motion. During our discussions we determined that the disadvantages outweigh the advantages of further pursuing this idea and going into detailed design.

Figure 8. Design Variation #1 Motion in SolidWorks
This idea grew out of our sliding cantilever idea, with the intent to reduce the moment arm generated by the cargo box load. The movement of the box is outlined in Appendix D in Figure 3. It has a pivot axis on the passenger side of the car, and the moving part of the pivots is a set of sleeves that permits the bars inside of it to slide (perpendicular to the pivot axis). These outside bars are attached on the ends to another identical set of bars, located between the outside bars, with the connections serving as a stop so the bars don't slide out of their sleeve. On the inside bars, there is a set of sliders that are mounted on the bottom of the cargo box. Then there is a crank that has a belt drive attached to it, which is used to move the box along the inside bars. When stowed on top of the car, the box is as far from the pivot axis as possible. The user then slides the outside bars out as far as possible, creating a large moment arm to support the weight of the cargo box. Then, they pivot the box down so that the assembly rests against the side of the vehicle. After this, the customer uses the crank to slide the cargo box down the inside bars, where it rests on the joint between the inside and outside bars. This layout will greatly reduce the moment the box generates at the pivot, lessening the force required by the user to lift the end of the bars. The crank eliminates the need to push the box up the sliders. The design is significantly more complex than the sliding cantilever design. The series of procedures to change position would be very complicated as well. We ended up eliminating this idea because of its overall complexity.
For our final design, we are primarily concentrating on the mechanism used to lower the cargo box from the top of the car. We also designed a set of mounting feet similar to the products from Thule and Yakima to attach our design to the top of the jeep. Our set of feet is similar enough that the system could still be used with an existing set of feet because the lateral rails fit in them as well. Other than the rail dimensions, we only restricted ourselves to keeping the loading at the feet below the vehicle manufacturer's factory specifications for the roof capacity. An isometric view of our design can be seen in Figure 9.

A layout of our design’s mechanism is shown in Figure 10 on the next page with the box not shown so the mechanism is more easily visible. It would be mounted on top of the box arm on the end where the connecting plate is shown. The layout of our prototype changed slightly because we decided to machine the mounting feet so that they could bolt directly to the roof of the jeep. We also added a tab on each box arm 6 inches from the support plate. These allowed us to bolt down the cargo box more securely. The tabs are necessary because we cannot bolt anything through the box arms without restricting the bearings ability to move along the inside of the arms. We also welded a small plate across the tops of each carriage assembly. This allowed a bike rack to be bolted to the tops of the carriages, increasing their rigidity and reducing binding. We also cut the connecting plate short so that it became a short tab on each box arm. The plate was not necessary because the box provides the same rigidity when it is bolted on, so the plate was just increasing weight.
Figure 10. Layout of the slider mechanism that lowers the cargo box for loading. The lateral rail runs left to right on the top of the vehicle, with the front being to the right.

Final Design Decision Process

Figure 11. Screen shots of the different slider configurations with the shorter slider (left), the long slider (middle), and the short slider with a bent cantilever arm (right).
The point where the rack will mount onto the vehicle is another area we have been focusing on. We plan on buying mounting feet from Thule (small tower-like pieces that bolt into the stock roof rails) and designing our rack so that it was compatible with these. As you can see in Figure 11, incorporating these feet (shown in blue) into the design began to cause some issues with the range of motion of our box. The mounting points for the feet limited the distance they can be placed from one another, reducing the travel distance the rollers have on the crossbars. This reduced the maximum length the cantilever arms could be, and made us lengthen the plates used for the rolling pivot so that the pivot point can still be moved far enough to get the same range of motion in the box.

We also considered a bent cantilever arm that allowed us to shorten the pivot rollers again, but the bend in the bars adds even more height to the box when it is stowed, and aesthetically it looks more unusual because the box is even more tilted while on the roof.

Our final design for the carriage assembly uses the configuration shown in the middle of Figure 10. After considering the price of the hardware, we decided we will design and manufacture our own mounting interface to stand in for the Thule feet, though the design will still be compatible with the real feet. We machined the feet out of aluminum and designed in a clamping feature to attach the feet to the roof rails on the Jeep. The design can be seen in Figure 12.

To hold the box arms in place, we drilled holes through each roller bearing flange and box arm, installing cotter pins. They are positioned so that the pins lift the box up off the roller bearings. Isolating the bearing shafts from road vibrations will greatly increase their life. The bearings are located on very small diameter steps, so the stress concentrations associated with fatigue loading while driving would eventually break them. Figure 13 shows the quick release pins locking the box arms to the lateral rails.
Project Scheduling

Originally, our schedule predicted an early completion of the design process and provided adequate time for fabrication, assembly and testing. Since creating the schedule, we have realized we underestimated the time we would spend on idea development. We still have plenty of time available on the back end of the schedule as a cushion. This excess time could prove essential should ordered parts have a long lead time. Assembly will occur as components are fabricated and as ordered parts arrive. At this point we will begin testing and determining whether the finished product meets our design requirements. Should it not, we will be forced to reexamine our design and determine where improvements can be made, and then rebuild, reassemble, and retest. A schedule and Gantt chart can be seen and Appendices B and C.

Cargo Box Design

The cargo box is a very important component in our final product because it is where the main function occurs. The car must be held somewhere secure and not exposed to the elements and road conditions. If the box fails to properly store cargo, then our product has no use to our customer. After researching construction processes and materials, we decided that making a box out of composites would be the best solution. Off-the-shelf cargo boxes are available, but the design of these existing boxes does not work well with our roof rack design because the roof rack puts the box at an angle when in the loading position. Most of these boxes open across a horizontal plane which would result in the luggage falling out when incorporated into our roof rack that tilts the box. Injection molding is not feasible for our prototype because of the tooling costs, and metal or wood construction would be too heavy. We have access to composite materials and tools, and the shape of the box would be almost unlimited using composites, so we decided to make the box out of fiberglass and carbon fiber.

Figure 13. Quick Release Pins Lock Cargo Box in Stowed Position
The design requirements specify that the box must be able to contain two suitcases with dimensions of 32" x 16" x 19" each. Based on making the box aesthetically pleasing as well as taking into account aerodynamic loads on the box, we decided to orient the luggage so that the maximum dimensions would be 64" from front to rear, 19" from side to side, and 16" from top to bottom. This arrangement would minimize the amount of drag and minimize how far the box extended above the vehicle's roof.

The box was then designed so that it would be able to encapsulate this volume, while retaining visual appeal and minimizing aerodynamic loads. We also chose to keep the shape relatively simple so that manufacturing time would be reduced. This is an issue because the Shopbot will be programmed to cut the plug of our final shape out of foam. A simpler design would reduce cost and time. The final design we came up with is a box with rounded edges and a nose that tapers from the top and bottom of the box towards the center to reduce drag.

We felt that an effective design would maximize ease of use for the customer. Part of this requirement means that the user should be able to access the luggage and load and unload the box with minimal interference. To do this, we designed a large lid on the top of the box. Originally we had planned on making the box open at the back, but we decided that this would not be as easy to access as a lid on the top. The lid is hinged on the driver side of the vehicle about halfway down the box and the free side of the lid mates with the rest of the box on the top horizontal plane, supported by a flange. Rotating latches will secure the lid shut when driving, and locks could easily be incorporated if desired. Friction hinges will allow the lid to stay open at any angle so that the operator does not have to support it and has both hands free to load or unload the box. This design results in a large opening in the top of the box that allows easy loading and unloading. There would also be a tall surface to rest luggage against so that it would not spill out while the box is tilted on its side.
FIGURE 15. SOLIDWORKS MODEL OF BOX AND LID ASSEMBLY

Structurally, the cargo box must be able to withstand loads due to travelling with the luggage inside, aerodynamic loads, and the loads applied by mounting the box to the rest of the roof rack system. In order to mount the box to the box arms, we will embed metal plates into the box that bolts could pass through. This way the compressive forces would not damage the composites or the foam core. A foam core will be embedded into the floor of the box to better support the loads due to the luggage and increase the overall rigidity of the structure. Holes will be cut in the foam for the box arm mounting plates to be placed in. A flange will also need to be attached to support the lid when it is shut. This will be made out of more composites and will allow the lid to be flush with the rest of the box. If we decide that the box needs to be stiffer, we will be able to add composite ribs to the inside.

Cargo Box Manufacturing

Fabricating with composites is very much an art, so we will likely be making discoveries and modifications as we build. Many of the materials will be supplied by resources on campus. Carbon fiber cloth will be donated by Dr. Mello. The Supermileage team has extra resin, hardener, and sanding primer that they acquired at a discounted price and will charge us according to how much we use. George Leone has foam, miscellaneous tools and materials that we may need as well as experience and knowledge that he has been sharing with us. The shop techs charge $300 to program the Shopbot, and Dr. Mello gave us permission to charge the senior project fund for this expense. The first step to making a finished part is to make a plug of the box. The plug will be identical in shape to the final product. To construct the plug, we made a model of the box in Solidworks. This model could then be used to program the Shopbot in the hangar to cut the shape out of a block closed cell urethane foam. To make a block big enough for our plug, we glued together 5 sheets of four pound foam to make a block slightly larger than
Four pound foam does not machine as precisely as denser foam, but it is good enough for our application, as we will be sanding it later.

After the plug has been cut to shape, it must be prepped so that the female mold can be made. The plug will be sanded and primed until it has a very smooth finish. The smoother the finish, the easier it will be to remove the mold from the plug, and the better the final piece will look.

Multiple layers of mold release wax will also be applied and buffed out to aid in the release. A parting line will separate the top and bottom sections of the plug so we can lay up one section at a time. The mold will be made out of approximately four layers of fiberglass matte and polyester resin. The matte should be ripped into manageable pieces. Resin and catalyst will be mixed according to manufacturer's instructions, and each piece of matte will be saturated in resin before it is applied on top of the plug. It is important to make sure that the matte lies smoothly on the plug, filling all corners and containing no air bubbles. More pieces of matte will be laid up until the entire surface is covered with four layers. This should provide a mold with sufficient strength, yet remaining flexible enough to pop our piece out.

Once the mold cures, it will be possible to start doing the final layup of the finished piece. The mold will be prepared with a layer of polyvinyl alcohol release film, which aids in releasing the part from the mold. The final layup will consist of layers of fiberglass cloth and carbon fiber cloth, both saturated with epoxy resin. To obtain maximum strength with minimal weight, the proper amount of resin should be prepared for each piece of cloth. This cloth will be
sandwiched between layers of plastic so that the resin can be squeegeed around to ensure the entire cloth is saturated. The first layer will be fiberglass cloth, so that if it needs any final sanding, we will not have to sand the carbon fiber. The cloth should be set with its weave at a 45 degree angle to any major bends or corners, because the cloth conforms to curves better in this orientation.

Layup technique is similar to that of the mold; the cloth should fill all corners and all bubbles need to be removed. The next layer will be carbon fiber cloth, giving us the appearance and strength that we desire. After the carbon fiber, more fiberglass cloth will be applied until we feel it is strong enough structurally. A foam core will also be embedded between some of these layers of fiberglass for the floor of the box. The core will also contain cutouts where mounting plates will be placed.

Once all of the cloth is on the mold, a vacuum bag will be used to make sure everything fits tight and there are no air bubbles. The first step to using a vacuum bag is to apply a layer of peel ply, which is a material that keeps the surface clean, smooth, and allows for easy post-bonding. Next up, a perforated film is applied that assists in the flow and spread of resin. Next up, a breather cloth ensures that the air flows from all parts of the bag. Finally the entire assembly is placed in the vacuum bag and a partial vacuum is applied. The fabric should be massaged by hand at this point to make sure that the layers are tight against the mold. Then the full vacuum is applied. After the composites have cured, the bag can be removed and the piece is ready to be removed from the mold. Wedges and air pressure will assist in the removal.

Next, the lid will have to be cut out of the top piece. After it is removed, a composite flange will be post-bonded to the original structure to support the lid. Now the two halves of the box will be bonded together using an adhesive. Final touches will include mounting hinges, gaskets, and latches to the lid as well as drilling holes through the mounting plates for attachment to the box arms. If we decide that the structure needs to be stiffer, then ribs can be.

A change in direction for the cargo box

The manufacturing process for the cargo box hit a road block when we were about to start covering the mold in carbon fiber. We were under the impression that there was some carbon fiber left over from various other projects that we could use to make our box with. This turned out to not be the case, and the cost of purchasing our own carbon put us way over budget. Considering that having a carbon fiber box was mostly superfluous, we decided to purchase our own box and adapt it for our mechanism.

One of the main things that needed to be changed was the hinge position on the box. The way the struts are factory installed only allows the box to open 45 degrees, making loading very awkward when the box is tilted sideways on the box arms. In the loading position, we experimented with the box position to see if the problem was severe enough to warrant a change. We decided that no box orientation solved the problem so we were forced to reposition the struts inside the box, allowing the box to open 90 degrees. With the box opened this far, the struts could not support the weight of the lid by themselves, so we added tension springs to assist the struts.
Because the box was designed to be loaded while horizontal, everything that we loaded into it would just roll out of it before you could close the box. To solve this, we fabricated a shelf that prevents items from falling out. In our prototype we just bolted it into the box, but we would ideally fasten it down with the same bolts that attach the box to the box arms. This transfers all of the loading directly to the arms, so the box is not acting as a structural component.

To attach the box to our box arms, the stock universal clamps need to be removed. This is easily accomplished without the need for any tools. Then with the existing slots and holes on the bottom of the box, there is no need to drill extra holes in the box to attach it to the box arms.

The box shelf modification is shown in the left image of Figure 17 below.

**Figure 17. Modified Cargo Box**

**Design Analysis**

The design we chose to pursue has an extremely complicated motion about a virtual pivot. To aid in detail designing and to verify design feasibility, we developed a Matlab model to analyze forces and failure modes for all cargo rack positions. This model assumes quasi-static motion; in each position analyzed, the system is stationary. The model first calculates geometric relations between components as a function of the carriage position. Forces applied to the cargo box and box arm assembly are calculated and then used to analyze stresses at key points on the system and determine safety factors, or the ratio of the material yield stress to the experienced stress.
process for each position step. This equation is shown in Figure 18, along with various geometric relations used to derive it. With the slope of the cargo box determined as a function of carriage position $x$, geometric relations for the rest of the system could be determined as a function of these two variables. With the geometric relationships fully defined, a free body diagram of the system was created generating three static equations used to determine forces at critical locations. Figure 18 shows this generic FBD. The three equations derived are as follows:

\[ \sum = 0 \]
\[ (dX + x + Dr \sin(\alpha)) \cdot \text{Load} + (Lb + Hand) \sin(\alpha) \cdot F_{x\text{User}} - (Lb + Hand) \cos(\alpha) \cdot F_{y\text{User}} - An = 0 \]
\[ \sum = 0 \]
\[ F_{y\text{User}} + An \cos(\alpha) - \text{Load} - By = 0 \]
\[ \sum = 0 \]
\[ F_{x\text{User}} + Bx - An \sin(\alpha) = 0 \]

The load is the only known force in these equations yielding five unknowns for only three equations. To eliminate one of these unknowns, we need to know the direction of the resultant user force acting at the end of the handle. Intuitively, this force will act in the direction that...
minimizes the required magnitude. We assumed that applying the user force in the direction tangential to the path of motion of the point at which the force is applied would minimize the required magnitude of the user force. This assumption makes sense intuitively, but we intend to prove its validity in testing. With the angle of the user force defined, the free body diagram simplifies to the one shown on the right in Figure 19. Knowing that simpler designs tend to lead to better results, we tried to eliminate the need for a force assist mechanism (such as a spring or gas shock) by adding the handle shown in Figure 19. This increases the leverage of the user and decreases the force required to operate the cargo box system. With no spring or shock, the $x$-component of the force at point $B_{x}=0$. This leaves us with a determinate system. We incremented the length of the user handle until the peak user force was less than the design requirement of 50lbs. This occurred when $H_{\text{hand}}=20$ inches. The user force curve is shown in plot 3 of Figure 21.

**Figure 20. User Handle Path and User Force Direction**
Figure 21. Geometric Relations and Relevant Forces.

Stress Analysis

To aid in material selection and detail dimensioning, key failure modes were analyzed for worst-case scenarios. Forces at points A and B are maximized when the cargo box CG moment arm $dX$ is greatest. The bending moment in the box mounted rails is also greatest while in this position. Figure 22 below shows a free body diagram of the cargo box and box-mounted rails.

Below the FBD, the shear and bending moment diagrams are derived. Only the normal components of the applied forces are projected onto the shear and bending diagrams. The tangential components are neglected, as they do not contribute to likely failure modes. The maximum internal moment occurs at the second peak on the bending moment diagram, corresponding to point A on the box arm.
The following equation calculates stress due to bending:

\[
\sigma = \frac{Mc}{I}
\]

for peak tensile stress and

\[
\sigma = \frac{-Mc}{I}
\]

for peak compressive stress. The second moment of area is calculated using

\[
I = \frac{bh^3}{12}
\]

as shown in Figure 22.

**Figure 22. Shear and Bending Moment Diagrams for Box-Mounted Rails.**

**Figure 23. Failure Analysis in Box-Mounted Rails due to Bending.**
Point B experiences large forces between several different components of different material composition. Figure 24 lists the seven main failure modes at this point, and Figure 25 further details these failure modes. The Matlab model calculates each of these stresses and compares them to the material yield stress to get a factor of safety (FOS). Materials can be selected to yield the desired FOS. Dimensions can be optimized for the same purpose.

**Figure 24. Failure Modes at Point B.**

Following the load path from point B through the carriage plates, several more failure modes become apparent. Figure 25 details four of these, though more exist which will be analyzed. The likely failure locations are at Φ and at bolts a and c in the lower drawing. Analyzing failure modes at these locations will help us determine how thick to make the carriage plates, what material to use, and what mounting hardware to use. The last place to analyze failure will be in the lateral rails due to bending.

**Figure 25. Failure Modes for the Carriage Plates.**
The resulting safety factors for each of the 18 failure modes analyzed are shown in Table 1. Small safety factors correspond to internal stresses close to the yield stress of a material. The smallest factor of safety, and therefore most likely failure mode, occurs due to bending in the cargo box arms. A safety factor of 3 is within the requirements of this project.

Table 1. Mechanical Failure Modes & The Resulting Safety Factor For Each.
Throughout operation of the cargo box, forces act on the vehicle roof at the base of the rack feet. Typical vehicle roof rack load ratings range between 100 and 200 lbs. To check the load our system applies to the vehicle, we used the FBD in Figure 27 to derive the statics equations shown below. Solving these equations for foot forces and plotting them against carriage position yields the graphs shown next to the FBD.

\[ \sum = 0 \]

\[ (dX + OH) \times \text{Load} + F_{x\text{User}} \times [Lb \times \sin(\alpha) - H - F_{y\text{User}} \times (Lb + Hand) \times \cos(\alpha) + OH] - w = 0 \]

\[ \sum = 0 \]

\[ F_{y\text{User}} + \text{Load} - \text{Load} = 0 \]

\[ \sum = 0 \]

\[ F_{x\text{User}} + \text{Load} = 0 \]

Assume:

Figure 27. System Free Body Diagram and Roof Forces.
Cost Analysis

A table of expenses for the project can be found in Appendix H. This describes the parts we purchased, their cost, the vendors, and more notes about the materials. This table has been updated as we progress to keep track of our budget.

Safety Considerations

It is important to our customer that the product does not put them or anyone else in danger. With our design, pinch points, heavy moving loads, and sharp corners are of main concern. We have attempted to minimize the risk in using our product by designing around these concerns. The corners of the carriage plates have been rounded to avoid causing injury to the user. The motion of our design unfortunately introduces some pinch points where the box arm pivots about the end of the lateral rails, but the danger has been minimized by enclosing the pivot point within the box arm.

Our handle and latching system was also designed with safety as a main concern. The handle ensures that the operator's hands will be away from the pinch points, and in a location where it is easy to support the load in the cargo box. The length of the handle gives the user a longer lever arm to support the load. The latch does not release until the handle is rotated out, so the box will not unlatch unless the operator's hands are on the handle. The box will also have latches that secure the lid closed. The box will not be able to open unless the user unlatches them. There will also be a pinch point where the lid hinges with the box however this will be on the side of the box opposite to where the user stands, so it should not be a safety concern.
Maintenance and Repairs

Our customer desires a product that makes loading and unloading their vehicles easier. If the design requires much maintenance, the user may find that using our product is more of a hassle than a benefit. If the product breaks and requires repair, it will not be useful and we will disappoint our customer. Every effort has been taken to design our system so that it will not fail under most circumstances and that minimal to no maintenance will be required.

To reduce maintenance, we used sealed ball bearings for all of the rolling and pivoting motion. The sealed bearings should be protected against contamination and the lubrication inside should be sufficient for the product's lifetime. If one of the bearings does happen to fail, they are all standard sizes available at most bearing suppliers. A bronze bushing will be used at the handle pivot, where wear and reducing friction is not as much of a concern.

The latches which secure the rack in its loaded position will be actuated by cables. The cables may stretch over time and require more tension in order to pull sufficiently on the latch. In order to address this, we have incorporated barrel adjusters into the design, which can be used to effectively lengthen the cable housing and increase tension in the cables.

If any component fails, we recommend that it is replaced with a new one rather than repaired. We do not want the user to continue using a part that has been fatigued, because it may be weaker than we designed it to be. Repair would be labor intensive and not a guaranteed fix. We will have to develop a warranty program or replacement part program.
Chapter 5: Design Verification Plan

User Force Verification

The objective of this experiment is to verify the user force model employed in the static failure analysis of our mechanism. We assumed the user's input force would be in a direction that minimizes the effort required to lift the box. Then, we decided to model this with an input force that is applied tangent to the path of motion of the point it is applied at.

In addition to verifying the direction of the user force, we want to verify the magnitudes that were used for each carriage position to validate the loading that the stress analysis is based on. The procedure can be seen in Appendix I.

From this experiment, we hope to show that our force model is adequate. If the actual user forces are higher than the model in our analysis, we will need to go back and revise the force model. Higher user forces could eat into our safety factors, as well as raising the lifting force past our design requirement of 50 lbs.

Carriage Plate Failure

FIGURE 28. PHOTO OF THE EXPERIMENTAL APPARATUS TO BE USED IN CARRIAGE PLATE TESTING.
If we load these plates and they hold up to the loads, we can then assume our newer plates will not fail because they are thicker, and more carefully machined. If failure does occur with these plates, we will go back and consider design changes.

Box Arm Bending Failure

**Figure 29. Failure mode of box arm under a bending load (deflection shown is magnified).**
Chapter 6: Project Management Plan

Team roles have been chosen based on each member's skills, experience, and desired tasks with the intended purpose of maximizing team efficiency. The roles are as follows:

Whit Ratcliff – Team Coordinator
- Arrange and Lead Meetings
- Sponsor Main Contact
- Develop Design Idea #3
- Develop Matlab Model to Aid in Development of Chosen Design

Travis McCart – Senior Documentation Specialist
- Record Meetings
- Timeline Management
- Develop Design Idea #2

Brian Plummer – Manufacturing Coordinator
- Interact with lab Techs
- Analyze Feasibility of Construction for Different Designs
- Create Manufacturing Drawings
- Develop Design Idea #6

All team members are expected to contribute equally to the design, analysis and construction of this project, as well as the plethora of written documents required by Senior Project. Participation in meetings and conferences is mandatory and these events will be scheduled so that all team members are available. Each member understands the level of commitment required for this project to be successful and agrees to put forth the necessary time and energy. Excuses for not providing adequate time and energy are limited to medical emergencies and obligations to other classes which are essential for receiving a passing grade in that class. Team members are expected to communicate well with each other and inform the team when concerned about their available time.

A tentative project schedule is available in Appendix B. The main deadlines are as follows:
- 11/2 – Preliminary Design Review with Mr. Allwein
- 12/1 – Conceptual Design Report Due
- 1/31 – Final Design Report Due
- 2/1 – Critical Design Review with Mr. Allwein
- 2/8 – Start Construction
- 3/9 – Finish Building and Start Testing
- 5/2 – Final Design Review with Mr. Allwein
- 6/4 – Final Report Due
Chapter 7: Conclusions and Recommendations

The final prototype confirmed that the chosen design is an effective solution to the problems with using current cargo boxes on the market. The motion of the mechanism was easy for the user to control, and having the cargo box lowered in front of the user made loading and organizing much easier than having to do it on top of the roof. The shelf installed in the box was able to support the loads and allowed for efficient use of the volume. With the box at the side of the vehicle rather than on top of it, the driver is able to enter low clearance areas such as a garage without removing the box. The driving test proved that the mechanism was secure in its stowed position. There was minimal vibration and only barely audible noise at speeds above 60 miles per hour. The loads due to driving were effectively transferred through all of the components of our mechanism, as well as the factory roof rack, without failure.

Future Development

The result of the prototype encouraged us that this idea may be worth pursuing further, however it also revealed some areas for improvement. Our design could be further optimized to reduce manufacturing costs, increase ease of use, and increase compatibility with existing roof rack components on the market.

Box Optimization

Overall we were satisfied with how well the existing box worked with our design and using existing products would increase our designs marketability. For the prototype, an existing cargo box was modified to meet our needs. Holes were drilled to relocate the hinges as well as for mounting points to the box arms and the shelf. The hinges had to be reinstalled using rivets and an additional spring was needed to keep the lid open while tilted at an angle. We would like to minimize these modifications for a production model. The existing slots in the box could be used as mounting points for the shelf and connecting with the box arms. There is also the possibility of using the same hardware to connect the shelf and box to the box arms. This would also ensure any loads seen by the shelf would be transferred into the structural members of the box arms rather than the box itself. A template for drilling holes to relocate the hinges would be supplied with our product, or new hinges could be designed. The same basic design would be modified to allow the lid to open up more and to securely hold the lid when in the loading position. These hinges could be installed with common household tools.
We had initially designed one rotating handle in the middle of the box arms that functioned as a latching mechanism and a form of mechanical advantage. After installing the majority of our mechanism and getting a feel for the motion, we decided that having two handles spaced farther apart is more favorable than having one in the middle. The initial rotating handle is shown on the left in Figure 29 below. One of the handles for the two-handle design we included in our prototype is shown on the right in Figure 29.

We also realized that having an extended handle to provide mechanical advantage is not really feasible because the end of these handles were much too close to the ground. After brainstorming some different options, we decided that adding some kind of spring force to the carriages to force them along the lateral rails would be ideal. We made a test rig with a pulley that we hung weights off of to simulate a spring force. We determined that only during the last 9 or 10 inches of carriage plate travel, where the box is still mostly vertical, there needs to be some form of user assist. Adding an assist force of only 30 pounds per carriage plate made a vast improvement on the level of user input required to lift the box. Figure 30 below shows our test rig used to determine the necessary spring force and travel of the user assist mechanism.
In the next iteration of the design, we would like to implement a gas shock enclosed in the lateral rails to provide the assisting force. For the desired preload, travel, and compression ratio, gas shocks are narrow enough to fit within the lateral rails. The preload and compression ratio will be designed to minimize required user force while not overpowering the user when the box is empty. In preliminary testing we applied over 150lbs laterally to the carriage plates simulating a user assist mechanism and proved that a locking mechanism for the box while in the loading position is unnecessary, as this force did not raise the empty box.
Appendix A: References

Existing Products:
http://www.safaricondo.com/kayak/indexeng.html
http://www.orsracksdirect.com/yakima-ez-loader-roof-rack.html
http://thule.com/en/
http://yakima.com/
http://www.dailymotion.com/video/xdy3uh_the-ultimate-roof-rack-system_auto
http://www.karitek.co.uk/ELRRIntroMulti.html

Specifications, standards and other information:
http://papers.sae.org/2011-01-0492
http://papers.sae.org/2006-01-0729/
http://www.toyota.com/
http://www.ford.com/

Contacts:
mikeallwein@sbcglobal.net
mlmclarl@calpoly.edu
Appendix B: Schedule

10/5 – Conference Call with Mike Allwein/System Requirements Review
Clarify specifications, schedule, and requirements. Discuss project proposal.

10/19 – Project Proposal (Requirements) Document Due
Demonstrates that we understand the problem and its extent, have studied background information and existing products, have a process/schedule to follow, and have the resources necessary to complete the project in the allotted time.

10/31 – Preliminary Design Review with Mike
Review multiple concepts and down select to the most promising.
During a preliminary design review it is appropriate to present hand calculations that show the concept is feasible. Critical areas of the concepts should be developed either with scaled hand sketches or 2D CAD. We should also layout how the team plans to comply with the remainder of the requirements (by design, inspection, demonstration, analysis, or test).

11/1 – Conceptual Model Due

12/1 – Conceptual Design Report Due
Builds on the project proposal as well as revises it. Includes sketches of top concepts, description of selection process, analysis to justify selected concept, solid modeling, preliminary plans for construction & testing.

1/31 – Final Design Report Due
Solid modeling, analysis to show design meets requirements, material selection, fabrication and assembly instructions, maintenance and repair considerations, BOM & cost analysis, detailed part drawings, Management Plan and Gantt chart.

2/1 – Critical Design Review with Mike
This should occur right before parts are made. This will summarize all the analysis and design work to prove the concept will meet the requirements. Detail drawings for components and test plans should be complete.

2/3 – Order materials

2/8 – Start Building

3/9 – Finish building/Start Testing

5/2 – Final Design Review with Mike
This will wrap up the project. It will include test reports summarizing the results.

6/4 – Final Report Due
This should contain all the information for a third party to build the design.
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<th>Finish</th>
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<td>Fri 12/23/</td>
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Appendix C: Gantt Chart
Figure 32. Concept drawing of the Folding Linkage with Locking Joints and accompanying basic calculations.
**Figure 33. Sketch of the Offset Parallel Four-bar Linkage.**

- **Support for box**: Elevates the box so it is above the links when in the stored position.
- **Cargo box**: Example cargo box.
- **Pivots for four-bar links**: Off-set pivot points so the links do not interfere during rotation.
- **Truck**: Key component of the system.
Figure 34. Simple calculations for the offset four-bar idea.
Figure 35. Concept drawing of the Slide and Tilt.

Figure 36. Concept drawing of the Fold-up.
Figure 37. Concept drawing of the Fold-up midway through its lowering motion.
FIGURE 38. CONCEPT DRAWING OF THE SLIDING PARALLEL FOUR-BAR.
FIGURE 39. CONCEPT DRAWING OF THE SLIDING CANTILEVER
Figure 40. Sketches of the unloading procedure for the crank and slider concept.
**Figure 41.** Solid model of the sliding cantilever design in the loading position.

**Figure 42.** Solid model of the sliding cantilever design in the stowed position.
FIGURE 43. CLOSE UP OF THE SLIDING PIVOT POINT IN THE SLIDING CANTILEVER DESIGN.
Appendix E: K’NEX Models

**Figure 44.** K’NEX model of the Sliding Parallel Four-bar concept

**Figure 45.** A K’Nex model of the Fold-up in its cargo loading position.
Figure 46. The Fold-up concept half-way through being folded up.

Figure 47. The fold-up in its stowed position.
### Table 2. Design Requirements

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<thead>
<tr>
<th>REQUIREMENTS</th>
<th>CAPABILITIES</th>
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<tr>
<td>ENVIRONMENTAL Prototype</td>
<td>System Requirements Review</td>
</tr>
<tr>
<td>Requirement</td>
<td>System Requirements Review</td>
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<tr>
<td>Operating temperature range</td>
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<td>Non-operating / Storage temperature range</td>
<td>32 to 100°F</td>
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<td>Shock</td>
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<tr>
<td>Corrosion</td>
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<tr>
<td>Other</td>
<td>Rain / Water intrusion</td>
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<td></td>
<td>Snow</td>
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<td>PERFORMANCE Weight (lbs) [this requirement is for mechanism]</td>
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<td>Size / Volume (stowed config)</td>
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<tr>
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<td>Duty cycle</td>
<td>50 load/unload cycles / year</td>
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<tr>
<td>Life</td>
<td>10 years</td>
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<td>Speed / Power</td>
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<td>Other</td>
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<tr>
<td>When transitioning from stowed to loading position, the operator shall not be required to exert more than 50 lbs.</td>
<td>To be satisfied by analysis</td>
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**COMPLIANCE**

http://papers.sae.org/2006-01-0729/ (I will clarify)
Inertia loads shall be calculated assuming a downward acceleration of 3.0. Upward acceleration need not be considered.

To be satisfied by analysis:

- Safety Factor between design loads and yielding

To be satisfied by analysis:

- Safety Factor between design loads and ultimate loads

MECHANICAL INTERFACE

Vehicle specific. Shall not require additional vehicle rail.

MECHANICAL INTERFACE

Interface loads on vehicle roof rack when stowed, loading, or transitioning between positions shall not exceed manufacturer's published ratings.

To be satisfied by analysis:

MAINTENANCE

n/a

TESTING

Vibration

TBD

Rain / Water intrusion

n/a

Endurance (Duty cycle x Life)

Test shall validate duty cycle and life requirement with 50% margin

Structural

Limit and ultimate load tests shall be performed.
## Engineering Requirements

<table>
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<td>Withstands Aero Loads</td>
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<td>Doesn't Hinder Door Opening</td>
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<td><strong>Interface with SUV</strong></td>
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<td>Doesn't Scratch Vehicle</td>
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<td>Interface Loads w/min MFG Tolerance</td>
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Benchmarks (1-4 scale)
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**Total to date:** $288.80
Appendix I: Testing Procedures

User Input Force Verification

The objective of this experiment is to verify the user force model employed in the static failure analysis of our mechanism. We assumed the user's input force would be in a direction that minimizes the effort required to lift the box. We decided to model this with an input force that is applied tangent to the path of motion of the point it is applied at. In addition to verifying the direction of the user force, we want to verify the magnitudes that were used for each carriage position to validate the loading that the stress analysis is based on.

Apparatus

For this experiment, we will be using only one side of our sliding mechanism. The feet will be bolted down to a solid base at a distance of 36.95" from each other. The roller-end face of the lateral rail is to be 4" from the outside edge of the roller-side foot. For clarification, these dimensions are shown on Figure 42. Then we will load the arm with half of our full load (about 50 lb). To model the weight at the center of gravity of the box, we will attach a structure to the box arm. We will hang these weights from the modeled C.G. location so the load is still accurately located as the box is lowered. To keep the carriage plates stationary during measurement, we will use a C-clamp on the lateral rail to restrict their motion. We will be using a stand-in for the handle, making sure it extends 20" from the end of the box arm.

Figure 48. Dimensions for properly setting up the experimental apparatus.
Procedure 1
With the box arm loaded appropriately and recording the location of the carriage assembly (x in notebook derivations), we will apply a load to the end of the handle with a fish scale (as shown in Figure 43). We will minimize the load readout on the fish scale, record it, and then measure the angle ($\Theta$) the load was applied at, using a plumb bob and a protractor.

After taking data for a particular box location, we will release the C-clamp, slide the carriage plates along the lateral rail a few inches, and then repeat the measurement process.

Procedure 2
With the box arm loaded, we will apply a force at the end of the handle. We will apply this at the angle specified in the code for that particular carriage position, measuring the angle with the plumb bob and the protractor.

Then, record the magnitude displayed on the fish scale, and the box arm x location that the measurement was taken at.

Then as in procedure 1, we move the carriage plate, lock it there with the clamp, and then take the force measurements again.

**Figure 49: Experimental apparatus showing where loads are acting on the box arm.**
Analysis 1
If we modeled the forces correctly, this should be an easy step. Simply show a table or plot of the modeled force components and experimentally determine forces vs. carriage position. If the model is too far off, we will need to explore why there is a discrepancy, and consider changing the model.

Analysis 2
Here we want to compare the magnitude required to hold up the box that we used in the code with the loads we measured in procedure 2. If the loads turn out to be less than the ones used in the code, it just means we have a larger safety factor than we anticipated. If they are higher than the ones in the code though, we should go back and adjust the loads in the code to see if they affect the failure modes of our mechanism.
Carriage Plate Failure Testing

Objective
In this experiment we are testing our prototype carriage plates for failure from loading at the pivot point. These prototype plates are made out of thinner steel than our final ones, and were used in a preliminary mockup of the design. We are trying to validate the stress analysis of the final design which has a significant stress concentration at the inner fillet radius, but we don’t want to break our finished pieces if we don’t have to.

Apparatus
The setup for this experiment consists of two of our prototype carriage plates attached to a stable surface. This will be done by bolting the plates to a rigid piece of wood (skate ramp) using the three bolt holes shown in Figure 44. The plates should be separated by the same distance that they are in the design (1.254"), and the load will be applied between the plates at the pivot point. For the load, we will hang lifting weights so we know what the magnitude is, and we can keep adding them until failure occurs (or we run out of weights). The weight will be hung from a suitable string or wire draped over a bolt at the location indicated in Figure H3.

Procedure
The two loading configurations are depicted below in Figure 44.

a. Perpendicular to the ground with top facing up and parallel to the ground:

Attach the carriage plates to the stable surface (perpendicular to the ground).

Bolt here and hang weights from it.

Figure 50. Apparatus for part a. of the procedure showing where the plates will be loaded.
Hang an increasing amount of weight from the pivot point in 25 lb increments. Record what loading the failure occurs at (if any).

b. Perpendicular to the ground with top facing down and parallel to the ground:

If the plates are still intact, flip the plates upside down and reattach to the base. Repeat the loading procedure, and record the loading that failure occurs at.

If failure still hasn't occurred in either plate, remove one of the plates and repeat the testing procedures above with the other plate by itself.

**Figure 51. Side view of the loading configurations used in testing. Part A. is on the left and Part B. is on the right.**
Box Arm Bending Failure

Objective

This experiment is a failure test of our manufactured box arms. We want to subject the arm to a moment and see if the arm fails. The arm has a long slot in the bottom that will significantly reduce the tube’s strength, so we want to verify our design’s integrity. The bending failure of this arm has the lowest safety factor of all of our components, so as the loading increases beyond the design loading, the arms will fail in bending before anything else.

Apparatus

*Figure 52. Cargo box arm strapped to a solid surface so it can be loaded and tested for bending failure.*

The setup for this test is very simple. We will fabricate some metal straps, and use them to fix the non-slotted end of the box arm to a fixed surface (modeled by the larger rectangular prism in Figure 46). Then, we will hang weights from the arm on rope or wire, keeping the wire from sliding off the end with a clamp. The distance from the back of the box arm to the edge of the solid surface needs to be 4", and the distance from the solid surface to the load point is 19". These dimensions are approximations of the maximum moment arm the arms see during operation.

*Figure 53. Example of the deformation that occurs during bending (taken from a Solidworks Simulation). The color spectrum shows the von Mises equivalent stress levels along the arm, with red for higher stresses, green for medium levels and blue for low stress levels.*
Procedure

Strap down the non-slotted end of the box arm so 29" of the arm hangs off the edge of the solid surface (as seen in Figure 46).

Load the arm by hanging 60 lbs. from a rope or wire 19" from the solid surface. Observe deflection (similar to deflection shown in Figure 47), check for failure.

Analysis

If the arm does fail, we will need to evaluate why it did. It could have been due to our manufacturing methods (which are inferior to the abilities of professionals), or we may have overlooked a significant stress concentration. The stress concentration shown in red in Figure 47 may prove to be enough to break the arm, depending on the loading.