DESIGN FOR MANUFACTURABILITY: OFF-ROAD TOYOTA BUMPER

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by
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Graded by:_____________ Date of Submission__________________________
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The purpose of this project is to design a new off-road bumper that is improved from the stock form of a 1996-2002 Toyota 4Runner and a 1996-2004 Toyota Tacoma. The current state of the component is too weak to endure to off-road endeavors, and a kit bumper market is virtually untapped for these vehicles. The objectives of this project were met by redesigning the stock front bumper, conducting a finite element analysis on the model to test for strength, prototyping the bumper with CNC cut cardboard, and conducting a full cost analysis including the costs for waterjet and laser cutting of the steel. The new bumper was designed to improve performance, reliability, strength, and to increase the approach angle while staying under Design for Manufacturing/Assembly methodologies. By prototyping the bumper and speaking with various metal cutting facilities, a full cost analysis has also been conducted in order to determine the feasibility of small, medium, and large production volumes.
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1.0 Introduction

This report will describe the design and manufacturing process of a front off-road winch bumper for the 1996-2002 Toyota 4Runner and 1996-2004 Toyota Tacoma 4x4. This project was presented to me from a local machine shop, Maglio, Inc., looking to enter into the off-road manufacturing market. The product has to be durable for rigorous use off-road and cost effective for the end-user while being easy to assemble.

The upgraded bumper will serve as a stock replacement with one mounting modification required to the front frame rails for added strength. The stock bumper on these generations of vehicles is inadequate for their intended use of off-roading due to a lack of approach angle (described in Figure 1.1 below), and the ability to harm the vehicle due to harsh environments. By redesigning and manufacturing a new front bumper for these vehicles, these problems will disappear allowing for an improved off-road utility vehicle. The new bumper weight will also be a factor since the plate steel will be heavier than the stock bumper. Keeping the bumper at, or under 110 pounds would be ideal to not stress the front end components too much.

The following is a list of main objectives for this project:

- Reverse engineer the front end of the donor vehicle with important features such as mounting holes and locations of the frame/cab
- Design bumper using existing mounting locations on frame
  - Include self-fixturing design for components being assembled and cut down on unnecessary materials
  - Conduct Finite Element Analysis (FEA) on bumper
- Make a cardboard prototype of the design
- Test for fitment and usability on vehicle
- Perform cost analysis

Since most companies who manufacture aftermarket bumpers are secretive on how they mount to the frame, I will go in and reverse engineer the frame rails and the cab of the vehicle to get the locations of the mounting holes using manual tools, and utilize SolidWorks to make a CAD model. By having this initial model, I will be able to check clearance and fitment of the bumper in the design phase, instead of after manufacturing a prototype. The bumper will be designed in a way to ease the assembly process, known as Design for Manufacture/Assembly, which will be further described in the literature review section. Other areas of research that will be required for the success of this project are material selection and welding methodologies.

A prototype will be made from the CAD models being designed. It will be made from either laser-cut ABS plastic or high-grade, CNC cut cardboard. This prototype will be test fit onto the
vehicle to determine if the initial design was accurate. A cost analysis will be conducted at the end to determine production costs and how affordable it is to the end-user.

Following in this report are the background, literature review, design, methods, results, and conclusion which will further show the relevance and purpose of this project.

Figure 1.1 – Approach Angle Example
2.0 Background and Literature Review

This section will deal with the background for this project as well as why it is relevant to complete. A literature review will follow, adding information on important subjects pertaining to the end product.

2.1 Background

In 1995 and 1996, Toyota introduced the first-generation Tacoma and the third-generation 4Runner respectively. Since the day they have come out, off-road enthusiasts have used these vehicles to their full extent. Climbing over rocks, racing through the desert, and cruising down a dirt trail are just some of the ways they have been used. Even though both trucks are great in their stock form, owners started to modify them to better handle the harsher environments. One of the most important modifications that can be made to these vehicles is an off-road bumper. These aftermarket bumpers allow for better protection versus the light metal and plastic that makes up the stock bumper on the vehicles, allowing for collisions with the terrain without serious damage. An upgraded bumper also has a more optimal approach angle, increasing the maximum angle the vehicle can climb from a horizontal plane without interference. Although the stock bumper is great for on-road driving, it does not meet expectations off-road. Aftermarket bumpers are very popular in the off-roading community, and many companies have been established in the market for many years. A few of the large companies include: CBI Off-Road Fabrication, Addicted Off-road, Northwest Trail Innovations, and Shrockworks 4x4 Products. While they make various other off-road components, they specialize in bumpers and other protection products. Each bumper is unique, but they all come fully fabricated and cost anywhere between $600 and $1200 before shipping and painting. This can be a daunting price point for enthusiasts just getting into the sport with other many other components they would need such as suspension, a rear bumper, and a winch.

There are three main types of bumpers being made by these companies as well: solid plate (Figure 2.1.1), tubular (Figure 2.1.2), and a hybrid of the two (Figure 2.1.3). The most popular style is the plate bumper since it blends well with the shape of the vehicle’s body versus the open-look of the tubular bumper. Each type of bumper made by these companies can be bolted onto the stock location, but some may require a new mounting point for strength if they are going to start winching. This is important because someone with little to no technical knowledge can install one of these bumpers, increasing the market size. Customers only have to fabricate an extra piece on their vehicles only if they feel they need to. Winching requires this extra plate because of the extreme forces that will be experienced at the frame. Below, Figure 2.1.4 shows an example of a winch in action while Figure 2.1.5 shows the damage that can be caused without the modification to the frame rails.
Although many companies manufacture a front, off-road bumper for the first gen Tacoma and the third gen 4Runner, none of them offer a Weld-it-Yourself (WIY) kit option. By designing a bumper that can be easily assembled without the need for special part holders, anyone would be able to, or have a trusted welder, assemble the bumper while saving money in the end. A cost analysis will have to be done at the end to make sure this holds true. I will also see how much it would cost to sell a fully fabricated bumper like the already established companies. Since both bodies are designed around the same frame, one design can work for both vehicles increasing the market size. Since this type of bumper has not been introduced for these vehicles, it definitely has the potential to thrive.

Figure 2.1.1 – Plate Bumper
Figure 2.1.2 – Tubular Bumper
Figure 2.1.3 – Hybrid Bumper
Figure 2.1.4 – Warn M-8000-s Winch
Figure 2.1.5 – Frame End Cap Failure
2.2 Literature Review

In order to effectively design an off-road plate bumper, I need to familiarize myself with the related subjects. This project requires knowledge in Design for Manufacturing and Assembly, material selection, and materials joining. By conducting this research, I have gained the necessary tools to complete this project.

2.2.1 Design for Manufacturing/Assembly

Design for Manufacturing (DFM) is the integration of product design and process planning which allows for an end product that is easily and economically manufactured. Design for Assembly (DFA) is the method of design a product for ease of assembly. Components can be produced at a low cost while keeping fit, form, and function of the end part. DFM/A allows potential problems to be found and fixed in the initial design phase where no resources have been wasted by scrapping them. This task is usually performed by a manufacturing engineer when they conduct a design review for an existing part. Some guidelines (as well as many others) as specified by Engineers Edge is as follows:

- Design around standard cutters, drill bit sizes or other tools
- Avoid small and intricate features such as holes and slots
- Design using “off the shelf” standard or OEM components
- Design for ease of fabrication and assembly
- Avoid complex tooling and equipment
- Simplify design and assembly (KIS)
- Design tolerances must be within the manufacturing processes capabilities
- Design parts to orient themselves (i.e. self-fixturing)

The design stage is very important and highly influential in the end-product’s cost, quality, and time to market. These guidelines must be taken into account for a successful and cost effective final product (McLean/Engineers Edge, 2011).

Dr. David Stienstra of the Rose-Hulman Institute of Technology states that in order for good DFA, the engineer must cut down on the number of parts in the assembly, design parts with a self-locating feature, and reduce the number of manufacturing operations. In order to effectively use DFA in this project, I have to take a look at the total number of parts being used and see if I can merge any of them together, or take it out completely. This will save time and money in the assembly step. In DFA, a big push is to get rid of unnecessary fasteners. Since this project is being welded together, the fasteners are not as important. I will have to take a look and see if the metal can be bent at a certain spot instead of being welded to another plate.

Since the bumper will be welded together during final assembly, it is important to make the design work well so there will not be extra steps grinding the metal for prep. Having the components fit up to each other well will allow the weld quality to go up. Having a large gap
between the parts will cause shrinkage and give some distortion along the seam. It is important to
leave enough space for the weld to get good penetration while keeping it a tight-fit (Manner
2016). If the space between the pieces getting welded together is not large enough, then there
will be not enough penetration. If this was the case, the welder would have to go in and grind the
metal to make room for the weld bead. If the design accounted for this in the first place, the
assembly would take less time and it would end up costing less as well. Another factor to take
into the design is the finish of the surface. If a perfectly smooth surface is required, MIG would
not be a good choice. However, if there can be some spatter on the material that can be taken off
with some light grinding, then MIG would be the correct choice in the design because of its low
cost.

Since the components of the bumper are going to be cut, either water-jet or laser, they have to be
designed in a way to accommodate for that. By making sure the components can be cut in 2D is
important since most cutting processes can only do that. If there was a complex angle in the Z-
plane, the part would have to be cut with a different process, or outsourced to a different cutting
facility. This is important to take into consideration since there would be a longer lead time on
the components to start assembling the bumper. Tolerances for the cut components are also
important. According to Laser Services USA, overall length and width have a tolerance range of
± .001” - .020” for a laser cut part. The hole diameters and internal machined features have a
tolerance of .005”. According to Waterjets.org, the water jet process can get within ± .002”.
Some water-jet companies have a taper issue though, cutting off the edges unevenly. A local
water-jet company in San Luis Obispo has a variable nozzle to combat this error. It corrects itself
at a certain angle to get a flat cut on the material.

2.2.2 Material Selection

The type of material being selected is a major factor in any manufacturing project. To design and
manufacture an off-road bumper, material will need to be chosen for the components being
fabricated as well as the fixtures (if there are any). Many types of materials are being used for
manufacturing today such as composites, organics, and metals. Of them, metal is most
commonly used for the protection of an off-road vehicle. While steel and various steel alloys
have been more popular in the past, some companies, such as Pelfreybilt, are starting to
introduce aluminum skid plates. The aluminum armor is harder to manufacture, but much lighter
on the vehicle compared to steel, allowing for better drivability and maneuverability. Both steel
and aluminum are good choices due to their cost per weight, strength, and material properties.

Generally, off-road bumpers are being made structurally out of steel plate and steel round tubing.
Both have unique characteristics and need to be looked into more to be used for this project.
Steel plate is usually rolled out in two ways: hot rolled and cold rolled. “Hot rolling of sheet
ingots carried out first since greater reductions in thickness can be taken with each rolling pass
when the metal is hot” (Smith, 2005). According to Metal Man Knows from the Metal
Supermarkets, cold rolling is always done after hot rolling has taken place. The steel is processed further in a cold reduction mill at room temperature allowing it to have tighter tolerances and a better surface finish. Both hot and cold rolled processes are followed by an annealing process to soften the metal. Hot rolled steel is typically less expensive compared to cold rolled steel since there is no re-processing times (Wick, 1960).

Round steel tubing is usually found in two different ways, welded round steel tube (HREW) and DOM steel tube. According to the Metals Depot, HREW is a hot rolled electric welded round tube. It is structural grade steel, but dimensional accuracy and precision tolerances are low. There is also a raised welded seam on the inside of the tubing. DOM steel tubing is a welded mechanical round steel tube with no internal weld seam. This tubing is drawn over a mandrel to produce more exact dimensional accuracy and tolerances. This type of tubing is recommended for high stress applications, increased mechanical properties, strength, and uniformity. DOM tubing is used in many bumper designs because of its strength.

There are numerous steel alloys that could be used in this application so they need to be researched and taken into consideration. Out of all of the steel alloys, A36 is the most common one. Since it is only hot rolled, it is cheaper to produce but it will have a rough surface finish. The yield strength of A36 is also lower than most alloys coming in at 36,300 psi. This type of steel is also more difficult to machine down. Since I will be using a water-jet cutter for the sheets, this should not be an issue. 1018 mild steel is the next most common alloy, but this is cold rolled. It is very similar to the A36, but since it is cold rolled, it has a better surface finish and physical properties such as strength, ductility and ease of machining. The yield strength of 1018 steel is higher than A36 at 53,700psi, but there is a significant difference in price. Finally, a high grade alloy is 4130 chromoly steel. It has an even higher tensile strength at 63,100 psi and good malleability. This alloy is also easily welded as well as being considerably stronger and more durable than the other two, but is the most expensive per pound (Oberg, 2012)

Lightweight and corrosion resistance is where 6061-T6 aluminum is used best. It is easy to weld and machine on making this aluminum alloy a good fit. 6061 is frequently found in aircraft construction and is one of the most common grade of aluminum, but requires a specific welding process to join together. The density is three times less than that of steel, but costs more per pound. Another commonly used grade of aluminum is 7075-T6. It is used primarily in the aerospace industry because of its high strength, making it comparable to many steel alloys while keeping the weight down.

Stainless steel is another commonly found type of metal in the automotive industry. Stainless has high corrosion resistance compared to typical alloy steel and similar yield strengths as well. Stainless steel is more expensive per pound compared to common alloy steels, but is still a viable option due to weldability and strength.
With the highest strength to weight ratio, titanium is used in high-end applications such as racing, aerospace, and health care. Titanium has a higher yield strength than the most high-end chromoly steel, but comes at an even greater expense. Even though the price of titanium is decreasing over time, it is still about 10 times more expensive than alloy steel (Online Metals, 2011).

Material selection will depend on the manufacturing process selection. In a fabricated part such as an off-road bumper, steel would be the better choice due to the sub-par fatigue characteristics of aluminum, especially along a weld joint as well as the cost per pound.

2.2.3 Welding Processes

Welding is an important part of the metal fabrication process, and there are many styles that can be taken into consideration. Of the many processes, I will be looking into GMAW, GTAW, SMAW, and FCAW. In order to choose the best welding method for this project, I have to look at the advantages and disadvantages of each.

Gas metal arc welding (GMAW), or MIG welding, is a process that uses a continuous bare, solid or tubular wire wound on a spool as the electrode. This thin wire goes through a wire feeder and out the nozzle of the welding gun to contact the work piece. The weld is protected by a shielding gas which also comes out of the welding gun at a controlled rate. Typical shielding gases are 100% CO\textsubscript{2} or a mixture of 75% Ar and 25% CO\textsubscript{2}. GMAW is typically the most common form of welding in the automotive industry since it can be highly automated with the wire feeding feature (Strahl, 2001).

Gas tungsten arc welding (GTAW), or TIG welding, utilizes an arc established between a non-consumable tungsten electrode and the work piece. A filler rode is used as the filler metal to join the two pieces together, but this is not always required. If the space is small enough, autogenous welds can be made without the use of a filler rod. The arc and weld puddle is protected by an inert shielding gas, usually argon. TIG welding is one of the most versatile methods of welding since it can be used on many types of metals and their alloys as well as varying thicknesses. TIG welding is one of the slowest processes though, making it one of the more expensive ones to use (Strahl, 2001).

Shielded metal arc welding (SMAW), or stick welding, is a manual process that uses an arc established between the tip of a covered metal electrode and the work piece. The electrode becomes a filler metal and mixes with the molten base to form the weld metal. This is known as a fusion welding process since electricity passes through the electrode and the work piece. The electrode uses a flux covering that is decomposed in the arc to produce gases and slag to shield the weld from the atmosphere. This helps create a better weld with less defects. SMAW is quick and is used on a variety of metals, but takes time to remove slag from the weld (Strahl, 2001).
Flux cored arc welding (FCAW) uses both the shielded metal arc processes and the gas metal arc welding processes. This makes it similar to GMAW, the main difference being a flux cored electrode wire is used instead of a bare solid wire. Two of the main processes in FCAW are self-shielding, and gas-shielding FCAW with the latter requiring an external shielding gas in addition to the flux core to shield the weld correctly. FCAW is being used to replace SMAW and GMAW processes in areas such as shop fabrication, maintenance, and field erection. Advantages of this process include being used outdoors under drafty or windy conditions, and producing a higher deposition rate. A disadvantage is that it can only be used on ferrous alloys and some nickel-base alloys (Strahl, 2001).

Other processes include submerged arc welding, plasma arc welding, electroslag and electogas welding, as well as many others. The processes looked at are the most common in industry and highly available in a commercial setting. Below are figures of the processes discussed.

![Figure 2.2.3.1 - GMAW](image1)

![Figure 2.2.3.2 - GTAW](image2)

![Figure 2.2.3.3 - SMAW](image3)

![Figure 2.2.3.4 - FCAW](image4)

### 2.2.4 Bolt Sizes

While most of the fastenings for this bumper will use the vehicle’s stock location, one bolt on each side will have to be added for added support. Determining the correct size of the bolt as well as the grade is very important since there will be a large moment and force surrounding them. According to Huw Kidwell of Nord Lock, “the function of a bolted joint is to clamp two or more parts together. However, the specific purpose of a bolt is to create a clamp force in the joint and not to sustain shear, bending, or excessive dynamic loads.” This is very important since the bolts that will be used to hold the bumper in place need to counteract all of those as well. Too
large of a bolt can cause the joint to have a low clamp load and a high risk for fatigue failure. These bolts are also more expensive since they are larger versus a smaller one. Too small of a bolt, and you can still lose clamp load and cause the joint to fail.

In order to determine the correct bolt for the specific joint, you must:

- Identify the load case
- Determine the necessary clamping forces in the joint
- Choose the smallest bolt diameter that can support the clamp load
- Choose an effective bolt securing method (i.e. nut)
- Decide on the most appropriate tightening method

Dr. Jeff Vogwell of Bath University, UK, in the Department of Mechanical Engineering states, “a good bolted joint is one which places the bolt in tension and hence the clamped members in compression. Friction between the camped members helps resist any sliding of the joint thus protecting the bolt in shear.” If this is followed, a correct bolt size will be chosen allowing for the joint being bolted together to have the most strength and not fail.
3.0 Design

This section will deal with the actual design of the bumper and key features involved in it. This section will also go over important design changes.

3.1 Bumper Design

The major design needed for this project to be successful is the plate bumper. The bumper’s design needs to be stronger, reliable, and have an increased approach angle while being cost effective to the end user. The bumper also has a scope of being close to 110 pounds after assembly. This design also needs to incorporate design for manufacturing and assembly (DFM/A).

In order to design the bumper, reverse engineering had to be done on a stock third generation Toyota 4Runner to get the correct dimensions of the frame horns and other key mounting locations. The stock bumper was removed to expose the three critical mounting locations: the front mounting, side mounting plate, and bottom tow points. Metrology equipment and techniques were used in reverse engineering these locations. A caliper, with an accuracy of 0.02mm, was used to measure the height and width of the frame rails. A metric steel rule, with an accuracy of 0.5mm, measured the distance between two holes as well as their location. The distance between the centers of the frame rails as well as the height of the rails and cab was measured using a class 2 metric tape measure and comparing it to spec drawings from Toyota.

Because of the poorly designed front plate by Toyota, a new, stronger plate has to be welded in its place. This will be the only non-stock feature for this design, but must be completed if the end-user wants to use this bumper as a winching platform. Without this modification, the frame’s endcaps will tear and cause damage to the vehicle. However, if the end-user will not be using a winch, they can skip the modification and not mount the bumper on the front plate. The bumper will still be strong for use which is backed up by the finite element analysis (FEA) done below.

Once each of the key features was measured, and rudimentary part drawings were made, SolidWorks was utilized to start the computer-aided design process. The mounting portion of the bumper is the most important part since it will be experiencing forces in various directions as well as moments from winching. The thickness of the plates being used is important as well since they need to be just strong enough for those forces without too above them. After researching the companies listed in the Literature Review section, it was made apparent that 0.25” was the standard mounting thickness. This will be proven to be sufficient below in the FEA analysis.

After the research done on the various alloys of steel, it was decided that A36 steel plate would be used due to the wide availability of it, the cost vs. strength ratio, and the high weldability of the material. The strength of the metal is approved in the Finite Element Analysis section in the
Results below. A36 is not as machinable as 1018 steel, but the components are going to be cut using laser, so it does not make a difference. The cutting process chosen is shown in detail in the cost analysis section below.

On the topic of laser cutting, each piece has been designed to be cut by a 3-axis waterjet cutter. This was done in order to get rid of complex machinery, such as a 5-axis cutter. These cutters are very expensive so most companies do not have them, or have access to them. This brings the cost of cutting the material significantly down since each part is made in a 2-D plane. The thickness of the mounting plates as described below will be cut from ¼” plate steel while the aesthetic front plates will be cut from 3/16” plate steel. Design for Manufacturing of the bumper was taken into consideration to increase the manufacturability of it while decreasing the overall cost. While the overall number of parts is high, the complexity of the assembly and the lack of specialty tools, such as a fixture, was a big part of it. Each bumper is made up of 42 parts, 26 of them being unique. Many of the components are also designed using tooth and slot construction to locate the parts on the bumper (Figure 3.1.1). The components are broken up into two sections (aesthetic and mounted) listed below (each component drawing is located in the Appendix as well):

**Aesthetic Components**

- Front Middle Plate
- Front Upper Plate
- Front Lower Plate
- Angled Upper Plate x2
- Angled Middle Plate x2
- Angled Lower Plate x2
- Side Upper Plate x2
- Side Middle Plate x2
- Side Lower Plate x2
- Rear Endcap x2
- Large Gusset x2
- Center Gusset
- Light Mounting Plate x2
- Light Mount Gusset x2
- Light Mount x2
- Top Plate
- Grille Guard
- Winch Plate Support

**Mounting Components**

- Lower Frame Mount Channel D
- Winch Mount Plate
- Side Tube Mount x2
- Front Frame Mount Plate x2
- Lower Frame Mount Channel P
- Side Frame Plate x2
- D-Ring Shackel Hanger x2
- Vertical Plate x2

While bending would decrease the overall number of parts required to assemble the bumper, the steel would be more brittle than its welded counterpart. This could cause the bumper to fracture if it took an impact which is not ideal for off-road use. It would also require that the plates go to another facility to get precisely bent on a large press brake. Once the plates are bent, the creases would then have to be welded to ensure that the plates would not get bent back from an impact.
Instead of going through these extra steps, adding the few extra parts would be more beneficial in order to keep transportation and manufacturing costs down.

At first, a steel tube was going to be used as the bottom brace, but standard channel steel was chosen instead since it would be nearly as strong while cutting back on the weight from the lower connecting plate (Figure 3.1.2). A vertical mounting plate was designed perpendicular to the channel steel. This plate has unique chamfers in it to locate the angled aesthetic components, and more importantly, increase the approach angle of the bumper (Figure 3.1.3). The mounting holes on the bumper were designed around the stock frame mounts as well as one reinforced plate needed to be welded to the front of the frame rail as described in the Background earlier. In order to reinforce the sides of the bumper, a connecting rod had to go from the bumper to the side of the frame. This will prevent the bumper from crushing in on itself and damaging the vehicle. This tube can be seen below in Figure 3.1.2. The horizontal plate that connects both mounting sides will hold the winch. This plate will experience a tremendous amount of torque and downward force from the winch, so it must be strong. An FEA analysis will be conducted on this plate to determine the failure point of the plate.

After discussing with users on various Toyota forums, it was made apparent that light features were a must have. On the angled plates, a large 5” diameter hole is included with a mounting tab and gusset to withstand the downward forces it will experience off-road. These holes are cut parallel to the front face in order to have all of the light to go straight out. A 5” DOM ID tube will be welded on the inside of the plate to direct the light outside of the bumper instead of having it trapped internally. A smaller 2.5” diameter hole is in the same plate to place an aftermarket LED fog light, or something similar. This light is meant to be pressed in as opposed to bolted down like the larger diameter light.

Each component on the Bill of Materials can be purchased by numerous metal companies in person or online. They were designed in SolidWorks to match the readily available stock in order to get very exact pricing.

The purpose of the design is to minimize the complexity of the assembly. This is done by having the self-locating tooth and slot features on the main components. Each plate can be located and welded to the bumper by the tooth and slots and matching the angles of the plates around it. The only tools required by the shop to assemble this bumper are a welder, some clamps, and basic hand tools. This will allow Maglio to continue their normal machining operations without taking too much space to manufacture the bumpers. The steel plate will be outsourced to a CNC waterjet facility to keep the footprint in the facility low. Since the bumper is a specialty off-road item, it will likely have a low volume, so it is important to keep the shop impact low. Figure 3.1.4 shows an isometric view of the bumper in its entirety.
Figure 3.1.1 – Tooth and Slot Features

Figure 3.1.2 – Mounting Assembly

Figure 3.1.3 – Vertical Plate

Figure 3.1.4 – Bumper Isometric View
3.2 Design Changes

In order to better implement DFM/A methodologies, I decided to get rid of a few of the aesthetic plates. Figure 3.2.1 shows the old design with the triangular side plates below. Initially, these plates connected the angled to the side plates. It blended the corner to have more of a radius, but taking out these plates allowed for 6 less parts and 8 less welded edges. Overall, this would make the bumper cheaper to manufacture. The other plates had to be extended to meet each other once the triangle plates were taken out, so a complete redesign of them was done. These plates were made to be easily waterjet-cut in 2-D, or saw cut since some of them are nominal bar stock. This will cut down on the total manufacturing cost of the bumper as well. The angled middle plate had to use some 3-D geometry on the large light feature, but these will be easy to manufacture on the waterjet. After the initial FEA analysis was complete, it was made apparent that the winch plate needed to be reinforced. A nominal bar stock of 1.5” coming down the back of the plate will do just that by being welded to the front frame plate and the side vertical plates. This cuts down on the displacement the bumper had when a load was applied as well as cutting down the stresses it endured. Overall, the design changes allowed for not only a stronger bumper, but cheaper manufacturing costs and ease of assembly.
4.0 Methods

This section will first discuss the finite element analysis (FEA) completed on the model in Solidworks. After the FEA is complete, a prototype of the bumper will be assembled and analyzed from CNC cut cardboard.

4.1 Finite Element Analysis

FEA is a type of program that uses the finite element method to analyze a material or object and find how applied stresses will affect the material or design. This will help determine any points of weakness in the bumper design before the actual bumper gets manufactured. In order to get the bumper ready for the analysis, it had to be made into one solid part. Because of the way the parts are joined together in the model, a mock weld had to be added in each of the open sections. Not only will these extrusions strengthen the whole model, but they show exactly what should happen since those channels will be filled with weld material. Once each of the holes in the model was filled, each part was able to be combined making one solid part.

In order to implement the FEA, three components have to be set-up: the fixed geometry, the load being applied, and finally a mesh that the analysis will run over. The fixed geometry has to match exactly how it will be bolted onto the car. This is done by placing the on each of the surfaces of the model that will be bolted to the frame of the car. A split line is used in order to get a small area around the bolt holes to be fixed in place. The split lines were placed on the front mounting plate and the lower mounting plate. By doing this, it gives a more realistic look into how the bumper will be attached instead of just doing the inner diameter of the bolt holes. This will let the computer know that these are fixed points and should not move around when a load is applied.

The next part that has to be added is the load being applied to the model. This will replicate the forces and the moment being applied to the bumper. These forces are brought on by the winch which is bolted onto the bumper. Since the winch line is not located right on top of the winch mounting plate, a new coordinate system had to be made in order to raise the load. Using the remote load feature, a load can be applied 2” above the mounting plate, which is where the winch line will be coming out. This load simulates the car being pulled by the winch line. It will be tested at 5000lbs (an average load of the winch) and 9500lbs (the max load the winch can handle). A moment is also applied on the same coordinate system and it will demonstrate the torque the bumper will experience from winching.

Finally, a mesh had to be created on the model so the computer can run the finite element analysis. A curvature based mesh was created with a very fine mesh density. This style of mesh places small triangles around each of the holes, getting a more precise analysis around them. The max element size is set to 1.00” while the minimum number of elements in a circle is set to 8.
Once the settings are applied, the computer creates a mesh over the entire model. This is what the computer will analyze using the finite element method. The picture below shows the forces being applied (in purple), the fixed geometry (in green), and the mesh (denoted by the small triangles everywhere).

Figure 4.1.1 – FEA Components
4.2 Prototype Analysis

In order to physically test the design, a cardboard bumper prototype needs to be made. While the cardboard being used is not the correct thickness for each of the plates, it works as a great example of how each component will fit together on the actual bumper. The cardboard is cut out on a CNC cardboard cutter on campus. The cutter does not have as tight tolerances as the waterjet cutter that will be used for the end product, but each part will be within ± 0.030”. The cardboard cutter is also only able to cut in 2-D unlike the waterjet. Some parts have to be modified to work on the cutter such as the large light holes on the angled middle plates. Even though the parts won’t come out as nice as a waterjet cut part would, they will work well for the prototype application. Each part will be glued together in the same way they will be welded together on the actual part. Assembling the bumper this way is a good indication on how the real bumper will be assembled. The prototype will show various flaws in the design (if any) in terms of ease of assembly, manufacturability, and fitment errors. Figure 4.2.1 below shows the cardboard components that are waiting to be assembled into the prototype.

Figure 4.2.1 – Cardboard Bumper Components
5.0 Results and Discussion

In this section, the results from the FEA study will be discussed, as well as how the prototype bumper went. These results will include what went wrong and what went right with the studies conducted. Various questions will also be answered to interpret the findings.

5.1 FEA Study Results

Setting up the FEA study was discussed in detail in the previous section. After running the first round of simulations in Solidworks, it was found that the stress was too high on the bumper with only the 5,000lb force. The yield strength of the material is 36,300 psi, but a few parts of the bumper exceeded this highlighted in Figure 5.1.1 below. Since the stress is higher than the yield strength in those highlighted zones, the bumper will fail. This can also be seen in the displacement image shown in Figure 5.1.2. The max displacement on the rear of the winch plate exceeds 0.40” which is shown in red. This kind of movement will cause the bumper to fold in on itself and make it completely useless. This result was completely unexpected at first. I thought the gussets that were placed in the design would be enough to reinforce the bumper, but this was proven wrong.

After researching what could make the winch plate stronger, a small flange coming down the back will make it much more rigid. This is due to the moment of inertia equation, where \( I = \frac{bh^3}{12} \). By adding height to the plate, it will increase the moment of inertia by an exponential factor of 3. This flange will span the length of the winch plate and come down 1.5”, increasing the moment of inertia on the rear of the plate from \(.0327\text{in}^4\) to \(11.234\text{in}^4\). Running the new simulation in Solidworks proves that the bumper is much more rigid now at the 5,000lb benchmark. Figure 5.1.3 highlights the two small sections where the stress is higher than the yield strength, but this is completely normal. The displacement image that is shown below in Figure 5.1.4 displays that the bumper only moved 0.012” in the same spot as the previous test. This is roughly 33 times less movement the previous iteration of the bumper. While there are more colors shown in Figure 5.1.4 compared to 5.1.2, the overall displacement is much lower. The areas that are blue in the previous figure were still moving a significant amount, but not as much as the actual winch plate. Since the winch plate is hardly moving now, the other components start to show their actual movement. The largest displacement from this simulation is just over 0.028” shown in red on the top plate.
While the bumper will not be used on a heavy vehicle and should not reach this kind of force, it is important to test the maximum the winch can handle to see the effects it will have on the bumper. By changing the remote load to a 9,500lb force, we will be able to see how much more the bumper will be stressed out as well as how much it will displace. Compared to the second stress test, the 9,500lb load did increase the stresses applied to the bumper, but only marginally. Only a few more areas are higher than the yield strength which is highlighted in the figure below. Since the bumper should never experience this high of a force, the bumper does not need to be reinforced any more than it already is. Looking at the displacement chart in Figure 5.1.6 shows a very similar spread compared to Figure 5.1.4. The winching plate moved 0.025” this time while the top plate moved 0.053”. Even though the displacement doubled from the previous test, a 0.050” movement on a non-important piece is completely fine. This is also reinforced since the forces should not reach the max load of the winch, but if it does, the bumper will still hold up. These results also prove that A36 steel is a viable alloy to choose. Since the stress is below the yield strength of the A36, it does not make sense to make it out of a stronger alloy that would also be more expensive.

![Figure 5.1.1 – Stress Test 1](image)

![Figure 5.1.2 – Displacement Test 1](image)
Figure 5.1.3 – Stress Test 2

Figure 5.1.4 – Displacement Test 2

Figure 5.1.5 – Stress Test 3
5.2 Prototype Assembly Results

In order to physically test the bumper and how it was to be assembled, a prototype had to be made. The prototype was made from CNC cut cardboard that was cut on Cal Poly’s campus. The components, as shown in Figure 4.2.1 in the previous section, were assembled to match a production bumper’s assembly. Each piece was fitted together and tacked into place in order to get the initial shape of the bumper. A larger glue bead was then placed in order to fully attach the bumper components. This would be very similar to a tack weld, and a final finishing bead. In order for this prototype to be successful, each piece that does not have a locating tab has to be placed in the correct location, otherwise it will not work. Figure 5.2.1 and Figure 5.2.2 below shows the fully assembled prototype.

Once the prototype bumper was assembled, it had to be fitted onto the vehicle. The stock bumper and tow hooks had to be removed in order to do this. With the bumper removed, the prototype could be lined up to get the top plate trimmed to the correct size and shape of the body. Overall, the bumper sat where it was supposed to go. Figures 5.2.3-5.2.5 show the bumper fitted on the vehicle. The front frame mounts were glued too close to the lower frame mount holes, causing them to not align by ¼”.

The next issue with the prototype was the overall height. The bumper was too tall for the body of the car. It sat between ½” below the correct location. In order to fix this, the overall height of the vertical plates will have to be lowered. This is problematic if the user wants to install a winch though. The vertical plate will have to be completely redesigned in order to place the winch plate lower to account for the loss in height. There needs to be at least 9 ½” between the top of the
winch plate and the bottom of the top plate to place a winch inside of the bumper. The redesign will have to lower the overall height by at least 1” and dropping the location of the winch plate. This issue was unexpected since the height of the frame, and the body had an accurate measurement. These heights were checked with technical drawings and rechecked using a precise tape measure.

The final thing that needs to be changed with the design is tucking in the front, far corners. Right now they stick out quite far, so in order to prevent the bumper from colliding with various objects, the angles will need to come in closer to the body. This was a little more expected since I didn’t know exactly how the body sat above the frame. This is a relatively easy modification in the design, done by just changing the angle of the top plate.

Figure 5.2.1 – Prototype, Rear
Figure 5.2.2 – Prototype, Side

Figure 5.2.3 – Assembly, Front
5.3 Cost Analysis

In order to making the bumper competitive on the market, it would need to be sold for less than the average price for a bumper on the market at $1,000. A full cost-analysis of the bumper had to be done in order to see whether or not the bumper is a viable option. Since waterjet and laser cutting would both provide tight enough tolerances and a good finish, the cutting cost will determine which one will be chosen. Various laser and waterjet cutting companies were asked to give a quote based off of the parts that needed to be cut out. They gave a quote in batch sizing of 1, 10, and 100 sets of the bumper components in order to see how many would need to be bought to make the budget realistic. Table 1, 2, and 3 in the Appendix below shows the full cost analysis including the average price for the two types of cutting, the material cost of the steel, and the total cost to weld the bumper together. The cost analysis does not include the cost of the welding rig as well as the rent since the owner of the machine shop already has the space needed for this process and the Miller welding rigs.

The total cost to make an infrequent, single bumper would be about $2,066 for waterjet cutting and $633 for laser cutting. This is a difference of $1,433 between the two processes, and $367 between the laser cutting process and the average bumper price. While this is not a sustainable business model, selling the bumper at $1,000 would still result in a 37% markup.

Another study showed how much 10 bumpers would cost to manufacture. The cost for waterjet cutting is $1,440, while the cost for laser cutting is $566. Using the laser cutter, this would result in a 44% markup. This batch size is more sustainable than the previous one, and the final price of the bumper can also be decreased to make the customer happier in the end.

The final batch sized used was a quantity of 100. Waterjet cutting would cost $1,353, and laser cutting would cost $531. This price is not much different than the batch size of 10, so either one would be beneficial to make. Both of these sizes have the potential to be profitable. Going further than 100 units per batch would not make sense for this type of product since it is already in a limited market, the shop would lose money in the end from not selling all of the bumpers they made. Since the difference between the batch sizes of 10 and 100 is only $34.69, it does not make much sense to take on the risk of buying enough materials for 100 bumpers. Once the 10 are sold, another batch can be purchased to keep up with the demand. This will cut down on storage costs in the shop as well as clutter from the material.

5.4 Final Remarks

Besides the setbacks found through the physical bumper test on the vehicle, it went together extremely well with no major issues. By lowering the height of the vertical plate, and decreasing the approach angle to drop the winch plate further down. The biggest downside to this change would be roughly a 15° loss in the approach angle. The overall weight of the bumper is a little over the initial scope at 120 pounds; it is relatively close and should not over-stress the front
suspension. While I knew there would have to be some trimming done to the top plate, the results were not expected at all.

These design changes are doable, but a second prototype will be needed to make sure each of the changes fixed the problem. The FEA analysis will not need to be conducted again since only the heights and angles of the components will need to be changed. The structural components are staying the same, and these are the most important of the bumper. None of the results from the finite element analysis and prototype build/analysis were difficult to understand. There was a learning curve to get the FEA up and running, but after it was completely set-up it was very easy to manipulate the inputs to get the data that was needed. The overall benefits of the bumper are also very similar to that of other competitors, and each of the objectives has also been met. These include a fully designed bumper, FEA and prototype analysis, and a full cost analysis.

This design has the potential for success as long as the changes are implemented correctly. Once the height of the bumper is corrected in the design, a new prototype can be made to check for fitment one last time. A finite element analysis will have to be done again just to make sure the plates are acting in a similar way to the previous design. With the slightly modified design, the product can be marketed below the average cost of a current bumper while still making a profit on it in the medium volume of production. Not including the cost of the material, the only added cost to the shop is that of energy to run the welders.
6.0 Conclusions

The 1996-2002 Toyota 4Runner and 1996-2004 Toyota Tacoma had many shortcomings in terms of the stock front bumper. Since it is extremely flimsy, the bumper would not take the abuse an off-road vehicle requires. The bumper also has a poor approach angle so it would rub on obstacles well before the wheels make contact with the rock or trail. While there are various companies that manufacture an aftermarket, off-road bumper, they are all extremely expensive and do not have a DIY kit for the people that want to fabricate their own bumper but not design it. Each of the objectives was met, including: reverse engineering the front end of the vehicle, modeling the bumper in CAD, performing a FEA, manufacturing and assembling a prototype, and finally conducting a full cost analysis.

By making a working design, Maglio, Inc. is now able to start manufacturing a test bumper in order to see how close the FEA was to what will actually happen when the bumper gets winched on. Many design changes occurred along the way in order to make the bumper easier to assemble/manufacture, as well as be stronger. These changes were uncovered from the simulations done in SolidWorks, and having conversations with the client to determine what would make it easier to build.

This project allowed me to apply all of the learnings I have had in the manufacturing classes as well as quite a few industrial engineering skills as well from the IME department at Cal Poly. By completing this project, I was able to become more familiar with SolidWorks that will help me much more in my future careers. I also taught myself useful skills such as conducting a Finite Element Analysis in SolidWorks, and using CAD models to be brought to life with a 2-axis cardboard cutter for the prototype. Seeing a project all the way through, from inception to production, was a very neat experience, allowing me to see the numerous steps that are required in making a useful and quality product. Many changes happened along the way as I got more familiar with visualizing the easiest way to put together the product and trying to get rid of unnecessary components. Since there were many design changes, the overall design time took much longer than expected, but was more accurate to the final design than it would have if the mistakes were found during the manufacturing step.

Prototyping the bumper proved to be very useful in order to see any design flaws, which did occur. Once the changes have been made to incorporate these fixes, a second prototype would have to be made to make sure everything was alright. It is tough to make the first prototype exactly right the first time, so one change I would make to this project would be to schedule more time to make a second, corrected prototype. The only reason I did not was due to time constraints on the cardboard cutter, which was being used by another class and could only be operated with the instructor present.
Overall, I learned a great deal about how to take a project from an idea to the design, and finally to a fully tested prototype. By doing this, I applied numerous skills I have learned from my time at Cal Poly in the Industrial Engineering major. Not only did I learn about how far I can push myself to finalize a product, but I enjoyed doing it.
### 7.0 Appendices

#### Table 1 – Bill of Material

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**Totals with Tax**

|                |            |            |            | $361.44 | $346.90 | $326.71 |

#### Table 2 – Waterjet Cutting Costs

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<td>30</td>
<td>$15.00</td>
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</table>

**Total Direct Costs**

- QTY 1: $633.94
- QTY 10: $555.90
- QTY 100: $530.21

**Indirect Costs**

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<tr>
<td>Shop Rent</td>
<td>Already Have Space</td>
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<tr>
<td>Millermatic Welding Rig</td>
<td>Own</td>
<td>$-</td>
<td>$-</td>
<td>$-</td>
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<td>$-</td>
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<tr>
<td>Energy Cost</td>
<td>1 month</td>
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<td>$100.00</td>
<td>$10.00</td>
<td>$100.00</td>
<td>$1.00</td>
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</tr>
</tbody>
</table>

**Total Costs with Laser Cutting**

- QTY 1: $733.94
- QTY 10: $565.90
- QTY 100: $531.21
Overview

Senior Project Design

MATERIAL: A36 Steel
FINISH: Black Powder Coat

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NAME: D Donlon
DATE:

DRAWN
COMMENTS:

A

Bumper

SCALE: 1:20
WEIGHT:

SHEET 1 OF 29
<table>
<thead>
<tr>
<th>Part Name</th>
<th>Quantity</th>
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<tr>
<td>Lower Frame Mount D</td>
<td>1</td>
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<tr>
<td>Lower Frame Mount P</td>
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<tr>
<td>Front Frame Mount</td>
<td>2</td>
<td>1/4</td>
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<tr>
<td>Vertical Plate</td>
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<tr>
<td>Center Gusset</td>
<td>1</td>
<td>1/4</td>
</tr>
<tr>
<td>Side Frame Mount</td>
<td>2</td>
<td>3/16</td>
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<tr>
<td>Side Frame Tube</td>
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<td></td>
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<tr>
<td>DRing Shackle Hanger</td>
<td>2</td>
<td>1/2</td>
</tr>
<tr>
<td>Front Upper Plate</td>
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<tr>
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<td>3/16</td>
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<td>Front Lower Plate</td>
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<td>3/16</td>
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<tr>
<td>Rear Endcap</td>
<td>2</td>
<td>3/16</td>
</tr>
<tr>
<td>Large Gusset</td>
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<td>3/16</td>
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<tr>
<td>Light Mount</td>
<td>2</td>
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<td>2</td>
<td>3/16</td>
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<tr>
<td>Light Tube</td>
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</tr>
<tr>
<td>Top Plate</td>
<td>1</td>
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</tr>
<tr>
<td>Tube Grille Guard</td>
<td>1</td>
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</tr>
<tr>
<td>Winch Support Plate</td>
<td>1</td>
<td>1/4</td>
</tr>
</tbody>
</table>
Senior Project Design

Mounting Assembly

Bumper

A36 Steel
Black Powder Coat

NAME: D Donlon
DATE: 

SCALE: 1:20
WEIGHT: 

REV:
SHEET 3 OF 29
Overview

Bumper

Material: A36 Steel
Finish: Black Powder Coat
Thickness: 1/4"

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NAME: D. Donlon
DATE: 

SIZE: A
DWG. NO.: 
FINISH:

SCALE: 1:10
WEIGHT:

REVDWG. NO.: 

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Winch Plate

Material: A36 Steel
Finish: Black Powder Coat
Thickness: 1/4"
Center Gusset

Material: A36 Steel
Finish: Black Powder Coat
Thickness: 1/4"

Center Gusset

Senior Project Design

Drawn: D Donlon

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**Side Frame Tube**

**MATERIAL:** A36 Steel

**FINISH:** Black Powder Coat

**Thickness:** 3/16"
DRing Shackle Hanger

Material: A36 Steel
Finish: Black Powder Coat
Thickness: 3/16"
Senior Project Design

Front Upper Plate

Material: A36 Steel
Finish: Black Powder Coat
Thickness: 3/16"

Drawing by D Donlon

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Scale: 1:10
Weight:

Sheet 13 of 29
Front Middle Plate

Material: A36 Steel
Finish: Black Powder Coat
Thickness: 3/16"

Scale: 1:10

D Donlon

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Senior Project Design

Front Lower Plate

Bumper

MATERIAL: A36 Steel
FINISH: Black Powder Coat
Thickness: 3/16"

DRAWN: D Donlon

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Senior Project Design

TITLE: Angled Upper Plate

A36 Steel

Thickness: 3/16"
Angled Middle Plate

Bumper

MATERIAL: A36 Steel
FINISH: Black Powder Coat
Thickness: 3/16"

5" Diameter Hole

105.18°

SCALE: 1:10
WEIGHT:

D Donlon

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Angled Lower Plate

Material: A36 Steel
Finish: Black Powder Coat
Thickness: 3/16"
Senior Project Design

Side Upper Plate

Material: A36 Steel
Finish: Black Powder Coat
Thickness: 3/16"

Drawn by: D Donlon

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**Senior Project Design**

**Title:** Side Middle Plate

**Material:** A36 Steel

**Finish:** Black Powder Coat

**Thickness:** 3/16"
Senior Project Design

TITLE:
Front Upper Plate

MATERIAL:
A36 Steel

FINISH:
Black Powder Coat

Thickness: 3/16”

SCALE: 1:10
WEIGHT: A

REV

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NAME: D. Donlon
DATE:

A SHEET 21 OF 29
Rear Endcap

Black Powder Coat

Material: A36 Steel
Finish: Black Powder Coat
Thickness: 3/16"
Senior Project Design

Title: Large Gusset

Material: A36 Steel
Finish: Black Powder Coat
Thickness: 3/16"

Drawn: D Donlon
Scale: 1:10
Weight: 

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Light Mount

Material: A36 Steel
Finish: Black Powder Coat
Thickness: 3/16"
Light Gusset

**Material:**
A36 Steel

**Finish:**
Black Powder Coat

**Thickness:** 3/16"
5" Inner Diameter

Light Tube

Material: A36 Steel
Finish: Black Powder Coat

Name: D Donlon
Date: 

Senior Project Design

Title:

A

Size: A

Drawing Number: Bumper

Scale: 1:10

Weight: 

Sheet 26 of 29

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Senior Project Design

TITLE:
Tube Grille Guard

MATERIAL:
- A36 Steel

FINISH:
- Black Powder Coat

Thickness: 3/16"

DRAWN: D Donlon

SCALE: 1:10
WEIGHT:

Sheet 28 of 29
Senior Project Design

TITLE: Winch Support Plate

MATERIAL: A36 Steel
FINISH: Black Powder Coat
Thickness: 1/4"

DRAWN: D Donlon

SCALE: 1:10
WEIGHT:

REVDWG. NO.
A

NAME DATE

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